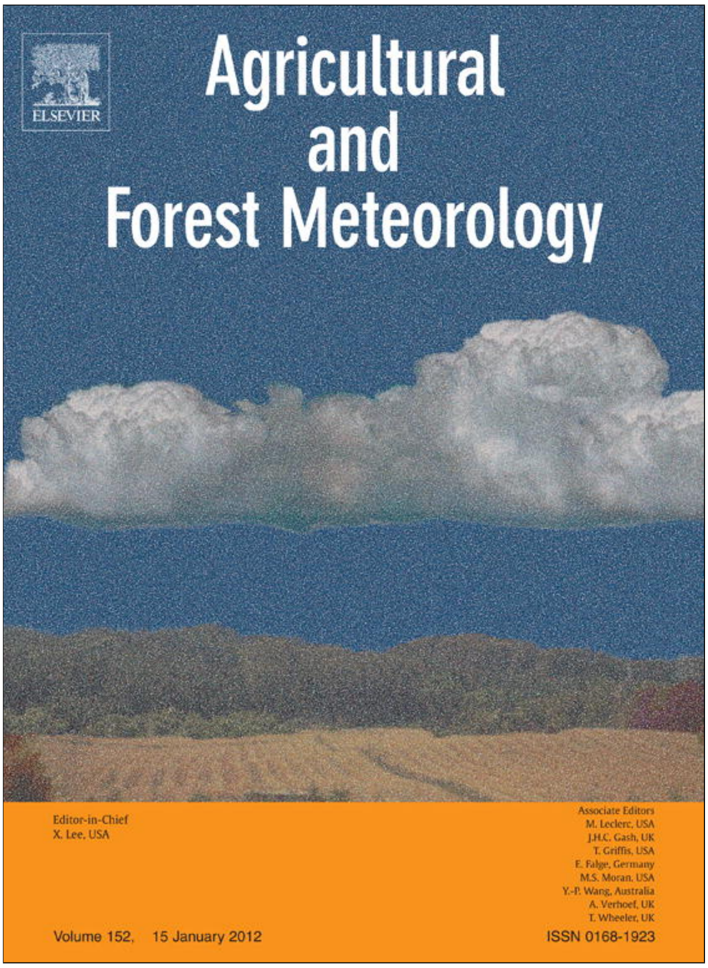
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Volume 152, 15 January 2012
ISSN 0168-1923

Agricultural and Forest Meteorology 161 (2012) 80–93

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

A novel mathematical procedure to interpret the stem radius variation in olive trees

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ARTICLE INFO

Article history:
Received 21 June 2011
Received in revised form 4 February 2012
Accepted 20 March 2012

Keywords:
Mediterranean environment
Point dendrometers
Radial growth
Seasonal course
Water relations

ABSTRACT

Stem radius variations result from the fluctuation of environmental factors, mostly temperature trend and water availability, in turn affecting plant water balance, and plant growth. High-resolution analysis of stem radius variation provides insights into the temporal patterns in radial growth and water balance, and their relationship with environmental variables. To test the causal effects of temporal climate fluctuation on stem radius variation, a mathematical procedure was applied to normalize and synchronize radial fluctuations and environmental parameters, whose baseline is largely unexplored.

Stem radius variations were continuously monitored during two consecutive years in four saplings field-grown olive tree cultivars (Canino, Cipressino, Leccino, Maurino) in an experimental farm in central Italy, between November 2004 and October 2006, using automatic high-resolution point dendrometers. A derivative analysis approach applied on point dendrometer records was conveniently used to describe stem radius variation and to distinguish the timing of transition from the dormant winter state to the active growth stage and till the slow expansion phase.

Stem diameter patterns showed intense shrinkage events suddenly after air temperature drop below 0 °C during winter. The onset of radial growth was delimited by the occurrence of rehydration (beginning of transpiration cycles) and increase of air temperature (end of cold cycles). The course of the growing season was described by patterns of air temperature, reference evapotranspiration, cumulative degree-days, vapour pressure deficit and soil moisture deficit, and correlated to patterns in stem radius cycles. Three phases of stem radius variation were evidenced through the seasonal course: induction signal, growth period, and slow expansion.

This approach provides new and objective insights on shrinkage–swelling phenomena in Mediterranean environments, related to dehydration and hydration cycles, which are difficult to detect with empirical treatment of stem radius variation records. The ability to switch quickly between dormancy to growth would enable the olive tree to restart physiological processes and to cope with erratic climatic conditions of the Mediterranean region.

1. Introduction

Monitoring of stem radius variation can detect patterns of plant growth stages and short-term changes in environmental conditions, such as temperature, soil water content and rainfall. Consequently, defining the relationship between stem radius variation and duration of growing season remains an intriguing issue given the potential impact of climate change on plant phenology (Chuine et al., 1998; Galán et al., 2005; Geßler et al., 2007; García-Mozo et al., 2010; Downes et al., 1999; Deslauriers et al., 2003; Giovannelli et al., 2007).

The rhythm of stem radius changes is mainly induced by water uptake (i.e., reversible changes) and wood growth (i.e., irreversible changes) (Zweifel et al., 2001; Deslauriers and Morin, 2005; Intrigliolo and Castel, 2007; Zweifel et al., 2010). Although, the activation and cessation of plant growth in spring and dormancy in winter has been mainly related to temperature (Heide and Prestud, 2005; Rossi et al., 2006; Cocozza et al., 2009), as well as to water availability (Eilmann et al., 2011), dendrometric records remain often difficult to interpret because the "signal" recorded

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http://dx.doi.org/10.1016/j.agrformet.2012.03.016

represents the non linear response to complex interactions between environmental conditions and plant traits (genotype, function, and structure).

The complexity of the interaction between environmental conditions and growth dynamics is indicated by the varying degree of temporal correspondences between stem radius variations and specific climate variables (e.g., Zweifel et al., 2001). Indeed, automatic measurements of stem radius variations provide an effective and sensitive proxy for plant water status assessment, which have also been proposed for precise irrigation scheduling and implementation in tree phenological modelling (e.g., Moreno et al., 2006; Fernández and Cuevas, 2010). Several empirical methods are currently applied on data gathered with dendrometers to monitor tree growth patterns and to evaluate water storage depletion and replenishment of stems (e.g., Kozlowski and Winget, 1964; Bouriaud et al., 2005; Offenthaler et al., 2001).

