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OLIVE TREE VEGETATIVE GROWTH AND FRUIT YIELD AT HIGH AIR TEMPERATURES

Joedna CAMPOS[1], Carla LIMA[2], Maria C. MANUELITO[1], José PRAGANA[1], Liliana FERREIRA[1], João FERNANDES[1], António M. CORDEIRO[1], Carla F. INÊS[1]*
[1]Instituto Nacional de Investigação Agrária e Veterinária, I.P., Portugal
[2]Universidade Federal de Sergipe, Brazil

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ABSTRACT

In the Olive Reference Collection of Portugal, indigenous olive tree (*Olea europaea* L.) cultivars undergo agronomic evaluation according to the standards of the International Olive Council. Olive trees were planted in 2012 and fifteen cultivars were selected for the analysis of genotype-environment interactions regarding the correlation between annual fruit yield and annual growth of trunk perimeter with the number of days with high maximum temperatures. The cultivars showed heterogeneous development in terms of trunk perimeter, canopy, and fruit yield. Fruit yield and the number of days with maximum temperature above 35 °C were negatively correlated, especially in April–May. In spring 2022, the maximum temperature reached or exceeded 35 °C on 11 days. It was hypothesized that the development of reproductive organs and the processes of flowering or ovarian fertilization were the most affected by the unusually early occurrence of high maximum temperatures. At the same time, vegetative growth was strongly conditioned by the limiting temperatures of photosynthesis.

Key words: climate change, heat wave, *Olea europaea*, flowering

INTRODUCTION

The cultivation of the olive tree (*Olea europaea* L.) began in Asia Minor, and over the centuries the species was spread in the western Mediterranean (Blázquez 1996). In Portugal, olive groves were associated with family farming and traditional agricultural systems. Recently, olive oil production has become an important and innovative economic sector (Fraga et al. 2021, 2022; Campello 2022).

The latitudinal belt of olive cultivation suggests that climatic conditions are a key factor in the growth and development cycle of this species. The vegetative growth period of the olive tree in Quiroga (Spain) is on average 259 days per year (Garrido et al. 2021). This location is a bioclimatic transition zone between Euro-Siberian and Mediterranean areas at the end of the olive tree distribution range, although vegetative growth reaches 8.6 months per year. The biological processes of the olive tree (shoot growth, inflorescence development, flowering, fruit development, etc.) are driven by energy-rich organic compounds produced during photosynthesis (van der Vyver & Peters 2017; Haworth et al. 2018a). In the olive tree, vegetative growth is mainly determined by photosynthesis and the existence of other alternative sinks with higher competitive capacity (Rallo & Cuevas 2008). The active growth phase is switched off or at least sharply shortened due to factors limiting photosynthesis, such as high temperatures in summer and low

*Corresponding author
e-mail: carla.ines@iniav.pt

temperatures in winter (Lavee 1996; Rallo & Cuevas 2008). The optimum temperature for photosynthesis is between 15 °C and 30 °C; temperatures above 35 °C have an inhibiting effect (Lavee 1996; Rallo & Cuevas 2008). The main flow of vegetative growth occurs in the spring phase, which lasts until about mid-July (northern hemisphere). Both heat stress and drought drastically reduce agricultural efficiency and productivity (Lavee 1996; Rallo & Cuevas 2008; Haworth et al. 2018a, b). As soil water availability decreases, stomatal closure is induced to reduce stomatal conductance and water loss through transpiration (Davies & Zhang 1991; Haworth et al. 2018a). Stomatal closure reduces atmospheric CO_2 uptake and its assimilation in the chloroplast (Tholen et al. 2012). High temperature exacerbates drought effects by reducing the photosynthesis to respiration ratio (Diaz-Espejo et al. 2007; Hernandez-Santana et al. 2017; van der Vyver & Peters 2017; Haworth et al. 2018a; Falcioni et al. 2024).

Most of the variability found for flowering phenology parameters is due to environmental influences (Osborne et al. 2000; Aguilera & Valenzuela 2012; Navas-Lopez et al. 2019; Di Paola et al. 2021). The length of the olive inflorescence developmental process (Sanz-Cortés et al. 2002) between BBCH stages 51 and 55 (Biologische Bundesanstalt Bundessortenamt and Chemical industry scale) generally decreased between 2012 and 2022, which was due to both a later occurrence of stage 51 and an earlier manifestation of stage 55 (Inês et al. 2023). In some monitored genotypes, phenological progression was shortened by 50%. The authors found stronger correlations between phenological stages and minimum temperatures than with maximum temperatures. The first phase studied – the release of ecodormancy – is reached only when the olive tree has accumulated a sufficient number of chilling units and heat accumulation is ongoing (de Melo-Abreu et al. 2004; Rallo & Cuevas 2008; Yu et al. 2020; Petruccelli et al. 2022). Therefore, it is reasonable that cold played a greater role in the studied phase (Lavee 1996; de Melo-Abreu et al. 2004; Aybar et al. 2015; Ben-Ari et al. 2021).

