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Different Suitability of Olive Cultivars Resistant to *Xylella fastidiosa* to the Super-Intensive Planting System

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Abstract: Until today, only Leccino and Fs-17 (=Favolosa®) olive cultivars proved resistant to *Xylella fastidiosa* subsp. *pauca* (Xfp) due to a low presence of bacteria in the xylem. Integrated disease management in olive growing areas threatened by the spread of Xfp is crucial to overcoming the environmental, economic and social crisis. Since the EU Decision allows for the plantation of resistant olive cultivars in infected areas, there is a need to define a suitable plantation system for these cultivars. The adoption of new planting systems, such as intensive and super-intensive (SHD), could compensate for the economic losses and restore the olive agroecosystem. The aim is to ascertain the suitability of the available Xfp-resistant cultivars to SHD planting systems that demonstrate the best economic and environmental sustainability. Hence, a five-year study was established in an experimental SHD olive orchard (Southern Italy) in order to analyse the main vegetative and productive traits of Leccino and Fs-17, together with four other Italian cultivars (Cipressino, Coratina, Frantoio and Urano), compared with the well-adapted cultivars to SHD orchards (Arbequina and Arbosana), by means of the von Bertalanffy function. The results indicated that cv. Fs-17 showed sufficient suitability for SHD planting systems, giving the best-accumulated yield despite some canopy growth limitations, whereas cv. Leccino did not show satisfactory results in terms of both vegetative and yield parameters, confirming its suitability for intensive planting systems. These results are useful for optimizing integrated resistance management in Xfp-infected areas by planting resistant host plants.

Keywords: integrated resistance management; Leccino; Favolosa®; von Bertalanffy function

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1. Introduction

The olive agroecosystem has long-lasting history and represents an invaluable local heritage for landscape, trade, and social traditions for the Italian people, especially in the Apulian region [1], where one-third of the country's olive trees are grown with a wide diversity accounting for between one-third to one-half of national olive oil production [2]. However, this agroecosystem is currently under severe threat by the occurrence of the plant quarantine bacterium *Xylella fastidiosa* subsp. *pauca* (Xfp), which was first detected in the olive agroecosystem in late 2013 in the Salento (Apulia region, Southern Italy) area [3]. Xfp is associated with the OQDS (Olive Quick Decline Syndrome), a severe plant disease that causes massive leaves scorching followed by branches wilting and tree death [3]. As of today, the Italian outbreak of Xfp, concentrated mainly in the south region of Apulia, has spread over 100 km, killing millions of olive trees, and is still expanding [4]; up to 2019, a total of approximately 54,000 hectares of olive orchards have been killed or seriously damaged [5]. The most susceptible olive cultivars (Cellina di Nardò and Ogliarola salentina) are the most diffused ones in the infected areas [6], where OQDS is causing an economic, social and environmental emergency [7]. Moreover, Xfp has also demonstrated an aggressive polyphagous bacterium with a potential threat to Mediterranean and European agriculture [8], which makes it presently considered a phytosanitary priority for all EU countries [9].

Several efforts have been made in order to define the best strategy for controlling Xfp. Agrochemicals did not appear to be the right strategy [10,11]. Nonetheless, an integrated disease management approach is possible in order to limit the spread of the pathogen: first of all, the use of resistant or tolerant host plants [12,13]. Indeed, an important agronomic management strategy to limit Xfp damages is the identification of cultivars that show tolerance/resistance to the pathogen for their potential use in the field or in breeding programs [14]. The use of pathogen-resistant cultivars in crop production is currently the most economical and effective way to reduce losses caused by diseases, as well as the most studied approach [15]. Up to now, converging lines of scientific evidence indicate that cv. Leccino has some tolerance traits to Xfp, which develop milder symptoms due to the smaller size of the bacterial populations in its xylem tissues compared to those observed on susceptible cultivars [8,16]. In addition, more recent observations on olive trees under field conditions identified cv. Fs-17 (=Favolosa®) is an olive genotype with more resistance traits [17,18]. A lower bacterial titre of resistant cultivars may also exert a beneficial impact on epidemiology as it may result in a lower rate of Xfp transmission, helping the containment of the disease spread [8].

The EU Decision ((EC) N. 2017/2352) [19] makes it possible for the plantation of new olive cultivars in infected areas but only with the resistant cultivar (Leccino and Fs-17), as a useful strategy to overcome the severe economic and environmental losses due to Xfp infections. Thus, once the planting of these resistant olive cultivars in infected areas becomes possible, integrated disease management will be needed. However, under recent climate change scenarios, it is crucial that the new olive orchards, planted with resistant cultivars, are coupled with the implementation of the current new orchard design and with a sustainable management strategy that can ensure constant production and, at the same time, protect the environment [7,15,20].

Olive orchard intensification proceeded in two stages. First, in the 80s, planting density was increased from 100 trees ha^{-1} in traditional orchards (low density, LD) to 400–600 trees ha^{-1} in intensive ones (medium density; MD) with lower vase-shaped canopies, adapted for efficient fruit harvesting by trunk shaker machines [21]. Later, a much bigger change was added in the middle 90s with the introduction of super high density (SHD) orchards (1500–2000 trees ha^{-1} [22]) with central leader trees in hedgerows to form continuous fruit-bearing canopies [23], fitting for over-the-row harvesting machines [24]. Compared to the MD system, several studies indicate that the SHD system represents a very encouraging advantage in terms of profitability through the reduction of production costs, thanks to full mechanisation from planting to harvesting, higher and more constant crop yield [23,25,26]. Mairech et al. [27] have conducted a spatial modelling analysis to investigate yield response to different olive orchards management systems around the Mediterranean and found that intensification from LD to SHD systems presented the greatest improvements in terms of productivity with an increase in yield ranging between 28 to 73%. The SHD olive orchard management system is spreading over 400,000 ha on five continents [28]. As a promising olive orchard management system, the yield performance of the SHD system is being studied, considering important agronomic aspects [22,24,29–32]. Furthermore, SHD systems showed higher environmental suitability compared to other ones. Indeed, these new planting systems represent now the best solution in terms not only of crop production [33,34] but also of ecosystem services: SHD orchards can (i) decrease both water and carbon footprint [35,36] and (ii) increase soil protection [37], therefore could be integrated into the "One Health" approach [38].