The use of automatic dendrometers defines large data sets at high resolution in space (micrometric variation) and time (from second to minute), which require adequate and complex time series analyses. Although a general pattern has been described based on graphical analyses of the time series (e.g., Zweifel et al., 2005), useful tools to clearly define the seasonal patterns of radius variation are still lacking. The time series analysis has several shortcoming, such as the algorithm application to raw data to extract information (Deslauriers et al., 2011); the choice of an approach to extrapolate water-related changes, for instance, could consider the stem cycle (Downes et al., 1999, Deslauriers et al., 2003), the seasonal course (Zweifel et al., 2005) and the daily trend (Bouriaud et al., 2005; Tardif et al., 2001). Furthermore, the plant phenology (Marsal et al., 2002), the plant genotype (Cocozza et al., 2009), the non linearity of response of biological organisms, as well as the erratic and extreme climatic events add to the elaboration of dendrometric data high degree of unexpected variability, which makes the output difficult to interpret. Even though automatic dendrometer measurements may introduce confusion in the identification of radial growth onset and main period of growth (e.g., Deslauriers et al., 2007a; Turcotte et al., 2009), the standardisation of stem radius variations and the synchronisation with environmental parameters is a prerequisite to define the non linearity of response of biological organisms.

The olive tree, *Olea europaea* L., is a Mediterranean tree highly adaptable to harsh environments, which may withstand water limiting conditions and poor soil fertility, while being sensitive to low oxygen conditions in the soil and low temperature. However, many different cultivars are cultivated worldwide, showing high degree of morphological and physiological plasticity in this woody species (Rugini and Lavee, 1992). We investigated four cultivars specifically differing in tree growth performances at maturity (trunk and canopy), and environmental stress responses (C. Cantini, personal communication); Leccino and Canino have similar growth patterns and are more vigorous than Maurino and Cipressino. These cultivars are of some interest for high quality timber production in agroforestry plantations (for parquet, veneer or furniture end uses), and are suitable in testing procedures for an objective analysis of stem diameter dynamics and disentangling overlaid ecological and genetic factors that affect stem radius variation.

In olive trees, stem diameter dynamics has been used to derive indices of water stress (Cuevas et al., 2010). Reference maximum daily shrinkage (MDS) values, needed to calculate the signal intensity, are obtained by relating trunk diameter measurements and plant water relations, (Moriana and Fereres, 2002; Fernández and Cuevas, 2010). Moreno et al. (2006) found that MDS at trunk level reflected changes in the evaporative demand, with daily mean vapour pressure deficit (VPD) and midday air temperature, therefore MDS can be used as control parameter for irrigation in olive tree plantations. Tognetti et al. (2009) studied 16-year-old olive trees, grown under different water treatments for 14 years in an experimental site plantation in southern Italy, and found that plants growing under rainfed conditions showed a small increase in MDS during drought periods, pointing to increasing water conservation and acclimation potential with progressively decreasing water availability. Drought indices based on stem diameter variation, including MDS and stem growth rate are, however, affected by factors other than water stress (such as seasonal growth patterns, crop load, plant age and size) and of difficult interpretation (Fernández and Cuevas, 2010). Thus, unbiased treatment of stem diameter variation records is needed, before using them for scheduling irrigation and in ecological studies.

Empirical links between stem radius variations and climate condition patterns could be processed to derive iterative models for wood properties as a function of environmental signals and physiological processes and to improve the synchronisation between these variables. The approach would be useful in predicting the response of olive trees to global warming in threatened Mediterranean-type ecosystems. Although several studies have been undertaken to link stem radial variations with climate, interpretation of the results is still uncertain because of the superimposed effects of water status, air temperature and cambial activity, and the role of fruit development and crop load in influencing stem growth dynamics in olive trees (Moriana et al., 2003). Stem radius changes must be deterended for growth before being used as an index of environmental stress in trees (Zweifel et al., 2005).

The study of stem radius variations may be addressed by using analytical solutions to seasonal synchronisation of stem phenology and environmental parameters. The importance of this study approach relies on studying stem radius variations through an original mathematical approach that provides new and thorough insights on tree adaptation to annual changing environmental conditions. The application of mathematical functions is preferable to perform quantitative solutions and sensitivity analysis (Baldocchi, 1994). It was hypothesized that seasonal changes in climate conditions, exerting a dominant control over stem radius variations would be synchronized through a mathematical approach that consider the non linearity of biological system.

A detailed high-resolution analytical approach to describe the correspondence between stem radius variation in the four olive tree cultivars and climate variables was applied, defining the duration of growing phases and coupling processes of stem diameter with minimum air temperature (T_{min}) in winter season, and reference evapotranspiration (ET_0) and VPD in the vegetative season. The study was conducted to define the possibility of applying mathematical functions on stem radius variation records.

2. Materials and methods

2.1. Study area and experimental plantation

The experiment was conducted during the years 2004–2006 at the Santa Paolina experimental farm of CNR- IVALSA, located in Follonica (GR), Toscana, central Italy (42°55′58″N, 10°45′51″E, 17 m a.s.l.), using olive trees of four cultivars (Canino, Cipressino, Leccino and Maurino) cultivated at single-trunk free canopy (Gucci and Cantini, 2000) at a spacing of 4 m × 4 m. The cultivars were chosen because of their different growing habit, vigour, frost resistance and water consumption. The olive orchard is on a sandy-loam soil with natural cover crop and no tillage traditionally managed again the main olive pests. The plants were not pruned during the three-years period of the experiment so that the canopy was set free to grow naturally without any modification. During the growing season preceding the experiment, all trees have been equally irrigated with a trickle system to guarantee the uniformity of plant development.

The monitoring was conducted on rainfed olive trees, and started when plants were three years old. The experimental design was a complete randomised block, replicated four times, with subplot for micro-morphometric analysis.

2.2. Meteorological data

Climate data were recorded every 15 min with a standard meteorological digital station placed at 100 m from the orchard (quality-controlled data were supplied by Regione Toscana). The variables measured were air temperature (T_{mean}, T_{max} and T_{min}, °C), total rainfall (P, mm), and relative humidity (R_h, %). The maximum temperature was 34.6 °C in July 2006 and minimum temperature was −6.6 °C in January 2006. The VPD was calculated by using the Goff–Gratch formulation for saturated water vapour pressure (Goff and Gratch, 1946). Climate of the area is typical Mediterranean with hot summer and relatively cold winter (Fig. 1), and hourly reference evapotranspiration (ET_0) was calculated following Hargreaves–Samani (Allen et al., 1998). Soil moisture deficit (SMD, mm) was calculated as the difference between cumulative ET and cumulative rainfall, with SMD < 0 set to zero.