Olive flowering period has been used as a bioindicator of potential changes expected in future climate. In southern Spain, the average flowering period is between 24 April and 15 June, and the average day of maximum pollen emission is 14 May (Aguilera et al. 2013). In this region of Spain, the onset of flowering occurs on days with maximum temperature (T_{max}) between 20 °C and 24 °C, and even the end of flowering occurs on days with T_{max} between 28 °C and 30 °C. Successful pollination and fertilization depend on many factors, such as the time of stigma receptivity, the viability or durability of the pollen grain and the development of the pollen tube. Water stress increases the risk of pistil abortion (Rapoport et al. 2012), and high temperatures exacerbate problems related to water deficiency (Diaz-Espejo et al. 2007; Lorite et al. 2018; Cardoni & Mercado-Blanco 2023; Kalfas et al. 2023).

High temperatures in spring (April–May) can strongly limit fruit set and lead to an earlier start of flowering (Alcalá & Barranco 1992; Lorite et al. 2018). In experiments with olive trees in plastic film cages, heat stress reduced fruit set and flower fertility (Vuletin Selak et al. 2014; Benlloch-González et al. 2018). For most cultivars, the optimum temperature for pollen germination is 20–25 °C, and for some genotypes 25–30 °C (Cuevas et al. 1994; Koubouris et al. 2009). Temperatures around 25 °C were most favorable for accelerating pollen tube growth *in vivo*, advancing fertilization, and achieving good initial fruit set (Cuevas et al. 1994). In ‘Manzanillo’, fruit set was completely inhibited at a constant temperature of 30 °C (Cuevas et al. 1994). Penetration of the ovule by the pollen tube was observed in 47% of flowers at 30 °C. However, the lack of growth of either functional ovules and ovaries suggests problems in zygote formation or endosperm development (Cuevas et al. 1994).

Several studies have shown an increase in arid conditions in southern Europe. Heat waves are predicted to become more frequent and longer-lasting in many regions, including the Alentejo region (Portugal) (Fraga et al. 2020, 2021; Droulia & Charalampopoulos 2022; Picornell et al. 2023). Over the past decade, changes in precipitation and air temperature have been observed, especially in spring and summer, coinciding with critical reproductive phases of the olive life cycle, such as flowering, fruit set, and fruit development (Benlloch-González et al. 2018; Lorite et al. 2018; Orlandi et al. 2020; Mafrica et al. 2021; Inês et al. 2023). Flower viability depends on the fruiting history of the tree (alternate bearing: ON and OFF years), their position on the shoot and environmental conditions (Lavee 1996). The alternate fruiting of olive tree cultivars is genetically determined, but can be strongly influenced by climatic conditions (Hackett & Hartmann 1967; Rapoport et al. 2012; Vuletin Selak et al. 2014; Di Paola et al. 2023). Many existing trends in olive flowering dates indicate that they will show a generalized progression that will ensure that the flowering period will take place under optimal temperature conditions (Aguilera et al. 2013; Benlloch-González et al. 2018). However, pronounced climatic changes could put this assumption at risk. The air temperature recorded in Elvas (Alentejo region) highlighted the maximum temperature behavior in spring and summer, which constitutes a serious threat to olive production in this climatic reality (IPMA 2023). In the Olive Reference Collection of Portugal (ORCP, INIAV, Elvas) several indigenous olive cultivars have been evaluated since 2012. In 2022, the agronomic behavior of the materials raised some doubts, especially regarding fruit production and vegetative growth. One of the most important was the question of whether high temperatures could affect fruit yield and vegetative growth of traditional Portuguese olive cultivars selected in different environmental conditions.

MATERIALS AND METHODS

Elvas is a municipality located in Alentejo, a region in southern Portugal, close to the border with Spain. The experimental field is part of the Olive Reference Collection of Portugal (ORCP) (FAO code: PRT196), located in Olivicultura – Herdade do Reguengo, National Institute for Agrarian and Veterinarian Research, I.P. (INIAV), Elvas Innovation Hub (latitude: 38°53′ N, longitude: 7°09′ W, 200 m AMSL).

This area is characterized by typical Mediterranean weather – hot, dry summers and mild, wet winters (Giorgi & Lionello 2008). In Elvas, the mean annual temperature is 16.3 °C and the annual rainfall is 535.4 mm. In summer, extreme events such as heat waves can increase the temperature (T_{max}) to about 40 °C. Reference period (RP) based on a 25-year (1985–2010) series of meteorological measurements. Daily weather variables were obtained from the meteorological station at Herdade do Reguengo, near the ORCP field.

The olive cultivars used in this experiment were installed in the ORCP Evaluation Field 1 in June 2012. The olive-growing areas extend from the north to the south of mainland Portugal. To represent these regions, fifteen indigenous cultivars were selected for study, namely: ‘Azeiteira’, ‘Blanqueta de Elvas’, ‘Cobrançosa’, ‘Conserva de Elvas’, ‘Cordovil de Serpa’, ‘Cornicabra’, ‘Galega Vulgar’, ‘Galego de Évora’, ‘Gama’, ‘Gulosinha’, ‘Lentrisca’, ‘Maçanilha de Tavira’, ‘Ocal’, ‘Redondil’, and ‘Verdeal Alentejana’. To propagate cultivars and avoid intra-cultivar variability, cuttings were always taken from a single plant. Self-rooted olive trees were planted at a spacing of 7 m × 5 m in a randomized complete block design with six replications of two trees side-by-side per cultivar. Standard cultural practices were followed, including fertilization and drip irrigation from spring to late summer to prevent plant water stress. Since planting, olive trees were subjected to agronomic characterization protocols (IOC 1997; Rallo 2005; Tous et al. 2005).