However, the success of the SHD olive management system depends on the suitable cultivars availability [34]. Indeed, if the LD orchards worked well with traditional high-vigour cultivars [39] and the MD orchards fit best with medium-vigour cultivars [21], the

SHD cropping system needs low-vigour genotypes, characterised by early bearing, slow canopy growth, and high yield efficiency [22,31,34]. Up to now, only a few cultivars have been identified as suitable for the olive SHD system [34]. The cv. Arbequina was by far the dominant cultivar used in SHD orchards, given its low-vigour, high and stable productivity and fruity oil, followed by cv. Arbosana showing, in addition to its characteristics of early bearing, low-vigour, and slow canopy growth, a higher yield efficiency under SHD conditions compared to Arbequina [22,30,40,41]. Unfortunately, these two cultivars and the most important traditional ones, such as Coratina and Frantoio, have shown susceptibility to Xfp infection [14]. Moreover, in the last decades, the Italian and the Spanish breeding programs have licensed some newly patented cultivars, such as Fs-17 (=Favolosa®), Chiquitita®, Lecciana®, Oliana® and Urano (=Tosca®) showing, in the short-term, some interesting features such as medium–low vigour and early bearing, which make them suitable to be planted under olive SHD systems [32,42–44]. However, there is still a need for medium to long-term studies to better understand the suitability of these cultivars for the SHD system.

Until recently, very few newly-established olive orchards were planted with Xfp-resistant cultivars in infected areas, most of them with Fs-17 following the SHD planting system. However, the crucial question would be to which available resistant cultivar(s) (Leccino and/or Fs-17) SHD planting system can be applied. In order to offer a scientific contribution to this issue, we studied eight olive cultivars within ongoing research for the selection of resistant olive cultivars to Xfp [14]. The aim was to evaluate the suitability of the Xfp-resistant cultivars to the SHD planting system. The varietal growth and yield were assessed by means of the von Bertalanffy function. This field investigation aimed to address the gap in knowledge by evaluating the main vegetative and productive traits of cv. Leccino and cv. Fs-17, together with other most diffused Italian cultivars, both the traditional (Coratina, Frantoio) and the new patented ones, compared to the well-adapted Spanish cultivars (Arbequina and Arbosana), dominating the new olive orchards planted during the last decades in Southern Italy, with the hypothesis that the cultivars Xfp-resistant can, at the same time, give good results in terms of yield and vegetative growth in new super-intensive plantings.

2. Materials and Methods

2.1. Olive Orchard

The experimental olive orchard was set up at Cassano delle Murge (Bari, Southern Italy; 40°54′ N, 16°47′ E, 307 m a.s.l.) on a not calcareous clay-loam soil, classified as Aploxeralf-Xerothent (USDA) or Luvisols-Phaeozems (FAO). The site, located about 40 km far from the buffer zone [7], is characterised by a typical Mediterranean climate with a long-term annual average rainfall of 560 mm, with 67% of precipitation occurring from autumn to winter, and a long-term annual average temperature of 15.6 °C. Agricultural practices were applied uniformly over the experimental area. Detailed information about agriculture practices and crop management can be found in a previous study [45].

2.2. Experimental Design

Within the experimental plots, eight olive cultivars (Arbequina, Arbosana, Cipressino, Coratina, Frantoio, Leccino, Fs-17 and Urano) were planted as rooted cuttings (18 months old) coming from mist propagation. The cvs. Arbequina and Arbosana, known to be well adapted to the SHD system [24,25], were considered as control. The examined Italian olive cultivars are already included in ongoing studies to investigate the Xfp resistance of olive cultivars [14].

Olive trees were trained according to the central leader system (SHD 1.0), spaced 4.0 m × 1.5 m (1660 trees ha^{-1}) and with a North–South row orientation. The experimental design was a randomised complete block with three replicates. Every block was composed of three rows with 30 trees of each cultivar. Within each row, 10 contiguous trees were chosen and were labelled just after plantation for a total of 30 trees per cultivar. As indicated in the previous studies [46,47], for the mechanical operations in the SHD cropping system, the canopy of the cultivated olive genotype was kept under approximately 1.50 m in width and 2.50 m in height. All cultivars met this threshold at the 4th year after planting (YAP) when manual hedging of later branches with a diameter over 2 cm was operated.

2.3. Experimental Variables

The field trial was monitored yearly for five consecutive years. The measurements related to canopy growth and yield were taken starting from the second year after planting and ending in the sixth year. The following parameters were measured for each tree once a year during harvesting: tree height (H; cm), transversal crown width (W; cm) and tree stem diameter (D; cm) at 50 cm from the ground. In addition, tree stem sectional area (A; cm^2), as a feature of tree vigour, was calculated as in the following equation:

$$A = \pi D^2/4$$

Every year, on the same trees, fruit yield (Y; kg $tree^{-1}$) was measured by manual harvesting. Additionally, yield efficiency (YE; g cm^{-2}) was calculated as follows:

$$YE = Y/A$$

Finally, the cumulated yield (CY, t ha^{-1}) was also determined.