In three periods of growing season, defined by distinctive stem radius variation (Table 1), cumulative degree-days (CDD) were determined by the single triangle method from daily maximum and minimum temperature, using the method of Zalom et al. (1983). Degree-day estimates, based on a lower threshold of 10 °C and higher temperature of 30 °C, were totalled for each day and compared to hourly sums for the same periods (Roltsch et al., 1999).

2.3. Dendrometer measurement

Stem radius variations were monitored between October 2004 and October 2006 using automatic point dendrometers (Label et al., 2000) on four individual trees per each olive tree cultivar. The used dendrometers measure the linear displacement of a sensing rod pressed against the bark. The operating principle of the linear variable transducer (AB Electronics Ltd., Romford, Essex, UK) that responds to stem radius variation is described elsewhere (Giovannelli et al., 2007; Cocozza et al., 2009). Trees were monitored with these high-resolution automated dendrometers installed on the trunk at 50 cm from the soil surface, and shielded from direct sunlight and weather damage by aluminium foils. Raw data were recorded every 15 min, and hourly and daily averages were then calculated.

2.4. Time series comparison

Continuous measurements of stem radius variation obtained with automatic dendrometers provide time series characterized by a strong seasonal trend. However, the response of olive trees to changes in environmental conditions (e.g., plant growth vs. increasing temperature) is complicated by ecological adaptation of the cultivar examined. The hourly values of stem radius of the four olive tree cultivars, measured using automatic point dendrometers, were statistically analysed with the Time Series Analysis Programme (TSAP) software package (Frank Rinn, Heidelberg, Germany), which was originally developed as a tool for cross-timing of tree-ring series. The degree to which the time series of different cultivars are correlated was estimated through cross-correlation method to evaluate intrinsic variability under the same environmental conditions. In dendrochronology two main concepts have been used to express the quality of agreement between time series: *Gleichläufigkeit* (Glk) and/or t-values. Raw diameter values were compared statistically by the percentage agreement in the signs of the first differences of the two time series (the Glk) (Kaennel and Schweingruber, 1995). In this case, the Glk is a measure of the day-to-day agreement between the interval trends of two time series based upon the sign of agreement, or the sum of the equal slope intervals as a percentage. With an overlap of 50 days, Glk becomes significant ($P < 0.05$) at 62% and highly significant ($P < 0.01$) at 67%. With an overlap of 10 days, Glk becomes significant ($P < 0.05$) at 76% and highly significant ($P < 0.01$) at 87% (Kaennel and Schweingruber, 1995). In this study, the analysed time series were mostly longer than 50 days and the quality of agreement between time series was considered successful if the value of Glk was > 60%. The statistical significance of the Glk (GSL) was also computed. The TVBP, a Student's t-value modified by Baillie and Pilcher (1973) and further developed by Munro (1984), was used for investigating the significance of the best match identified. The TVBP is commonly used as a statistical tool for comparing and cross timing of time series, determining the degree of correlation between curves. This method eliminates low-frequency variations in the time series, as each value is divided by the corresponding 5 days moving average.

2.5. Stem radius variation

The analysis of seasonal patterns was conducted by studying periods of 10 days, evaluating the amplitude and frequency phase of stem radius variation. To characterize seasonal stem radius variation over the year, the duration (days) of each phase was calculated considering the occurrence of environmental conditions (T_{min}, ET_0 and VPD, depending on the season) and the intensity of stem shrinkage, defined by the amplitude of daily stem radial oscillation. The growing season was classified in phases according to three criteria: (i) duration, (ii) environmental conditions that origin cycle phases and (iii) net radius variation (stem radius variation or increment) (Table 1).

Two phases of the diurnal cycle of stem radius variation were defined, according to Downes et al. (1999): 'shrinkage' was considered as the decrease in stem size from a local maximum to a local minimum of the same event (i.e., the daily period during which the stem radius decreased in the dormant and growing season); 'recovery' was measured as the increase in stem radius from a previous minimum until a successive maximum in the growing season, when stem returned to its size before shrinkage in the dormant season (i.e., the portion of the daily cycle during which the stem radius increased until reaching the same or upper position with respect of the local maximum before stem shrinkage, in the dormant and growing season, respectively) (Drew et al., 2008).

Stem radial fluctuations (i.e., stem radius shrinkage in winter and stem diameter increment, SDI, in the growing season) correspond to circadian variation calculated as the difference between the maximum point of stem shrinkage and the onset of this event. The diurnal thermal minimum and thermal excursion (variation) were recorded for every stem shrinkage event. The amplitude of the stem shrinkage was calculated considering the variation between the beginning and the end of the shrinkage phase. The daily mean approach gave results more similar to the stem cycle than the daily maximum (Deslauriers et al., 2007a).

The seasonal course was classified and analysed starting with the identification of daily stem radial variation in each period, according to the classification of Tardif et al. (2001), allowing a division of the year into three periods: winter shrinkage, spring rehydration and summer transpiration. Seasonal climatic changes were determined with the environmental data (air temperature, ET_0, VPD, SMD), which define specific ranges of meteorological data, and, then, observing the stem dynamics in relation to environmental conditions (Fig. 1). The relationship between stem radius variation and environmental variables defined characteristic patterns of (i) a period of instability in winter, with strong episodes of swelling and shrinking of trunks (Figs. 2 and 3); (ii) a short period