Trees were trained as a single vase-shaped trunk with three or four main branches and minimal pruning to allow expression of cultivar canopy architecture and fruiting habits.

After planting, fifteen olive cultivars were systematically evaluated for several traits such as vigor, fruit yield, and productivity (IOC 1997). Vigor traits were measured in the plantation and before the start of the growing season, in January–February. The trunk cross-sectional area (TCSA) was calculated according to the formula for the area of a circle, using the trunk perimeter (P) recorded at 10 cm above the soil level (del Río et al. 2005a).

The total height of the trees was measured manually, distinguishing between the canopy height (H) and the trunk height (from the soil level to the base of the canopy). To calculate the mean (D) canopy width, the longitudinal diameter (D1) and transverse diameter (D2) were measured manually. The canopy volume (CV) was calculated as a spherical shape (del Río et al. 2005a).

Productivity or fruit yield (FY) was measured in kg per tree (del Río et al. 2005b). Productive efficiency was calculated as the ratio of total fruit yield to CV (Tous et al. 1998).

Data analysis

Annual FY per tree and annual trunk perimeter data were subjected to descriptive analysis to obtain the average values of the cultivars (twelve trees per cultivar – six replications of two plants). Graphs were then constructed to show the behavior of these characteristics over time. Agronomic data were subjected to analysis of variance and post hoc tests, with Duncan's correction, to assess differences between each pair of groups ($P < 0.05$). Necessary procedures were performed to identify outliers and confirm that normality has been assessed and that the variance was shared and normally distributed. The corresponding Spearman coefficients were calculated ($P < 0.05$) to examine the correlation between FY, annual growth in trunk perimeter, and production efficiency with the number of days with T_{max} above 30 °C and 35 °C. The strength of the correlation can be divided into six levels: very weak (0–0.2), weak (0.2–0.4), moderate (0.4–0.6), strong (0.6–0.8), very strong (0.8–1), and excellent (1) (Landis & Koch 1977). All statistical calculations were performed using SPSS Statistics 27.0.

RESULTS

The vegetative development of these olive tree cultivars was characterized based on their TCSA and CV. The olive trees were kept in the field conditions for 11 years, after which significant differences were observed. The thinnest trunks belonged to 'Galego de Évora' and 'Blanqueta de Elvas', with 121 cm^2 and 122 cm^2 TCSA, respectively (Table 1). The largest trunks were observed in 'Conserva de Elvas', 'Ocal', 'Galega Vulgar', and 'Verdeal Alentejana', with TCSA ranging from 292 cm^2 to 325 cm^2. Considering CV, 'Galego de Évora' was the genotype with the smallest canopy (3 m^3) (Table 1). The largest canopy volumes were observed in 'Conserva de Elvas' and 'Lentrisca' (12 m^3 and 14 m^3, respectively).

The lowest yielding cultivars were 'Ocal' and 'Conserva de Elvas', around 46 kg and 60 kg per tree, respectively (Table 1). Considering the vegetative development, they were at higher levels (Table 1), so their lower productive efficiency compared to the other cultivars was not surprising (4 $kg \cdot m^{-3}$ and 5 $kg \cdot m^{-3}$, respectively). 'Azeiteira' and 'Galega Vulgar' showed the highest total fruit yield (around 130 kg and 136 kg per tree, respectively). However, considering the productive efficiency, with the highest value (28 $kg \cdot m^{-3}$) was reached by 'Galego de Évora', followed by 'Azeiteira' (Table 1). The four characteristics listed in Table 1 illustrate the cultivar heterogeneity of these indigenous olive cultivars (cultivated in the environmental conditions of the southeastern region of Portugal). This information is extremely important for making better decisions regarding the selection of cultivars depending on field conditions and the availability of production inputs, as well as for orchard management.

Annual fruit production and vegetative development

The annual FY shows ups and downs in the vegetation cycles, which is a consequence of the alternating fruiting behavior of the *Olea europaea* species. However, in 2022, the cultivars seemed to be in an OFF year, despite the cultivar differences in FY and productive efficiency (Table 1). The highest FY was around 10 kg per tree. For most cultivars, this is not a value that occurs regularly (Fig. 1). In fact, the low yields in 2022 were an exception in the observations of 'Galego de Évora' and 'Maçanilha de Tavira' (Fig. 1).

Trunk perimeter (and also TCSA) is a good way to characterize the vegetative development of perennial plants such as olive trees, because this parameter cannot be influenced by pruning, as is the case for the canopy. In each of the cultivars, the linear regression analysis between trunk perimeter and time after planting showed a strong R-squared (R^2) (Fig. 2). This statistical measure ranged from 0.958 ('Galego de Évora') to 0.993 ('Lentrisca'). Further measurements will show whether this relationship persists or becomes more curvilinear.

In general, the trunk perimeter showed an annual increase, except for 2022, when the measurements were quite similar to those of the previous year (Fig. 2). The discrepancies between the trunk perimeter measured manually in olive trees and the value predicted by the linear-regression equations (Fig. 2) were greater in the 11 years after planting than in the previous periods (Table 2). In the 2022 growing season, the cultivars did not follow the pattern, and the incremental growth of the trunk perimeter decreased in the 11th year after planting. Despite the cultivar differences in the vegetative development, this behavior was observed in all cultivars (Table 1).