2.4. Statistical Analysis

Descriptive statistics were computed on canopy growth and yield parameters collected over the experimental period to synthesise the main features of data distribution. Canopy growth parameters, in particular tree transversal canopy width (W) and tree height (H), showed skewness and kurtosis coefficients close to zero (−0.283 and −0.049 respectively for W; 0.280 and 0.369 respectively for H), indicating no substantial departure from a normal distribution [48]. On the contrary, yield response variables (Y and YE) showed instead highly skewed distributions (2.517 and 7.714, respectively, for Y and YE). For this reason, a non-parametric analysis of variance was performed to investigate these two parameters, and the Nemenyi–Damico–Wolfe–Dunn test was used to assess differences among groups. Variables that showed no substantial departure from the normal distribution, as in the case of canopy growth parameters, were processed according to a repeated-measures analysis [49,50]. Sub-replicates (trees within each plot) were considered nested observations. SAS software for MS Windows was used SAS/STAT. Multiple comparisons of the main effects of time and cultivar were performed by post hoc analysis using the SNK test ($p < 0.05$). In addition, where significant interactions with time were identified, further analysis of simple effects was conducted with the slice test, which uses the full model degrees of freedom and MSE to assess differences among the means [51]. Considering that the fruiting potential of olive trees affects canopy size evolving over time [52–55], an appropriate mathematical function fitting growth and yield data could be very useful to describe and compare patterns among different genotypes [56]. Within the mathematical functions available, the von Bertalanffy function (VBF) has been widely applied for forest tree growth modelling as well as for the genetic study of plant development [57–59]. Tree growth parameters (H and A) and the experimental data of cumulated yield (CY), collected over the study years, were fitted by the VBF [60]. The fitting was not performed for W nor YE, considering the hedging made in the fourth year as a derived, non-cumulative parameter. The VBF includes three mathematical parameters, and it is expressed as in the following equation:

$$L_t = L_\infty[1 - e^{-k(t-t_0)}]$$

where L_t represents the growth/yield at year t; L_∞ is the maximum potential growth/yield; k is the growth/yield coefficient accounting for the rate of achieving the maximum growth/yield; t_0 is an estimate of the year at which the growth/yield is zero; t represents the year [61].

Olive growth/yield functions were fitted by the Iterative Marquardt Method (IMM) within the NLIN procedure of SAS/STAT [62]. The goodness of fit was evaluated through the significance of each parameter by computing the respective standard error and by the pseudo-R^2 statistics [50]. In the case of non-convergence, the associated functions were excluded. In addition, a comparison among functions of each cultivar for the parameters under study (H, A, CY) was performed through the Analysis of the Residual Sum of Squares (ARSS) according to the procedure proposed by Ratkoswsky [63] and modified by Chen et al. [56] and Zar [64]. Finally, to test the differences in VBF between cultivars for each parameter (H, A, CY), the calculated F value was compared with the critical F. We repeated F comparisons for all possible cultivars twins for the three parameters. Finally, polynomial regressions were calculated using SigmaPlot software (version 11.0). The significance of equations was indicated in Statistical Normality Test (Shapiro–Wilk) with a 0.05 significant level.

3. Results

3.1. Growth Parameters

Tree height (H), crown width (W) and stem sectional area (A) increased over time and were significantly affected by the cultivars and the year (significant year × cultivar interaction (Table 1).

Table 1. Results of the repeated measures analysis carried out on canopy growth variables (Tree height, H; Crown width; Stem sectional area, A).

Source of Variation		Tree Height (H, cm)	Crown Width (W, cm)	Stem Sectional Area (A, cm^2)
Year (Y)		***	***	***
	2nd year	167.48 e	134.31 d	3.880 e
	3rd year	228.04 d	179.11 b	16.804 d
	4th year	245.06 c	193.68 a	25.374 c
	5th year	271.29 b	171.29 c	32.965 b
	6th year	289.68 a	192.27 a	46.062 a
Cultivar (cv)		***	***	**
	Arbequina	226.10 c	164.77 c	20.347 bc
	Arbosana	201.35 d	140.60 d	17.134 c
	Cipressino	285.53 a	160.61 c	36.531 a
	Coratina	243.50 bc	201.43 a	25.869 bc
	Frantoio	260.77 ab	181.80 b	29.654 ab
	Fs-17	261.77 ab	192.00 ab	23.617 bc
	Leccino	268.13 ab	200.40 a	26.915 bc
	Urano	175.33 e	151.47 cd	20.069 bc
Y × cv		***	***	***

, * indicate differences at $p \leq 0.01$ and $p \leq 0.001$.Means followed by the same letter in each column are not significantly different according to the SNK test at $p < 0.05$.

Detailed single effects of cultivar on H, W and A for each year are reported in Figures 1–3, respectively.

As expected (Table 1), mean tree height values (H) increased, from second to sixth YAP of about 73%, with cv. Cipressino reached the highest mean value (285.5 cm). Cultivars Leccino (268.1 cm) and Fs-17 (261.8 cm), followed by Frantoio (260.8 cm) and Coratina (243.5 cm), showed greater tree height values than the cv. Arbequina (226.1 cm), Arbosana (201.4 cm) and Urano reported the lowest H value (173.3 cm). Similar behaviour was observed for W values (Table 1). Leccino (200.4 cm) and Fs-17 (192.0 cm), together with Coratina (201.4 cm), showed the highest W values throughout the experimental period, while cvs. Arbequina (164.8 cm), Arbosana (140.6 cm) and Urano (151.5 cm) presented W values lower than the mean, as in the case of the H parameter. In general, moving from the second to the fourth YAP, W values increased significantly in all cultivars and reached their maximum average (193.7 cm). At the fifth YAP, after manual hedging, the W value was reduced significantly by about 13.5% as average in all cultivars except for the cv. Cipressino, varying from a minimum value of 7% for cv. Urano to a maximum value of 20.0% for cv. Fs-17, followed by cvs. Arbosana and Arbequina with 18 and 15%, respectively. Finally, A values tend to increase gradually and significantly (about 12 times on average), reaching their maximum value in the last year as compared to the first one. Cv. Cipressino reported the highest A mean value (36.5 cm^2), followed by Frantoio (29.7 cm^2); Leccino (26.9 cm^2) and Fs-17 (23.6 cm^2) behaved no longer from Arbequina (20.3 cm^2) and Arbosana (17.1 cm^2) that showed the lowest A values. In order to evaluate the relation among the growth parameters, a correlation matrix was performed (Table 2). The results indicate, as expected, a high correlation among all parameters. In particular, the highest Person's coefficient (0.88 ***) was recorded between tree height (H, cm) and stem sectional area (A, cm^2). Similar results were obtained in other experiments [65].