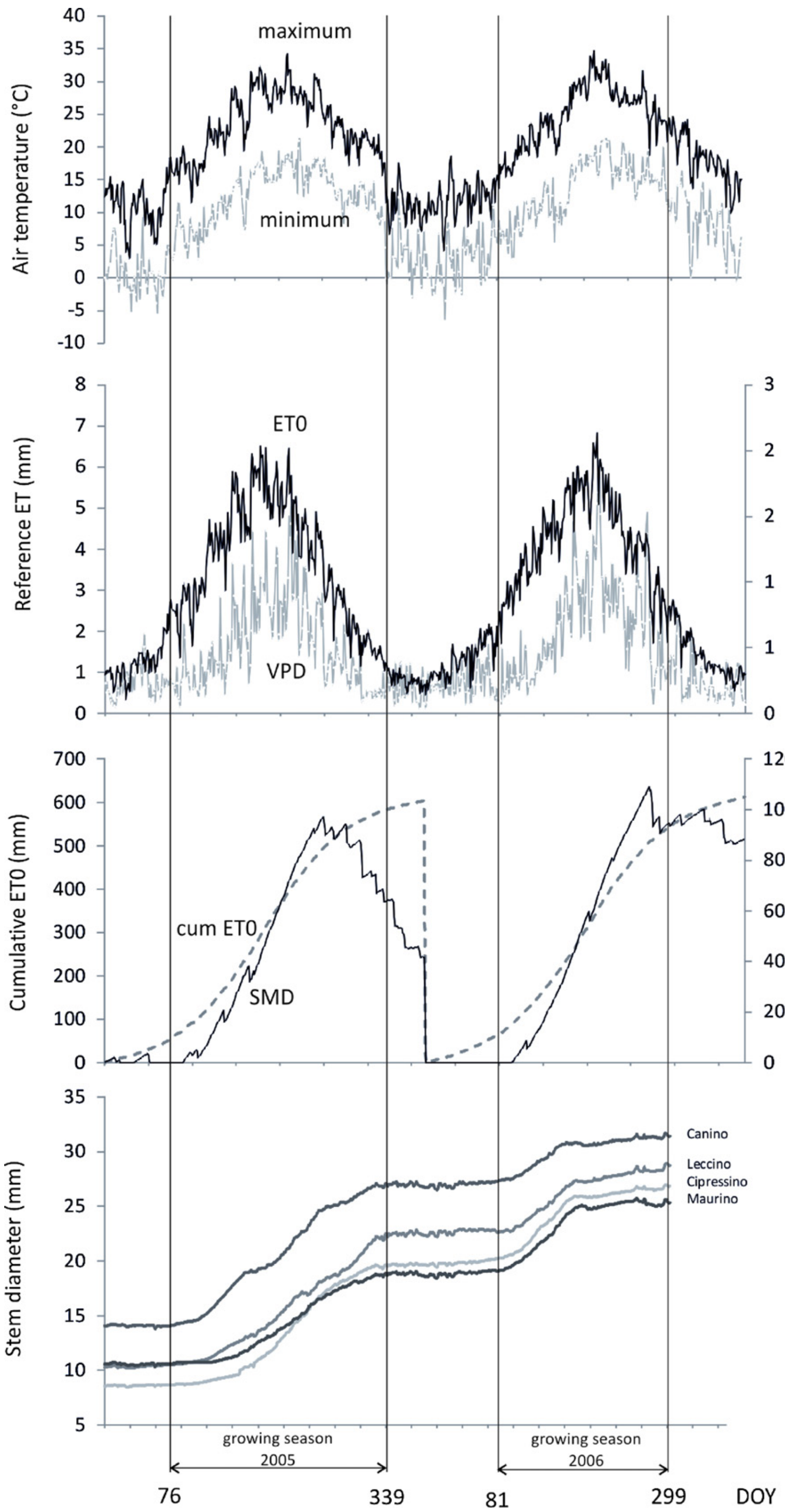


Fig. 1. Daily values of maximum and minimum air temperature (T_{max} and T_{min}), reference evapotranspiration calculated following Hargreaves–Samani (ET_0-HS), vapour pressure deficit (VPD), cumulative values of reference evapotranspiration (ET_0 cum), soil moisture deficit (SMD), and mean stem diameter in the four olive tree cultivars, during 2004, 2005 and 2006.

Table 1
Timing (DOY) and duration (days) of seasonal course, thermal range (T_{min} range), shrinkage amplitude (shrinkage range), stem diameter increment (SDI), and cumulative degree day (CDD) were reported per each cultivar, in the two years of monitoring.

cultivar		dormant season 2004-2005	dormant season 2005-2006	growing season 2005 stage I	2005 stage II	2005 stage III	growing season 2006 stage I	2006 stage II	2006 stage III
Canino	DOY	341 ÷ 75	340 ÷ 80	76 ÷ 110	111 ÷ 187	188 ÷ 339	81 ÷ 111	112 ÷ 165	166 ÷ 299
	days	101	106	35	77	152	31	54	134
	T_{min} range (°C)	12.3 ÷ -5.6	11.1 ÷ -6.6	2.4 ÷ 11.7	5.2 ÷ 19.4	4.6 ÷ 21.5	2.8 ÷ 11.1	5.2 ÷ 15.4	8.4 ÷ 21.5
	shrinkage range (mm)	0.05 ÷ 0.34	0.10 ÷ 0.50						
	CDD (°C)			76.6			73.4		
					730.0			416.9	
					2011.8			1949.7	
	SDI (mm)				12.88			4.27	
Cipressino	DOY	341 ÷ 75	340 ÷ 80	76 ÷ 110	111 ÷ 210	211 ÷ 339	81 ÷ 125	126 ÷ 182	183 ÷ 299
	days	101	106	35	100	129	45	57	117
	T_{min} range (°C)	12.3 ÷ -5.6	11.1 ÷ -6.6	2.4 ÷ 11.7	5.2 ÷ 19.6	4.6 ÷ 21.5	2.8 ÷ 12.0	5.2 ÷ 19.1	8.4 ÷ 21.5
	shrinkage range (mm)	0.02 ÷ 0.16	0.04 ÷ 0.38						
	CDD (°C)			76.6			146.7		
					1012.1			620.1	
					2011.8			1949.7	
	SDI (mm)				10.91			6.84	
Leccino	DOY	341 ÷ 75	340 ÷ 80	76 ÷ 110	111 ÷ 182	183 ÷ 339	81 ÷ 136	137 ÷ 182	183 ÷ 299
	days	101	106	35	72	157	56	46	117
	T_{min} range (°C)	12.3 ÷ -5.6	11.1 ÷ -6.6	2.4 ÷ 11.7	5.2 ÷ 19.4	4.6 ÷ 21.5	7.6 ÷ 12.4	5.2 ÷ 19.1	8.4 ÷ 21.5
	shrinkage range (mm)	0.04 ÷ 0.20	0.12 ÷ 0.54						
	CDD (°C)			76.6			210.7		
					669.3			620.1	
					2011.8			1949.7	
	SDI (mm)				11.64			5.84	
Maurino	DOY	341 ÷ 75	340 ÷ 80	76 ÷ 131	132 ÷ 182	183 ÷ 339	81 ÷ 105	106 ÷ 182	183 ÷ 299
	days	101	106	56	51	157	25	77	117
	T_{min} range (°C)	12.3 ÷ -5.6	11.1 ÷ -6.6	2.4 ÷ 11.8	7.1 ÷ 19.4	4.6 ÷ 21.5	2.8 ÷ 10.7	5.2 ÷ 19.1	8.4 ÷ 21.5
	shrinkage range (mm)	0.06 ÷ 0.26	0.12 ÷ 0.46						
	CDD (°C)			172.0			48.7		
					669.3			620.1	
					2011.8			1949.7	
	SDI (mm)				8.12			6.26	

of stability, with practically no stem radius increment; (iii) a period of radial growth during spring and summer, with a steep and continuous increase of the stem radius (SDI). Data of stem radius in the growing season were related to ET_0 (VPD and SMD, data not shown). The variable function coefficients allowed defining three stages, consequently to the degree of agreement of stem and ET_0 behaviour. Moreover, each stage was characterized by duration in days and CDD (Table 1).