Table 1. Trunk cross-sectional area (TCSA), canopy volume (CV) of 11-year-old olive trees, total fruit yield and productive efficiency (2014–2022) of olive trees grown in the Olive Reference Collection of Portugal

Cultivar	TCSA (cm^2)	CV (m^3)	Total fruit yield (kg per tree)	Productive efficiency (kg per m^3)
'Galego de Évora'	121±11.7 a[1] (1)[2]	2.99±0.51 a (1)	77.8±11.3 cde (4)	28.2±3.41 e (15)
'Blanqueta de Elvas'	122±6.85 a (2)	5.82±0.36 bc (2)	64.5±3.98 bc (3)	11.2±0.62 c (9)
'Gulosinha'	195±5.01 b (3)	7.58±0.70 cd (6)	81.9±7.37 cde (6)	11.6±1.49 c (10)
'Gama'	198±15.1 b (4)	6.61±0.38 cd (4)	81.8±4.88 cde (5)	12.4±0.60 c (12)
'Cornicabra'	200±13.9 b (5)	7.53±0.61 cd (5)	87.7±4.38 de (8)	12.1±1.16 c (11)
'Maçanilha de Tavira'	212±12.7 bc (6)	11.1±0.49 ef (9)	117±6.34 fg (11)	10.6±0.60 c (6)
'Redondil'	226±24.1 bcd (7)	9.11±0.92 de (7)	82.4±8.63 cde (7)	9.09±0.51 bc (4)
'Azeiteira'	233±19.8 bcd (8)	6.56±0.87 cd (3)	130±9.42 g (14)	21.0±1.82 d (14)
'Cobrançosa'	242±15.8 bcd (9)	11.5±0.86 ef (13)	118±5.38 fg (13)	11.1±0.84 c (8)
'Cordovil de Serpa'	260±18.1 cde (10)	11.2±1.03 ef (10)	114±10.5 fg (10)	10.8±1.75 c (7)
'Lentrisca'	264±10.4 de (11)	13.5±2.42 f (15)	117±12.8 fg (12)	9.89±2.05 bc (5)
'Conserva de Elvas'	292±19.6 ef (12)	12.0±1.04 f (14)	59.7±5.16 bc (2)	5.22±0.73 ab (2)
'Ocal'	305±12.8 ef (13)	11.3±0.70 ef (11)	45.8±5.63 ab (1)	4.44±0.91 a (1)
'Galega Vulgar'	313±9.10 f (14)	11.4±1.02 ef (12)	136±5.47 g (15)	12.5±1.54 c (13)
'Verdeal Alentejana'	325±23.8 f (15)	10.8±0.47 ef (8)	102±10.4 ef (9)	8.75±0.79 abc (3)

[1] Different letters indicate statistically significant differences according to Duncan's test ($P < 0.05$)
[2] Ranking order in parentheses; mean values ± SE

Table 2. Discrepancies (expressed in cm) between trunk perimeter (manually measured) and its predicted value based on linear-regression analysis applied to trunk perimeter and time (years) after planting of olive trees

Cultivar	Years after planting					
	6	7	8	9	10	11
‘Azeiteira’	1.05	2.97	4.47	0.26	-0.03	-6.70
‘Blanqueta de Elvas’	-0.70	0.81	2.14	0.88	0.54	-3.80
‘Gama’	1.88	2.39	3.09	0.57	0.02	-5.79
‘Galega Vulgar’	0.45	2.30	3.58	0.16	-0.48	-5.11
‘Redondil’	1.14	2.70	2.83	0.88	-0.86	-4.56
‘Lentrisca’	-1.15	0.40	0.31	-2.62	3.06	-0.42
‘Cobrançosa’	2.33	1.69	3.68	-0.71	0.52	-5.29
‘Galego de Évora’	1.18	2.28	1.98	1.35	-0.45	-5.25
‘Maçanilha de Tavira’	1.54	2.61	3.01	0.12	-0.15	-5.39
‘Conserva de Elvas’	1.35	1.15	4.72	-0.42	0.52	-5.45
‘Ocal’	3.23	0.79	4.13	0.29	1.38	-6.31
‘Cordovil de Serpa’	1.91	3.16	4.10	-0.18	-0.32	-5.53
‘Gulosinha’	1.53	1.36	5.21	-0.02	0.28	-5.41
‘Cornicabra’	1.39	2.45	3.14	0.62	-0.68	-4.58
‘Verdeal Alentejana’	1.13	1.28	4.47	1.11	-0.49	-4.51

Drip-irrigated trees planted in June 2012, at the end of the 2022 harvest season the trees were almost 11 years old; Experiment was carried out in the Olive Reference Collection of Portugal (Alentejo region)