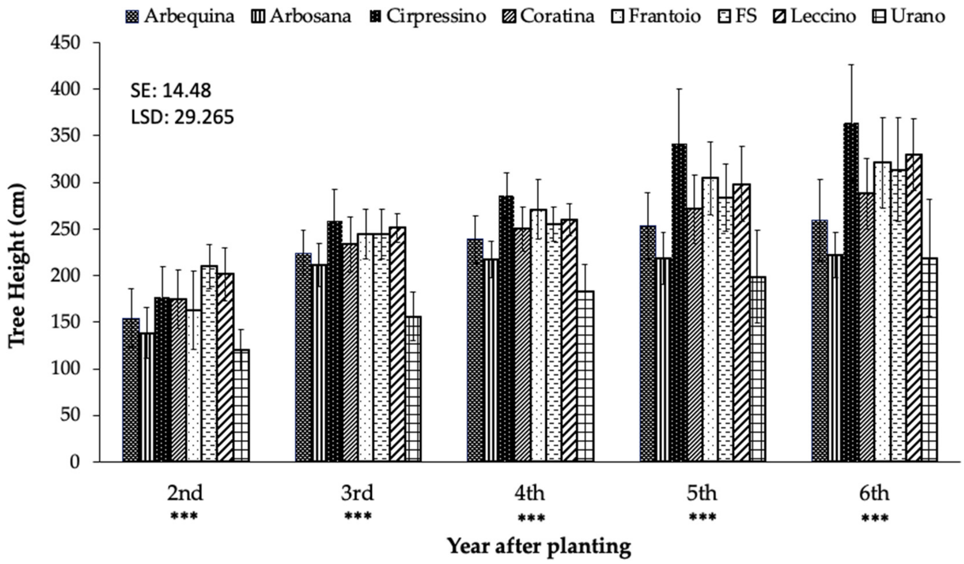

Figure 1. Effect of cultivar on tree height (H, cm) for each year. Standard error (SE) of the mean difference and least significant difference ($p < 0.001$) are reported. Bars in each column indicate the standard deviation. *** means $p < 0.001$.

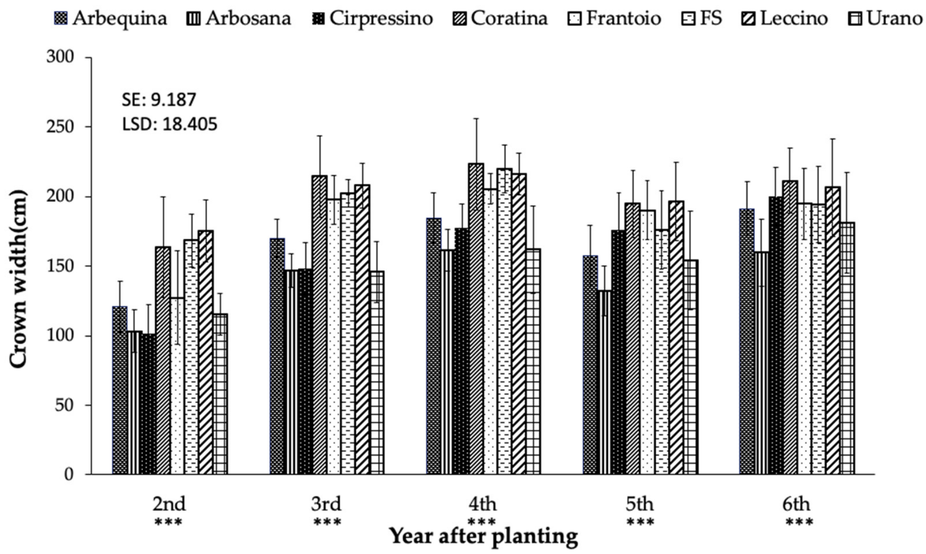

Figure 2. Effect of cultivar on tree transversal canopy width (W, cm) for each year. Standard error (SE) of the mean difference and least significant difference ($p < 0.001$) are reported. Bars in each column indicate the standard deviation. *** means $p < 0.001$.

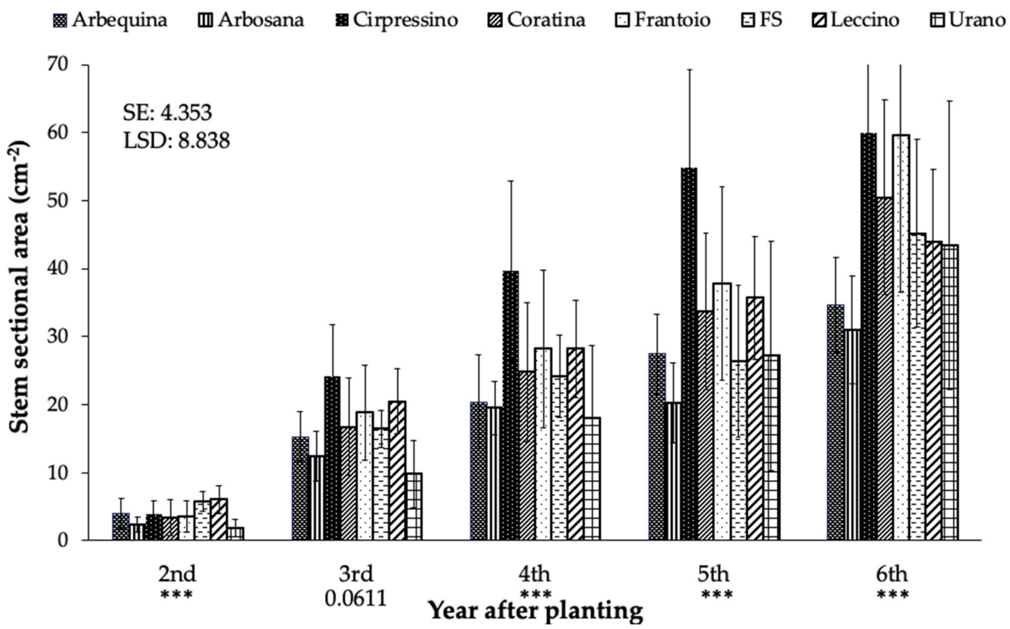

Figure 3. Effect of cultivar on stem sectional area (A, cm^2) for each year. Standard error (SE) of the mean difference and least significant difference (LSD) ($p < 0.001$) are reported. Bars in each column indicate the standard deviation. *** means $p < 0.001$.