2.6. Mathematical approach

The first exploration at the data analysis was made classically through the use of rough data on the seasonal rhythm of stem radius variation. The data analysis was done on a tree-by-tree basis, and then averaged by cultivar. The relationship between climate data and stem radius variation using a mathematical approach was tested. Rough data collected through year were first analysed measuring the duration of each daily phase (and the rate of change in diameter). The shrinkage values (mm or μm) correspond to stem radius variation calculated as the difference between the maximum point of shrinkage and the onset of this event. The diurnal thermal minimum and thermal excursion (variation) were recorded for every shrinkage event. The daily mean approach gave results more similar to the stem cycle than the daily maximum (Deslauriers et al., 2007a).

Whereas, records of the growing period, spring and summer, were focused on the high-frequency signals of stem growth through the "detrending" or "standardisation" method, which removes the effects of tree growth from the time series, retaining the environmental variability, as widely applied in dendrochronology for tree-ring growth series (Cook and Kairiukstis, 1990; Fritts, 1976). Considering an idealized series of radial increment measurements, that is n days in length, collected from a tree growing without disturbances, and the basis of the allometry that affects the tree growth, it is usually the case that this 'raw' radial increment series, such as ring-width series of tree rings, exhibits a decreasing trend with increasing seasonal course, such as age in tree ring. A useful model for this time-related trend in radial increment (such us ring-width) series is the modified negative exponential curve (Fritts et al., 1969) of the form:

$$G_t = ae^{-bt}$$

where a is the growth intercept at $t = 0$, b is the decay constant, and t is time in years. Since this observed trend in ring widths is believed to be mostly non-climatic in origin (as it is related only to tree age and size), the usual practice is to remove it from the tree-rings by fitting smooth growth curves to the ring widths, like the modified negative exponential curve (Cook and Peters, 1997).

However, the pronounced noise signal, due to the sensitivity of the transducer, required an accurate data analysis to allow a precise and correct elaboration. As a consequence, stem variation, air temperature and VPD records were processed through the use of the derivative mathematical function as a support to the use of rough data. The derivative analysis was done through OriginPro software package (OriginLab, Massachusetts, USA). The derivative of a function represents an infinitesimal change in the function with respect to one of its variables. For a function of a single real variable, the derivative at a point is equal to the slope of the tangent line to the graph of the function at that point. As the experimental data are a function of time $f(t)$, the analysis was performed through time derivative $f'(t)$:

$$f'(t) = \frac{df(t)}{dt} = \lim_{\Delta t \to 0} \frac{f(t + \Delta t) - f(t)}{\Delta t},$$

where t corresponds to time, and Δt is the time increment.

The derivative of the function at a chosen input value describes the best linear approximation with respect to time of the function near that input value. This analysis allowed the rate of variation of a function to be emphasized; when the derivative is found to be positive, the input function is increasing, when it is negative the function is decreasing. Moreover, the higher value of the derivative the faster is the change in the value of the function. In the present work, the magnitude of peaks of derivative curves was not considered, as it was not chosen to study the rate of change of the input function. In fact, due to the sensitivity of the transducer, the data present a permanent noise, which means, on the derivative curve, a high number of events (peaks, x-axis intersection), without correspondence with the scope of the present study. In order to amplify the eventual differences between cultivars in the response to air temperature and VPD, normalized derivatives were used. For each olive cultivar and each considered season period, the derivative curve was simply divided by the maximum absolute value in order to provide data ranging from −1 to 1. The intersection of the derivative curve with the x-axis, i.e., the null value of the derivative, corresponds to an extreme of the input function. A positive (negative) derivative that intersects the x-axis indicates a local maximum (minimum) of the input function.

2.7. Pointer day analysis

Pointer days were analysed as pointer years in dendrochronology (Neuwirth et al., 2007), in order to show daily radial growth patterns as affected by abrupt changes in meteorological conditions (e.g., Schweingruber et al., 1990). Extreme growth reactions within a sequence of days were classified as "pointer days" representing extreme days of individual trees (positive or negative growth conditions). All raw daily stem radius measurement series were transformed into high-frequency time series of pointer values using a two-step approach. Ratios between the raw daily measurements for single cultivar series and their 13-day moving average were calculated according to Cropper (1979). Cropper-values were then normalized to have a mean of zero and a standard deviation of one over the season, which all cultivar have in. The resultant data highlight inter-daily growth anomalies. The time series of normalized Cropper-values, allowed for the interpretation of daily standard deviation units of site- and species-specific growth characteristics. In addition to the intensity of the growth anomalies, Cropper-values defined three classes of positive and negative growth deviations: "weak" for values > 1, "strong" for values > 1.28, and "extreme" for values > 1.645. Growth deviations with Cropper-values between −1 and 1 are named as "normal". These thresholds correspond to the probability density function of the standardized normal distribution.

3. Results

3.1. Stem radius variations

The dynamics of environmental data showed the typical pattern, with the lowest values of temperature, VPD and ET_0 during the winter months, and highest values in the rest of year (Fig. 1). The daily stem radius variation showed a highly significant correlation between trees within each cultivar.

A strong similarity between comparison coefficients was found for patterns of the time series of stem radius variation. Glk values were highly significant ranging between 74 and 96%, i.e. 72% ($P < 0.001$), likewise GLS values always highly significant ($P < 0.001$). The TVBP values also showed 100% degree of correlation between time series (except for one case). As a consequence, the four trees per cultivar were pooled together for the following analysis. Significant pointer days were not observed; however, all cultivars showed positive radial growth anomalies following Cropper-values that were below the threshold of 1, regardless of the season (spring or summer) or year (2005 or 2006) in the four studied olive tree cultivars.