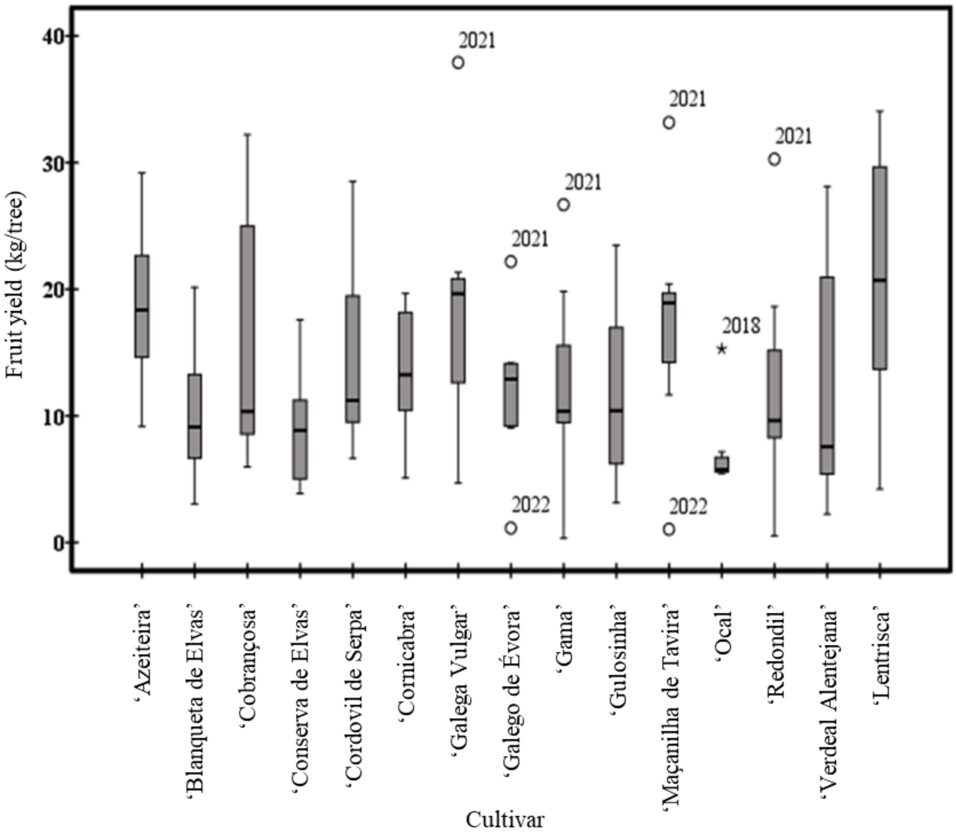

Figure. 1 Distribution (box plots) of fruit yield from individual cultivars per tree in the 2014–2022 harvest seasons

Drip-irrigated trees were planted in June 2012; Boxes show the 25th and 75th percentiles, and the line inside each box represents the median; Circles and asterisk indicate outliers (labels indicate harvest year); Mean values ± SE for ‘Azeiteira’: 15.7 ± 2.84, ‘Blanqueta de Elvas’: 10.3 ± 2.19, ‘Cobrançosa’: 16.5 ± 3.99, ‘Conserva de Elvas’: 8.13 ± 1.85, ‘Cordovil de Serpa’: 14.9 ± 2.96, ‘Cornicabra’: 13.6 ± 2.02, ‘Galega Vulgar’: 15.6 ± 3.60, ‘Galego de Évora’: 10.5 ± 2.15, ‘Gama’: 11.2 ± 3.05, ‘Gulosinha’: 11.9 ± 2.89, ‘Maçanilha de Tavira’: 15.4 ± 3.70, ‘Ocal’: 6.50 ± 1.42, ‘Redondil’: 10.9 ± 3.47, ‘Verdeal Alentejana’: 13.0 ± 3.96, ‘Lentrisca’: 20.8 ± 4.13