Table 2. Matrix correlation (Person correlation) among growth parameters of all cultivars. *p*-values: *** $p < 0.001$.

	Tree Height (H, cm)	Crown Width (W, cm)	Stem Sectional Area (A, cm^2)
H	1.000	0.71 ***	0.88 ***
W	0.71 ***	1.000	0.58 ***
A	0.58 ***	0.58 ***	1.000

3.2. Yield Parameters

Significant effects were detected between cultivar and year by non-parametric analysis carried out on yield parameters (Table 3); the effect of temporal variation on the yield and yield efficiency of the cultivars was reported in Figures 4 and 5, respectively.

Table 3. Results of the repeated analysis carried out on yield response variables.

Source of Variation		Yield (kg $tree^{-1}$)	Yield Efficiency (g cm^{-2})
Year (Y)		***	***
	2nd year	0.009 a	6.896 a
	3rd year	0.736 bc	52.737 b
	4th year	0.859 d	49.438 d
	5th year	0.427 b	15.151 b
	6th year	0.548 c	12.811 c
Cultivar (cv)		***	***
	Arbequina	0.488 a	28.83 a
	Arbosana	1.051 b	73.34 b
	Cipressino	0.082 c	3.50 c
	Coratina	0.287 d	12.13 d
	Frantoio	0.065 c	1.13 c
	Fs-17	1.126 a	52.93 a
	Leccino	0.370 d	13.91 d
	Urano	0.657 d	33.49 d

*** indicate differences at $p \leq 0.001$; ns indicates not significant difference. Means followed by the same letter in each column are not significantly different according to the Nemenyi–Damico–Wolfe Comparison test at $p < 0.05$.

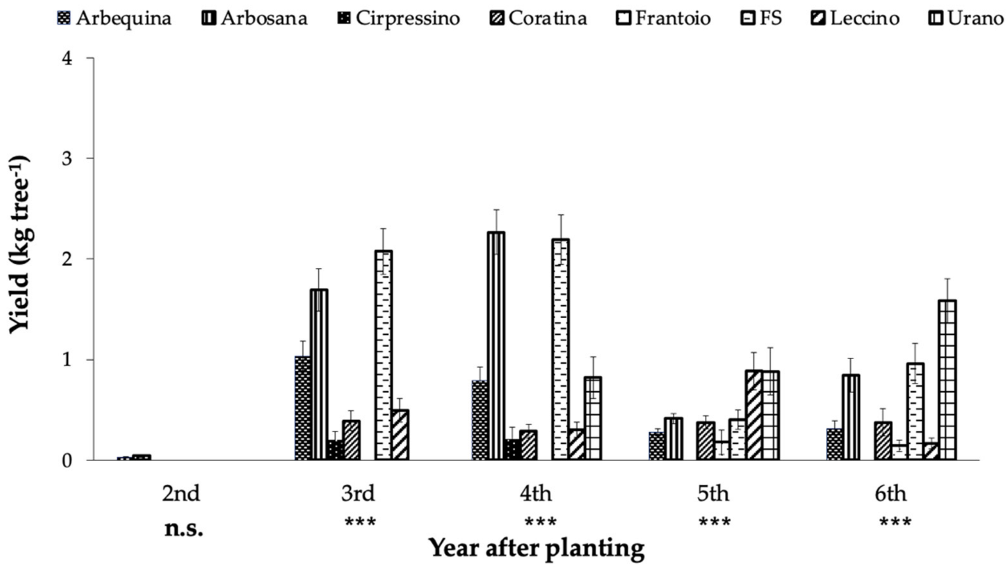

Figure 4. Effect of cultivar on yield (Y, kg tree^{-1}) for each experimental year. Standard error (SE) of the mean difference and least significant difference (LSD) ($p < 0.001$) are reported. *** means $p < 0.001$. n.s. means no significance.

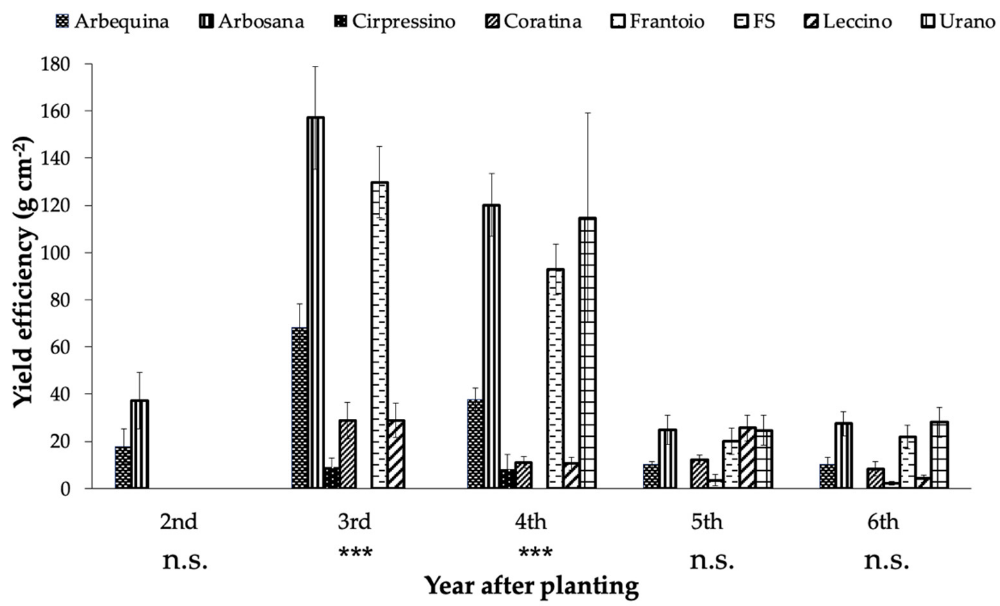

Figure 5. Effect of cultivar on yield efficiency (YE, g cm^{-2}) for each year. Standard error (SE) of the mean difference and least significant difference (LSD) ($p < 0.001$) are reported. *** means $p < 0.001$. n.s. means no significance.