The preliminary analysis of unrefined dendrometer measurements collected in winter showed that the peaks of shrinkage prompted with thermal peaks of minimum daily air temperature recorded immediately below 0 °C (Fig. 2).

The study of daily temperatures showed succession of negative minimum thermal peaks in winter, when minimum temperatures ranged between −5.6 and 12.3 °C in 2004–2005 season, with the lowest value in March, and between −6.6 and 11.1 °C in 2005–2006 season, with the lowest value in January. The seasonal trend in stem radius variations of the four olive tree cultivars went with the cyclic phenological patterns (Fig. 3). At the beginning of the monitoring period (19 October 2004) the mean diameter was 9.99, 8.30, 10.39 and 13.40 mm, while at the end of experiment (26 October 2006) was 27.86, 26.25, 25.34 and 31.01 mm in Leccino, Cipressino, Maurino and Canino, respectively. Stem radius dynamics were characterized by marked stem shrinkage in winter and moderate and continuous SDI in the growing season (Table 1).

In winter, from early December to mid March, the stem radius variations showed, per each stem shrinkage event, a recovery phase not characterized by stem increment (Figs. 2 and 3). The effects of T_{min} were recorded in stem winter shrinkage events of 101 and 106 days in length, respectively, for 2004–2005 and 2005–2006 (Table 1). Stem shrinkage occurred in coincidence of minimum temperatures during winter, which at the end of the season was completely reversible. Stem shrinkage events showed different amplitude ranges, up to 0.34 mm in 2004–2005 and 0.54 mm in 2005–2006 (Table 1). Stem shrinkage, suddenly appeared when