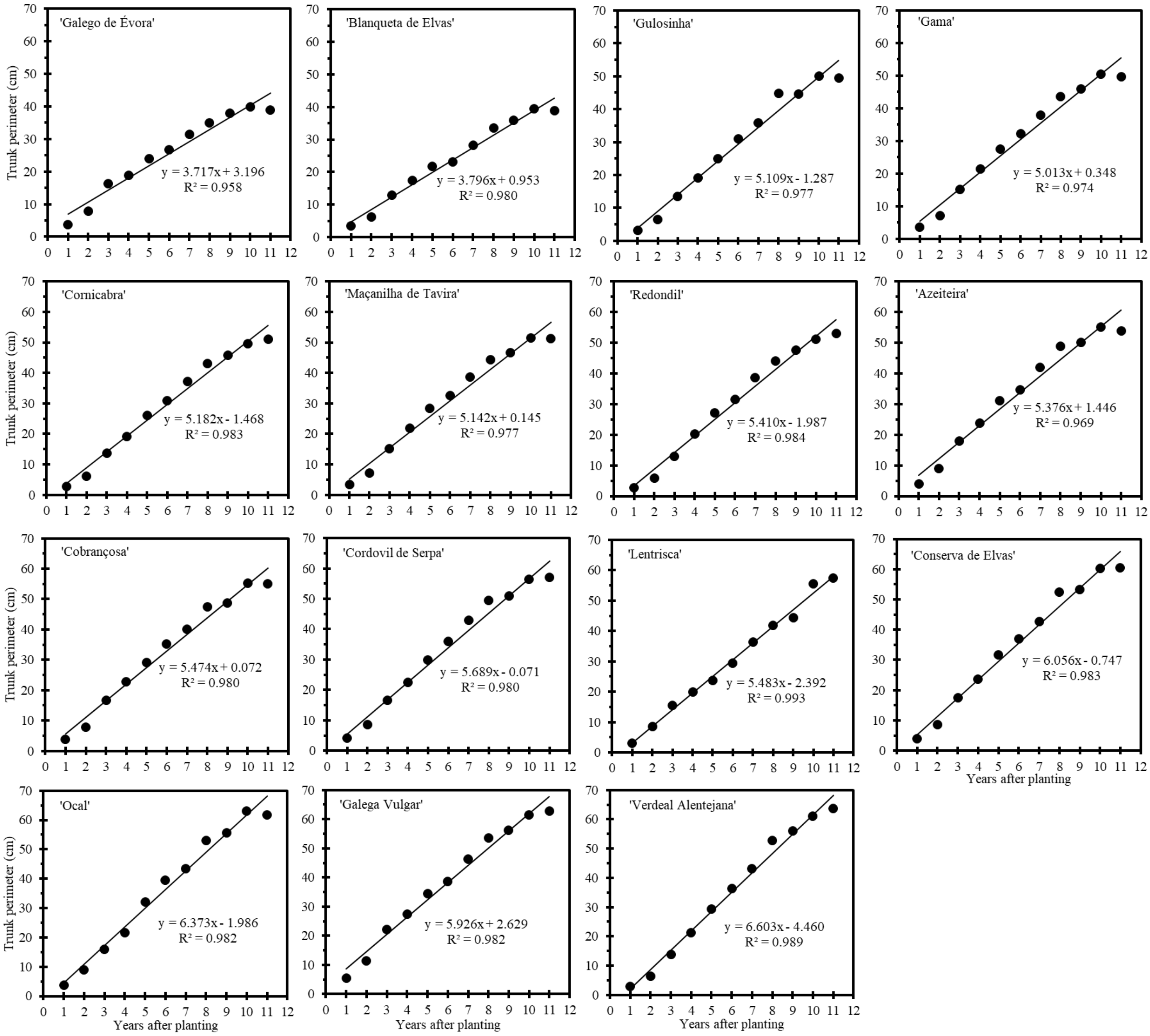

Figure 2. Linear regression between the annual trunk perimeter (measured 10 cm above the soil surface) and time (years) after planting of fifteen olive cultivars

Drip-irrigated trees planted in June 2012, at the end of the 2022 harvest season the trees were almost 11 years old; Experiment was carried out in the Olive Reference Collection of Portugal (Alentejo region)

Correlation of yield and vigor with maximum temperature

A statistically significant and negative correlation was found between the annual growth of trunk perimeter and the number of days with T_{max} above 30 °C in April–May and the number of days with T_{max} above 35 °C in April–September (Table 3). The strength of the correlation was higher for the number of days with T_{max} above 35 °C in May–September (−0.643). A statistically significant and negative correlation was also found between the FY in the year and the number of days with T_{max} above 30 °C in April–May and above 35 °C in April–September. The strength of the correlation was higher for the number of days with T_{max} above 35 °C in April–May (−0.406) (Table 3). Productive efficiency showed a statistically significant and positive correlation with the FY in the year. The strongest negative correlation was observed with the number of days with T_{max} above 35 °C in April–May (−0.521) (Table 3).

Up to this point, the data did not show whether the T_{max} in April–September had increased compared to the 25-year RP (1985–2010). During the RP, the T_{max} in April–September never exceeded 45 °C (Fig. 3). Over the period 2015–2022, the T_{max} reached 46 °C in both 2018 and 2022. On the other hand, the number of days with T_{max} above 30 °C and 35 °C increased in April–September (Fig. 3). In April–May, the development of inflorescence and flowering of olive trees continued. In these months, there were 6 days with air temperature above 30 °C in the RP and many more in the period 2015–2022 (except for 2016 and 2018) (Fig. 3). The situation was even worse when the T_{max} was above 35 °C. Over the 25-year period (RP), only one day recorded a T_{max} equal to or higher than 35 °C in April–May, in contrast to 9, 8, and 11 days in recent years (Fig. 3). The growing season was also under pressure. In May–September in 2015–2022, the number of days with a T_{max} equal to or higher than 35 °C was higher than in the RP (44 days), with increases ranging from 1.6 times (2015: 70 days) to 1.9 times (2022: 85 days) (Fig. 3).

In the climatic conditions of the Mediterranean basin, flowering, fruit set, fruit development, and onset of ripening occur sequentially from April or May to September, with harvest time starting in mid-October (fruits for oil extraction). In this specific five-month period and compared to the RP (1985–2010), it was observed that the number of days with T_{max} above 35 °C increased from 59% (2015: 70 days) to 93% (2022: 85 days) (Fig. 3). The largest increases were observed in the flowering–fruit set phases. In April–May, the number of days with T_{max} above 35 °C increased from 100% (2021: 2 days) to 1000% (2022: 11 days) (Fig. 3).