In the second YAP, only cv. Arbequina and Arbosana began their first fruiting, although with very low values (Table 3). At the third YAP cvs. Fs-17 and Leccino started to bear appreciable values, mainly for Fs-17 with over 2 kg tree^{-1}. Between the third and the fourth YAP, all other cultivars started bearing except for cv. Frantoio. Between the fifth and the sixth YAP, the yield was reduced significantly in all the cultivars because of the hedging effect (Table 3). The highest Y mean values were obtained by cvs. Fs-17 and Arbosana (1.1 kg tree^{-1}), followed by cvs. Urano (about 0.7 kg tree^{-1}), Arbequina (0.5 kg tree^{-1}) and Leccino (0.4 kg tree^{-1}). The lowest yields were reported for cv. Cipressino and Frantoio, with negligible mean values (Table 2) (Figure 4). Finally, the highest YE mean values were recorded during the third and fourth YAP (52.7 g cm^{-2} and 49.4 g cm^{-2}, respectively); then, in the following years (fifth to sixth YAP), YE significantly decreased (Table 3). Cv.

Arbosana (73.3 g cm^{-2}) and cv. Fs-17 (52.9 g cm^{-2}) showed similar highest YE mean values, followed by cvs. Urano (33.5 g cm^{-2}), Arbequina (28.8 g cm^{-2}) and Leccino (13.9 g cm^{-2}), without significant differences among them (Table 3). The lowest mean YE value was found for Frantoio (1.1 g cm^{-2}), with values higher than 0 only during the fifth and the sixth YAP (Figure 5).

3.3. Fitting by the von Bertalanffy Function

Fitting the experimental data over the study years employing the von Bertalanffy function (VBF), the curves reported in Figures 6–8 were obtained for tree height (H), stem sectional area (A) and cumulated yield (CY), respectively. The curves showed that the H and A slopes of Cipressino were higher compared to other cultivars, as expected (Figures 6 and 7). For the CY, instead, cvs. Fs-17 and Arbosana slopes were much higher as compared to other cultivars; opposite trends were shown by Cipressino and Frantoio (Figure 8). This variation in the slopes for the different cultivars was clearly related to the CY data. Indeed, during the sixth YAP cvs. Fs-17 and Arbosana showed the highest CY values (9.4 t ha^{-1} and 8.7 t ha^{-1}, respectively), followed by cvs. Urano (5.5 t ha^{-1}), Arbequina (4.0 t ha^{-1}), Leccino (3.1 t ha^{-1}) and Coratina (2.4 t ha^{-1}), whereas the lowest CY values were reported for cvs. Cipressino and Frantoio (0.7 t ha^{-1} and 0.5 t ha^{-1}, respectively).

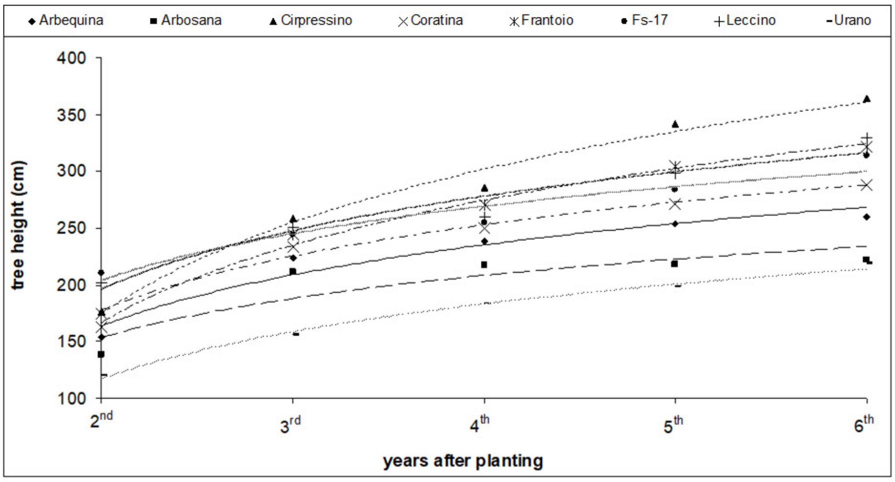

Figure 6. The von Bertalanffy functions of tree height (H, cm) for eightcultivars from second to sixth year after planting.

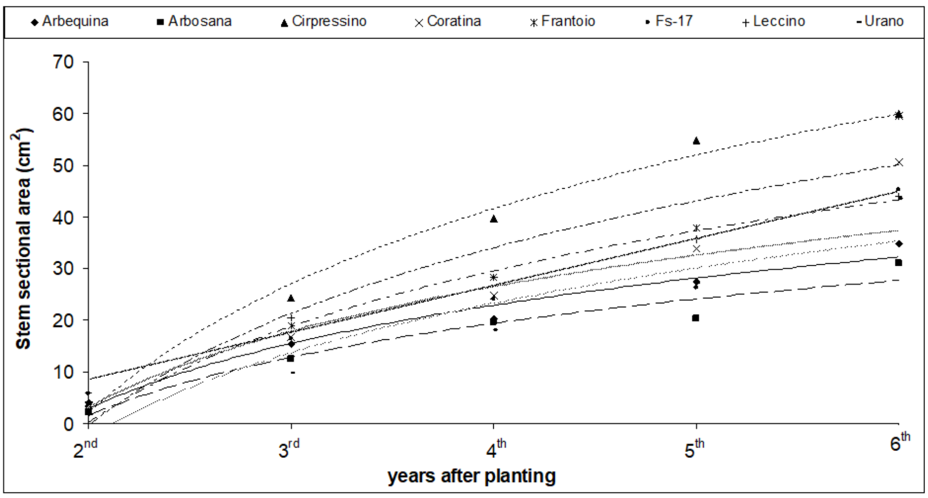

Figure 7. The von Bertalanffy functions of stem sectional area (A, cm^2) for eightcultivars from secondto sixth year after planting.