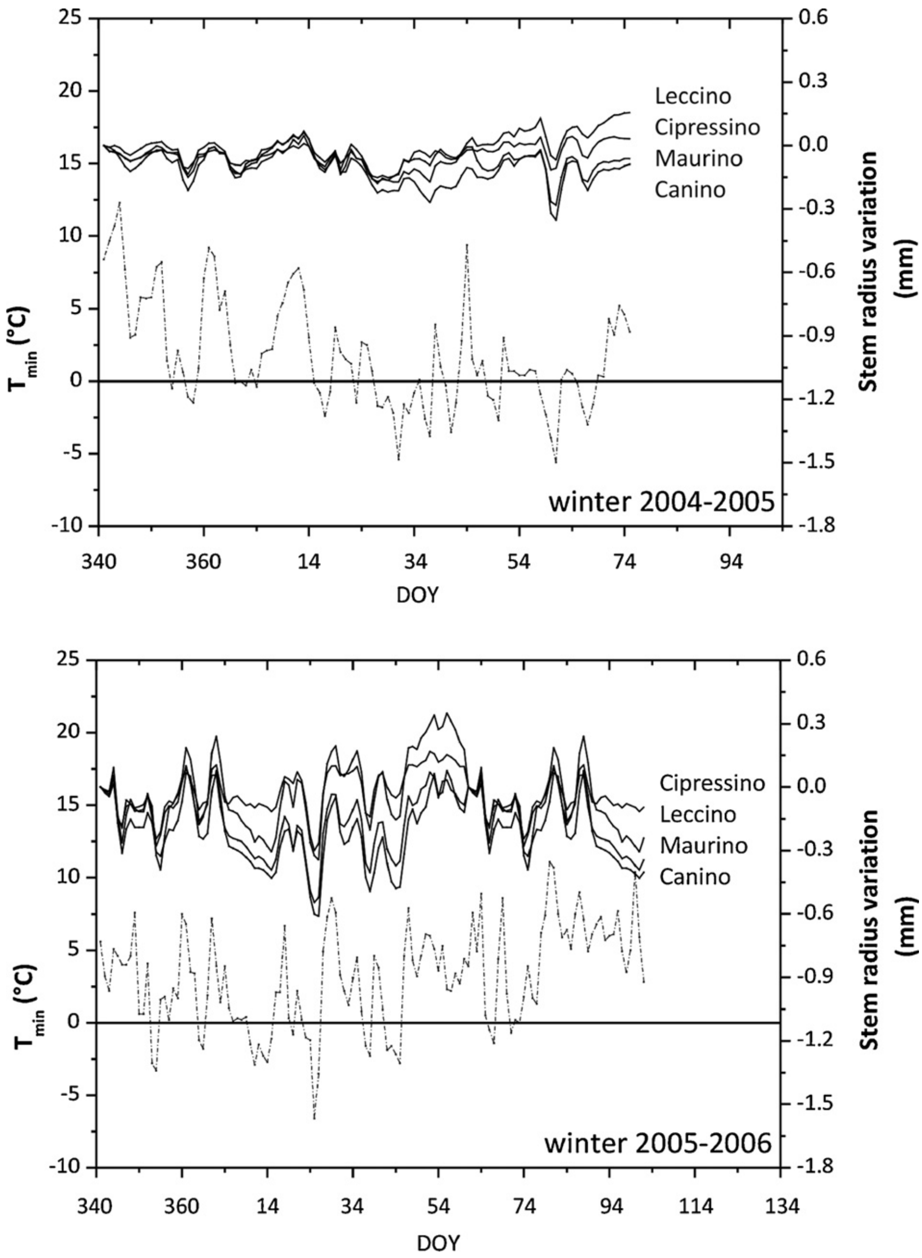


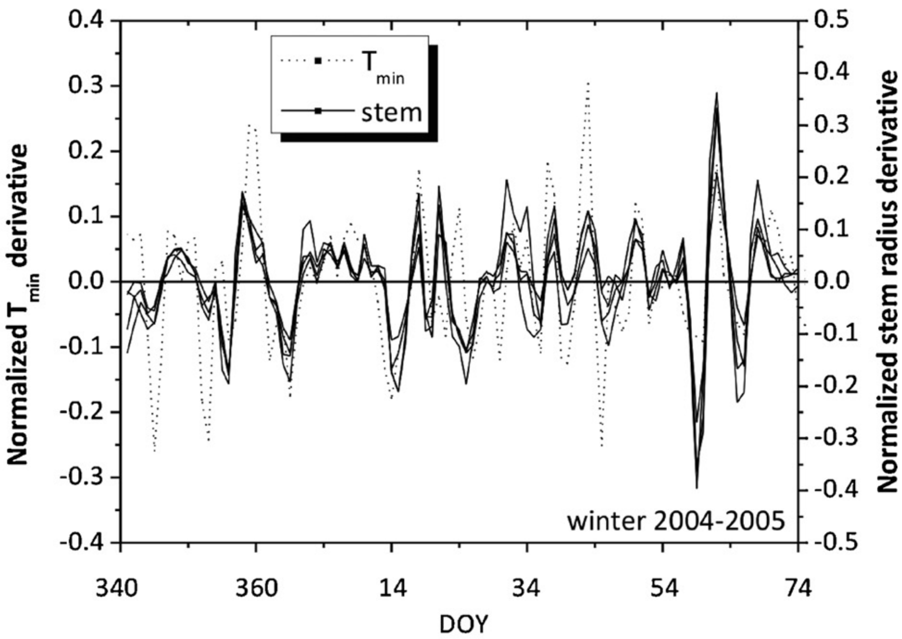
Fig. 2. Daily values of minimum air temperature (T_{min}, dashed line) and mean stem diameter variation in the four olive tree cultivars, (continuous lines), during the two winter seasons.

T_{min} dropped below 0 °C (Fig. 2). In 2004–2005, 11 negative thermal cycles, defined as daily temperature fluctuation from the maximum to the negative thermal peak, were recorded, in the range of minimum air temperature between −0.3 and −5.6 °C; whereas, in winter 2005–2006, 10 negative thermal cycles were between −0.7 and −6.6 °C.

A correspondence of minimum thermal peak and maximum stem shrinkage was observed through normalized derivative function (Fig. 3), highlighting the coincidence of reduction in air temperature and stem shrinkage in winter. The study of derivative suggested that the variation of the function with respect to $y = 0$ defined the change in curve behaviour, concurrently for stem radius variation and minimum air temperature in the four 4 cultivars (Fig. 3).

3.2. Stem diameter increment

The onset of radial growth was defined by the occurrence of stem increment following reduced stem shrinkage events in combination with varying environmental conditions, namely induction of transpiration cycles and increase of air temperature in correspondence with the end of cold cycles (Fig. 1). The growing seasons were characterized by mean air temperature ranging between 3.7 and 26.0 °C in 2005 and between 8.8 and 27.0 °C in 2006, with the highest maximum temperatures of 34.1 °C and 34.6 °C in July of both years. In the growing season, the increase of air temperature boosted SDI values (Fig. 1), SDI enduring from mid March through mid November in both years of study. In the 2005 growing season SDI values were higher than in the following year, with different



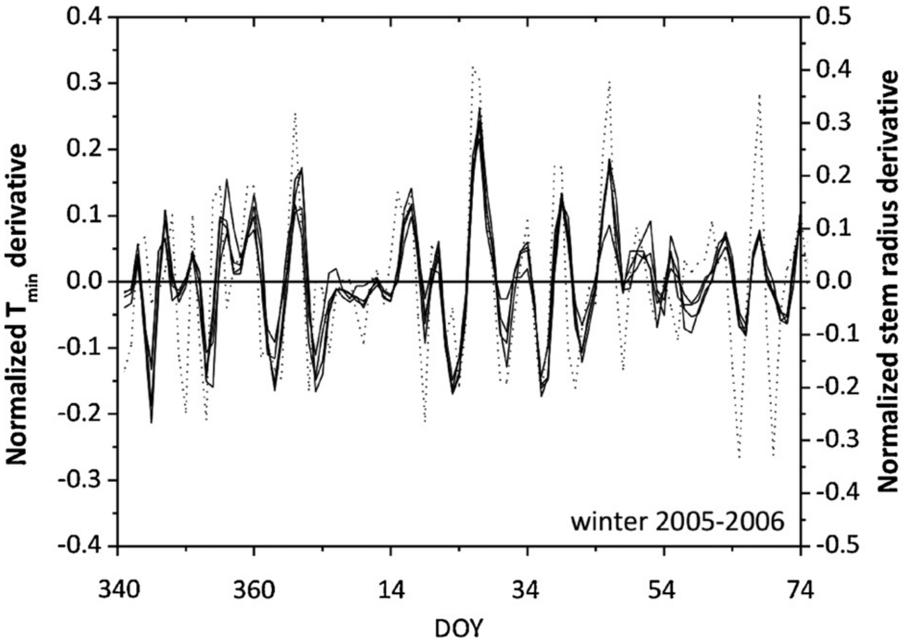


Fig. 3. Normalized derivatives of stem radius in the four olive tree cultivars (continuous lines), and minimum air temperature (dotted line), during the two winter seasons. The standardisation was carried out using the equivalent derivative of stem radius and minimum air temperature, and the relative value range between −1 and 1.

incremental threshold between cultivars. Indeed, in 2005, SDI was higher in Canino (12.88 mm) and Cipressino (10.91 mm) than Leccino (11.64 mm) and Maurino (8.12 mm); whereas, in 2006, SDI was 4.27 mm in Canino, 6.84 mm in Cipressino, 5.84 mm in Leccino and 6.26 mm in Maurino.

Radial growth continued with the increase in SMD and cumulative ET_0 during summer (Fig. 1). Daily mean ET_0 increased up to 6.25 and 6.48 mm in 2005 and 2006, respectively (DOY 209 and 195), decreasing thereafter, whereas cumulative values in ET_0 reduced the slope of increasing rate (Fig. 1). The present study showed a direct correspondence between the normalized and detrended stem radius and ET_0 time series in the growing season (Figs. 4 and 5). A specular and opposite behaviour was evident in the two curves (SDI and ET_0 time series). The negative (or positive) values of stem diameter corresponded to positive (or negative) values of derivative functions of ET_0 in the four cultivars, during spring and summer, in both years of monitoring.

Daily mean VPD values increased from the beginning of the measurement period, reaching maximum values in July, and then gradually decreased, from DOY (day of year) 210 in 2005 and DOY 197 in 2006 (Fig. 1). The VPD ranged from 0.01 to 1.92 kPa in 2004, from 0.03 to 1.58 kPa in 2005 and from 0.03 to 1.94 kPa in 2006. Values of SMD increased from a baseline reached in DOY 74 (2005) and 84 (2006) to a maximum value in DOY 245 (2005) and 251 (2006) (Fig. 1). The SDI showed statistically significant linear relationships with ET_0 (Table 2), and VPD and SMD (data not shown), considering the three seasonal stages.