Table 3. Spearman correlation coefficients between fruit yield (FY), annual growth of trunk perimeter (P), and productive efficiency (2016–2022) with FY of both the year and the previous year (year − 1), cultivar, and number of days with high maximum temperatures (T_{max}) in April–September

			Number of days T_{max} > 30 °C	Number of days $T_{max} \geq$ 35 °C	
	FY (year)	FY (year − 1)	April–May	April–May	May–September
Annual growth of trunk perimeter	0.124	-0.047	**-0.377****	**-0.522****	**-0.643****
Fruit yield	1.000	-0.178	**-0.351****	**-0.406****	**-0.335****
Productive efficiency (kg per m^3)	**0.709****	**-0.478****	**-0.357****	**-0.521****	**-0.257***
n	105	90	105	105	105

Data collected from olive trees grown in the Olive Reference Collection of Portugal; Mean values by cultivar and year
* Correlation significant at the 0.05 level (two-sided)
** Correlation significant at the 0.01 level (two-sided)

	RP	2015	2016	2017	2018	2019	2020	2021	2022
Tmax (°C) April-September	45	43	43	45	46	42	44	44	46

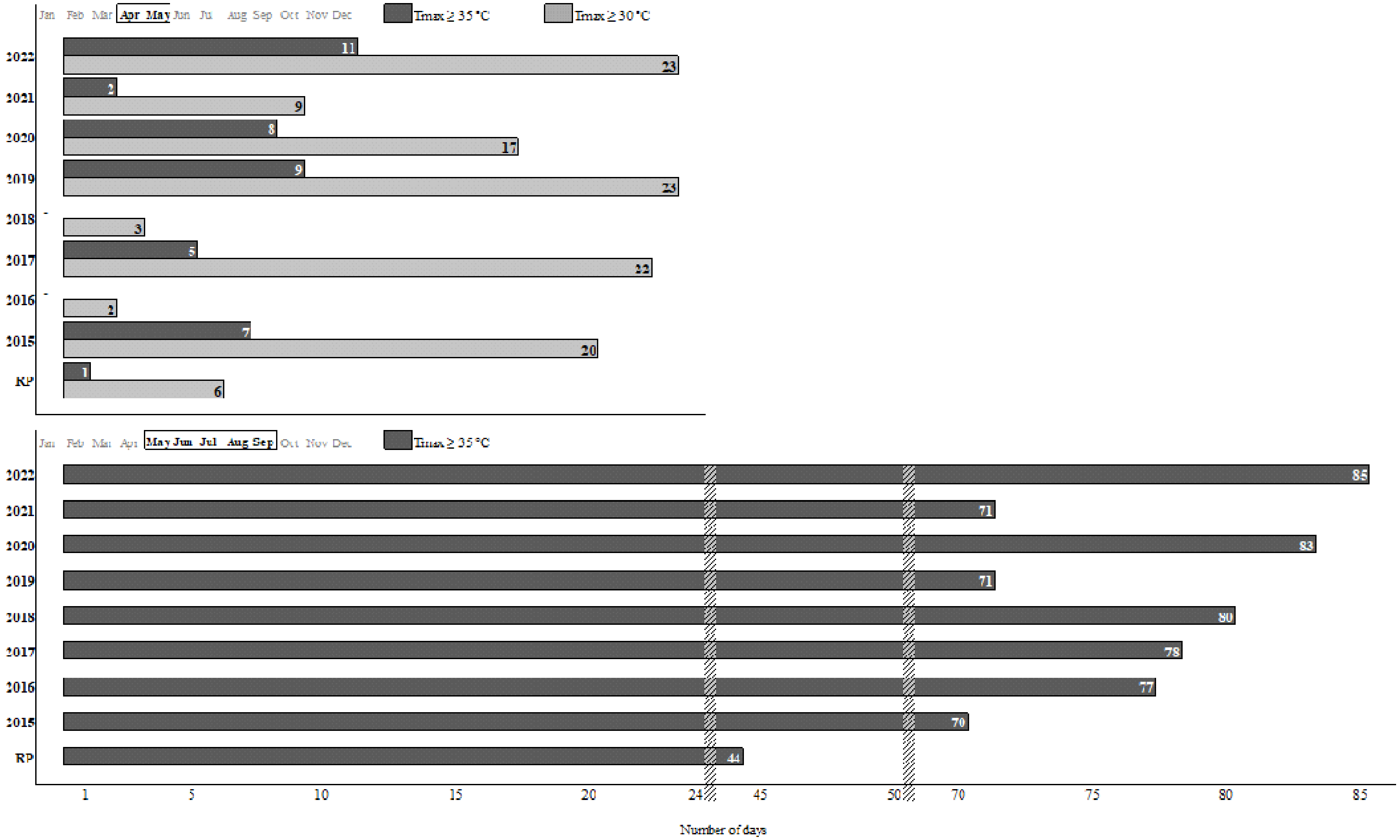

Figure 3. Maximum temperature (T_{max}) and number of days (horizontal bars) with air temperature above 30 °C and 35 °C in Elvas (Portugal) in April–September of the 25-year reference period (RP) (1985–2010) and in 2015–2022

DISCUSSION

The conservation, management, and sustainable use of plant genetic resources for food and agriculture have become a priority. To protect the genetic resources of Portuguese olive trees, the Olive Reference Collection of Portugal (ORCP) (FAO code: PRT196) was established (MAM 2015). The characterization (morphological and molecular) and evaluation (agronomic, technological, etc.) of the germplasm conserved in the ORCP aims to obtain information enabling the use of indigenous olive genotypes in commercial orchards and to provide a source of genes for breeding programs.