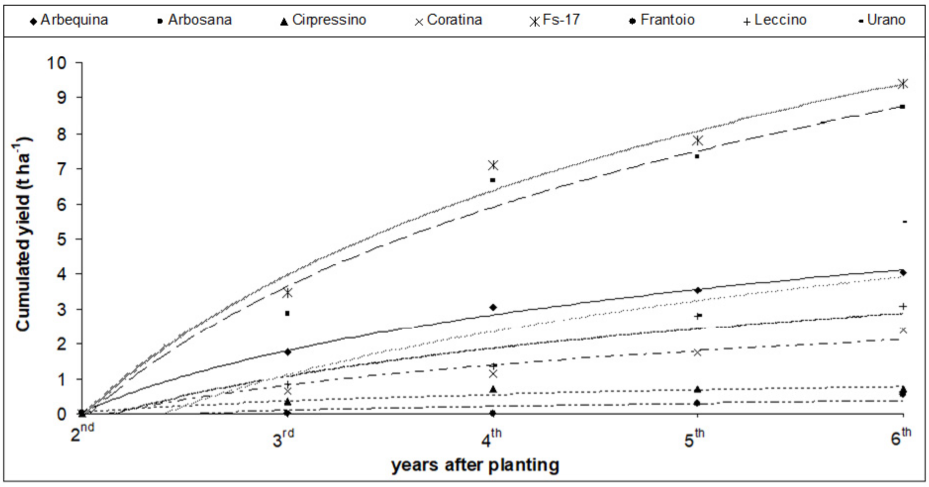

Figure 8. The von Bertalanffy functions of cumulated yield (CY, t ha^{-1}) for eightcultivars from second to sixth year after planting.

In Table 4, the von Bertalanffy equation parameters and the corresponding goodness of fit passed by the Iterative Marquardt Method (IMM-passed) are reported for H, A and CY parameters. The VBF results showed well adaptability for Arbequina, Arbosana and Leccino for all parameters, as confirmed by the pseudo-R^2 statistics values. The best fitting was recorded for stem sectional area A, where good results were achieved, and also for Cipressino. IMM test failed to find convergence in Fs-17 for H and A parameters and in Coratina, Urano and Frantoio for A and CY parameters.

Table 4. The von Bertalanffy fitting functions passed by the Iterative Marquardt Method (IMM) for the three parameters.

Cultivar	Tree Height (H)	Pseudo-R^2
Arbequina	$L_t = 2.59(1 - exp(-0.99(t - 0.08)))$	0.575
Arbosana	$L_t = 2.19(1 - exp(-2.25(t - 0.55)))$	0.632
Coratina	$L_t = 3.00(1 - exp(-0.51(t - (0.72))))$	0.595
Cipressino	$L_t = 4.43(1 - exp(-0.30(t - (-0.72))))$	0.399
Frantoio	$L_t = 3.40(1 - exp(-0.53(t - (-0.25))))$	0.681
Leccino	$L_t = 10.00(1 - exp(-0.04(t - (-4.60)))$	0.671
Urano	$L_t = 2.65(1 - exp(-0.27(t - (-1.21)))$	0.419
	Stem sectional Area (A)	
Arbequina	$L_t = 77.12(1 - exp(-0.13(t - 0.13)))$	0.781
Arbosana	$L_t = 62.79(1 - exp(-0.14(t - 0.64)))$	0.747
Cipressino	$L_t = 86.78(1 - exp(-0.29(t - 0.86)))$	0.756
Leccino	$L_t = 69.98(1 - exp(-0.21(t - 0.53))$	0.758
	Cumulated Yield (CY)	
Arbequina	$L_t = 4.67(1 - exp(-0.49(t - 0.99)))$	0.505
Arbosana	$L_t = 11.31(1 - exp(-0.37(t - 1.02)))$	0.585
Cipressino	$L_t = 0.76(1 - exp(-0.79(t - 1.02)))$	0.061
Fs-17	$L_t = 11.46(1 - exp(-0.42(t - 1.02)))$	0.567
Leccino	$L_t = 49.47(1 - exp(-0.02(t - 1.04)))$	0.323

In Table 5, the twin-comparison significance for Leccino and Fs-17 vs. Arbequina and Arbosana is reported. ARSS demonstrated that the functions of all the cultivars were statistically different for the three examined parameters. A very interesting exception was observed for the cv. Fs-17 as compared to cv. Arbosana, where no statistical differences were observed between their CY functions. In the remaining cases, the cultivars behaved differently for the same growth/yield parameters. Regarding the usefulness of the Von Bertalanffy function to predict the behaviour, in terms of vegetative growth and yield of the investigated olive cultivars over the study years, our results demonstrated that Arbequina and Arbosana showed a good fitting; on the contrary, Leccino provided a good fitting only for vegetative growth parameters. Among the evaluated parameters, we found that stem sectional area (A) was a reliable descriptor of vegetative growth, showing the highest values of Pseudo-R2 (Table 4).

Table 5. Twin-comparison significance of von Bertalanffy functions for three agronomic parameters for cultivars Fs-17 and Leccino vs. cultivars Arbequina and Arbosana (*** p= significant at $p \leq 0.001$, n.s. = not significant; ARSS).

Cultivar	Tree Height		Stem Sectional Area		Cumulated Yield	
Fs-17 vs. Arbequina	–		–		3.8×10^{-14}	***
Fs-17 vs. Arbosana	–		–		3.6×10^{-1}	**n.s.**
Leccino vs. Arbequina	4.3×10^{-25}	***	5.3×10^{-96}	***	2.0×10^{-52}	***
Leccino vs. Arbosana	2.2×10^{-61}	***	–		2.9×10^{-30}	***
Fs-17 vs. Leccino	–		–		2.0×10^{-18}	***

4. Discussion

This is one of few agronomic studies aimed at evaluating different olive cultivated genotypes for their suitability to be grown under the SHD system over a medium-term period [25,45,46]. The key factors for assessing olive cultivars' suitability for SHD orchards are canopy size (height and width) and tree vigor (stem sectional area) [66–69]. The canopy size of the studied cultivars was smaller than those observed in the previous studies [25,46] for the same cultivars in warmer climatic conditions; however, higher values than those observed in colder areas [40,70] indicate the importance of climate conditions on the canopy size. Similarly, data on tree fruit production and cumulated yield were much lower than those reported in different cultivation areas [40,46,70]. The yield reduction of the studied cultivars was due to climate effects on the phenology of some olive cultivars, as confirmed by the work of Caruso et al. [67], who analysed Arbequina growth and yields in high-density orchards in three different Italian olive growing areas.