Vegetative development and fruit production characteristics are very heterogeneous among extreme cultivars (Table 1). Genotypes have different development rhythms and it seemed very peculiar that in 2022 all cultivars showed the same behavior in terms of annual FY and trunk growth (Fig. 2 & Table 2). Differences between cultivars were somehow leveled out and all genotypes showed a decrease in fruit production and trunk perimeter growth. The main hypothesis formulated to explain such an effect in all cultivars concerned environmental conditions (Nissim et al. 2020; Petruccelli et al. 2022; Inês et al. 2023). Indeed, annual trunk perimeter, annual FY, and productive efficiency were negatively correlated with T_{max} in April–September (Table 3). Correlations were stronger when evaluating the number of days with T_{max} equal to or higher than 35 °C in April–May and vegetative growth in May–September (Table 3).

In olive tree species, growth is strongly controlled by temperature (Lavee 1996; Rallo & Cuevas 2008). Under northern hemisphere climatic conditions, vegetative development stops in winter due to low temperatures and in summer due to high temperatures, which determine the closure of stomata (Davies & Zhang 1991; van der Vyver & Peters 2017; Haworth et al. 2018a). High temperatures (above 35 °C), which are common in Mediterranean climates in summer, gradually lead to stomatal closure. This impedes gas exchange and photosynthesis and indirectly reduces shoot growth (Marino et al. 2014; Haworth et al. 2018a; Parri et al. 2023). The negative correlation between the number of days with temperatures equal to or higher than 35 °C during the spring–summer growing season and the annual increase in trunk perimeter was statistically confirmed (Table 3). In addition, 2022 was a challenging year in terms of tree resistance to high temperatures or heat stress. Between May and September (five months), 85 days had temperatures equal to or higher than 35 °C (Fig. 3). About 12 weeks (3 out of 5 months) showed conditions limiting photosynthesis due to high temperatures (Rallo & Cuevas 2008; Haworth et al. 2018a; Parri et al. 2023). This climatic situation seems to largely explain why all cultivars had a difficult growing season in 2022 and, consequently, the annual increase in trunk perimeter was very low or nonexistent, even among genotypes with different vigor characteristics (Table 1).

In the olive tree, metabolic activity is maximal between 20 °C and 30 °C (Lavee 1996; Rallo & Cuevas 2008), making temperatures above this threshold a strong limiting factor (Haworth et al. 2018b; Parri et al. 2023). In 2022, cultivars showed low FY, a strong negative correlation was found between the FY in the year and the number of days with a T_{max} equal to or higher than 35 °C in April–May (occurrence of flowering and fruit setting processes) (Table 3). In Mediterranean climate conditions, flowering of olive trees occurs on average on days that do not exceed the maximum threshold of 30 °C (de Melo-Abreu et al. 2004; Benlloch-González et al. 2018; Didevarasl et al. 2023; Parri et al. 2023). In this study, the number of days with a T_{max} above 30 °C in April–May has increased strongly, but in addition, the occurrence of days with a T_{max} above 35 °C in April–May is also becoming more frequent (Fig. 3), which is very worrying. Other authors reported that the T_{max} in spring and summer (March–August) showed a negative correlation with olive production, while precipitation always showed a positive correlation (Orlandi et al. 2020).

Abnormally hot weather in 2022 in the Alentejo region, Elvas, could have caused damage at different stages – in the formation of flowers and pollen grains (Rojo et al. 2015; Rojas-Gómez et al. 2023) or during pollination, fertilization, and fruit setting (Cuevas et al. 1994; Lavee 1996; Rallo & Cuevas 2008; Koubouris et al. 2009; Vuletin Selak et al. 2014). The result of these factors was lower fruit production.

Several studies have shown that the olive growth sector in the Mediterranean region is going through difficult times in terms of flower development and fruit growth processes, which will soon become even more difficult (Orlandi et al. 2020; Fraga et al. 2021; Di Paola et al. 2023; Inês et al. 2023; Picornell et al. 2023; Villalobos et al. 2023). The increase in T_{max} is a worldwide problem. In this study, the comparison of the T_{max} of the period 1985–2010 with the T_{max} of the period 2015–2022 was worrying due to the drastic increase in the number of days with a T_{max} equal to or higher than 35 °C in April–May. According to IPMA (Portuguese Institute for Sea and Atmosphere), 2022 was the hottest year in Portugal since 1931 (data available in February 2024) (IPMA 2023). The adaptability and resistance of olive tree species and their cultivars are being tested and the future success of the olive sector depends on them.

CONCLUSIONS

Fruit production and vegetative growth of fifteen indigenous olive cultivars have been drastically affected by high temperatures experienced since April. In spring 2022, the number of days with maximum temperatures above 35 °C was much higher than the average for the region. The development of reproductive organs and the processes of flowering or fertilization of the ovary were probably the most affected by this situation. The phenology of genotypes must be a feature that will be included in the criteria for cultivar selection and breeding programs. For a cultivar to become very productive and have a very high oil content, it must be able to complete the flowering and fruiting processes before the period of high temperatures. The drastic change in the rhythm of the annual cycle of the plant may not be sporadic but increasingly regular.

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Conflict of interest

There is no conflict of interest among the authors.

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