Canopy height and width are two important parameters that need to be measured in order to evaluate the adaptability of the studied cultivars to the SHD system. In particular, tree height has a great influence on establishing the appropriate design for hedgerow plantings [71]. In this study, the vertical growth of Arbequina, Arbosana and Urano did not overtake the threshold until the sixth YAP, whereas Cipressino and Frantoio reached the threshold at the fourth YAP. The threshold limit was exceeded at the fifth YAP for the remaining cultivars. This is a clear varietal response; in fact, vertical growth can be considered a selective varietal parameter for the best adaptability to SHD planting [23,30]. As for tree width, all cultivars overcame the width threshold at the fourth YAP; therefore, winter hedging was operated. We correlated the reduction percentages of W and Y from the fourth to fifth YAP for the selected cultivars (Arbosana, Arbequina, Fs-17 and Urano) in order to understand better how the hedging affected crop yield, and we found a positive and significant regression: r = 0.99, $p < 0.001$, W Statistic = 0.8645 and Passed $p = 0.2765$. In fact, in the studied cultivars, we found that the more pruning, the greater the Y losses, always depending on the cultivar. Indeed, the removal of peripheral branches increases the competition between vegetative and reproductive shoots, reducing total fruit yield, especially for medium-high vigor cultivars [31]. Concerning tree vigor, expressed by stem sectional area [45,72], an increase in all cultivars over the studied years was observed; however, the rate of increase was reduced in the Spanish control cultivars (Arbosana and Arbequina), and the new Italian cultivar (Urano) resulting in lower vigor. A similar result was previously reported [40,67] for the control cultivars. For the Fs-17 cultivar, our findings show that this cultivar resulted in a medium vigor, while traditional Italian such as Cipressino, Frantoio and Leccino cultivars reported a high to very high stem sectional area, in agreement with the results of Rosati et al. [73] who found that Frantoio produced higher trunk diameter compared to Leccino after seven years of study.

Other important keyfactors for classifying an olive genotype as suitable for the SHD cropping system are early bearing and high yield, which have the same importance as the canopy growth parameters [74,75]. In this regard, we found, in this medium-term study, that Fs-17 and Arbosana are the highest productive cultivars with the best yield efficiency, in contrast with previous work by De la Rosa et al. [64]. Moreover, Fs-17, the new patented cultivar, showed an early bearing similar to the control cultivars Arbequina and Arbosana, as these cultivars started to provide yields from the third YAP. The very similar productive behaviour of Arbosana and Fs-17 was confirmed by the von Bertalanffy growing function with plenty of close equation parameters for CY. Nevertheless, Fs-17 showed, at the 6th YAP, a bigger canopy growth with respect to Arbosana in terms of tree height (+40%), width (+22%) and vigor (+45%). These vegetative parameters would limit the Fs-17 cultivar for its suitability in SHD orchards since excessive canopy growth after the first years could reduce light interception and therefore yield efficiency per unit of canopy volume [22,76–78]. Nevertheless, it has long been assumed that it could reduce tree growth through agricultural field practices, such as regulated deficit irrigation and pruning [52,79].

The other patented Italian cultivar (Urano = Tosca®) resulted in good fruit tree production and yield efficiency. Compared to other cultivars, Urano reported the second-highest production at the sixth YAP (significantly higher after Arbosana and Fs-17), although it started bearing one year later than Arbequina and Arbosana. Moreover, Urano showed a slow canopy growth similar to that of the control Spanish cultivars. On the contrary, the cultivars; Leccino, Coratina, Cipressino and Frantoio gave lower and late production and low yield efficient results. On the other hand, cv. Leccino could be successfully considered in new intensive olive orchards [80] and for table olive production as well [81]. Once the cultivar starts to bear, the yield will compete with and reduce vegetative growth and, therefore, vigour [55,82]. Moreover, reduced growth might be the consequence of early and abundant fruiting: in mature olive trees, it is well established that vegetative growth is more abundant in off (i.e., with low yield) years [83]. The general assumption indicates that trees that spend more energy on production are expected to grow less in terms of vegetative growth because both reproductive and vegetative growth competes for the same sources within a tree [82]. Early bearing and more abundant fruiting are the major causes, rather than merely a consequence, of lower vigor in young Arbequina trees [54]. In our study, this premise is confirmed since the cultivars with earlier bearing (Spanish control cultivars in the second YAP) have a lower vigor than the other cultivars. Although the reference cultivars (Arbequina and Arbosana) proved their best fit for the SHD system, they may not be resistant to Xfp; therefore, they are not suitable to be planted in infected areas for the new olive orchard. Under the SHD planting system, cv. Fs-17 resulted in the best-cumulated yields; however, it presented some limitations due to its higher canopy growth. Nevertheless, the vegetative limitations of Fs-17 can be overcome by a proper pruning technique, as recently demonstrated by Vivaldi et al. [31], in order to better adapt this model to medium-low vigor cultivars. These findings should overcome the contradictory information up to now reported in the literature about the suitability of the cv. Fs-17 under the SHD planting system in different environments [22,44].

5. Conclusions

This medium-term field study demonstrated that the von Bertalanffy function can be successfully used to investigate and compare olive cultivars' behavior, thanks to properly fitting in most of the experimental data. The overall results indicated that cv. Fs-17 (=Favolosa®) showed acceptable suitability to SHD plantings, thanks to its best-accumulated yield. It should increase the prospect of planting this cultivar in the infected areas sensibly.

On the contrary, cv. Leccino, like the other traditional Italian cultivars, did not perform under the SHD system in terms of both growth and yield parameters. The results of this study could be useful for optimizing integrated resistance management in Xfp-infected areas by planting resistant host plants. The identification of low-vigor, early bearing and high-yielding cultivars would meet this challenge. However, further research is needed for the investigation of the long-term varietal behaviours of other cultivars belonging to the very large Italian olive platform. Moreover, this study highlighted the crucial role of worldwide olive breeding programs for both low vigor and Xfp resistance, looking at sustainable new climate-smart planting systems.

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