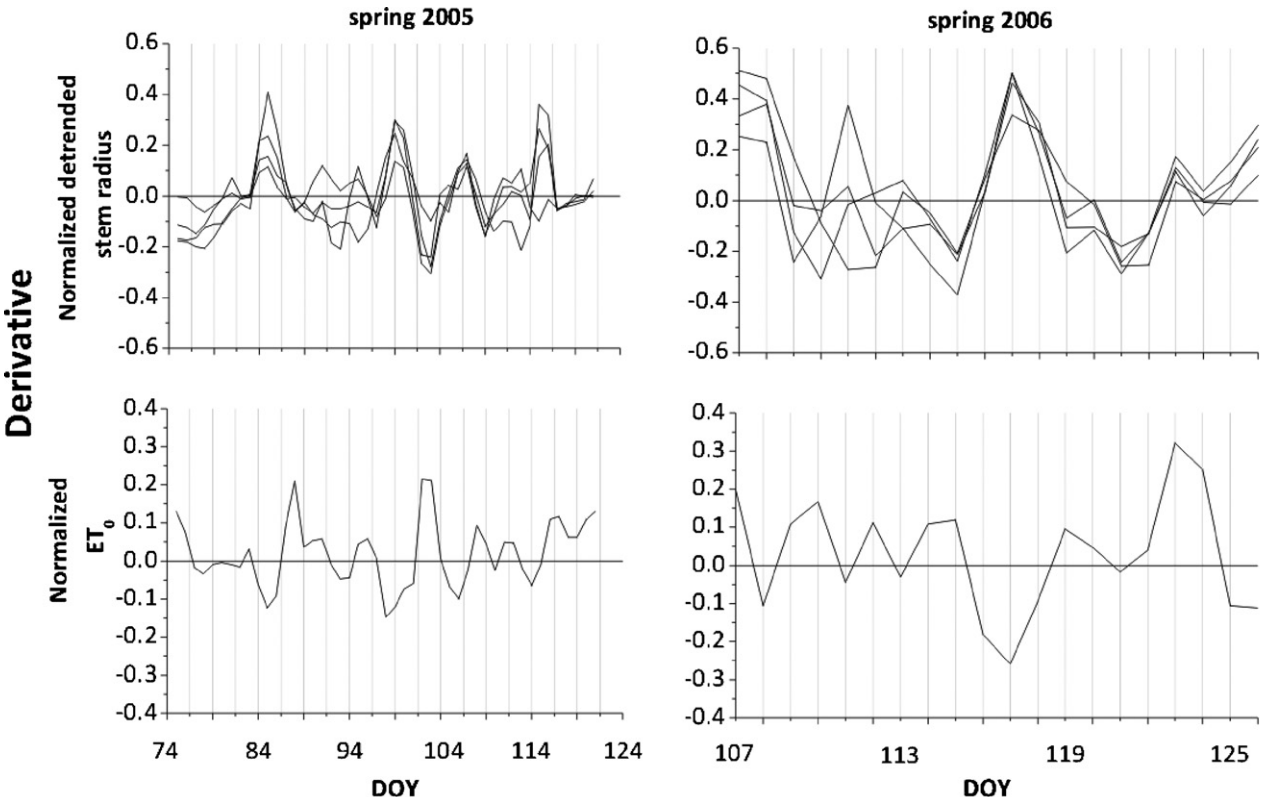


Fig. 4. Normalized detrended derivative values of stem radius in the four olive tree cultivars and ET_0 in spring 2005–2006. The standardisation was carried out using the equivalent derivative of stem radius and minimum air temperature, and the relative value range between −1 and 1.

Table 1 showed the timing and duration of seasonal course, characterizing each cultivar per stem shrinkage ranges in winter, and stem radius increments in spring and summer, in the two monitored years. In 2005, stage I was equally long from 17 March to 20 April in Canino, Cipressino and Leccino, whereas it was 56 days, up to 11 May, with 172 °C CDD in Maurino. Stage II differed in period length between cultivars and consequently in CDD, ceasing in 1 July in Leccino and Maurino, in 6 July in Canino, in 29 July in Cipressino. Stage III ended in December the 5th. In 2006, stage I varied in period length from shorter in Maurino to longer in Leccino, ending in April (15 and 21, respectively) in Maurino and Canino, and in May (5 and 16, respectively) in Cipressino and Leccino; CDD decreased from Leccino > Cipressino > Canino > Maurino. Stage II extended up to 14 June in Canino and up to 1 July in Cipressino, Leccino and Maurino; with similar CDD in Cipressino, Leccino and Maurino. Stage III was longer in Canino than other cultivars; Cipressino, Leccino and Maurino showed similar values.

4. Discussion

4.1. Resolution of stem radius variation

The study was aimed at normalizing and synchronizing stem radius variations and meteorological variables in four olive tree cultivars, through a mathematical approach. Stem radius variation, generally, is defined by stem water content and wood growth, including bark and the degradation of dead phloem cells (Zweifel and Häsler, 2000). A detailed description was provided of seasonal phases in olive trees, defining shrinkage cycles during winter and growth stages during the growing season. This information may be conveniently used in the agronomic management of commercial olive tree plantation and in the sensitive monitoring of varying ecological circumstances, and extended to species with indeterminate growth habits and in climate with erratic patterns (Sprugel et al., 1991).

Table 2
Relationship between SDI and ET_0 during the growing season 2005 and 2006. The three consecutive growth stages, defined by the relation between SDI and ET_0, were reported.

Function SDI = aET$_0$ + b	Cultivar											
	Canino			Cipressino			Leccino			Maurino		
	a	b	R^2	a	b	R^2	a	b	R^2	a	b	R^2
Year 2005												
Stage												
I	0.09	0.02	0.07	0.02	0.01	0.03	0.05	0.00	0.05	0.03	0.00	0.29
II	1.32	3.67	0.62	0.78	−2.42	0.33	0.72	−2.14	0.62	0.40	−1.36	0.40
III	−1.46	9.19	0.90	−1.39	7.97	0.90	−1.53	9.40	0.91	−1.17	7.36	0.92
Year 2006												
Stage												
I	0.16	−0.29	0.53	0.33	−0.65	0.63	0.31	−0.68	0.25	0.05	−0.07	0.31
II	0.96	−2.93	0.60	1.49	−4.84	0.62	1.07	−3.84	0.52	1.62	−5.03	0.73
III	−0.21	1.49	0.82	−0.23	1.49	0.85	−0.32	2.10	0.87	−0.12	1.14	0.38

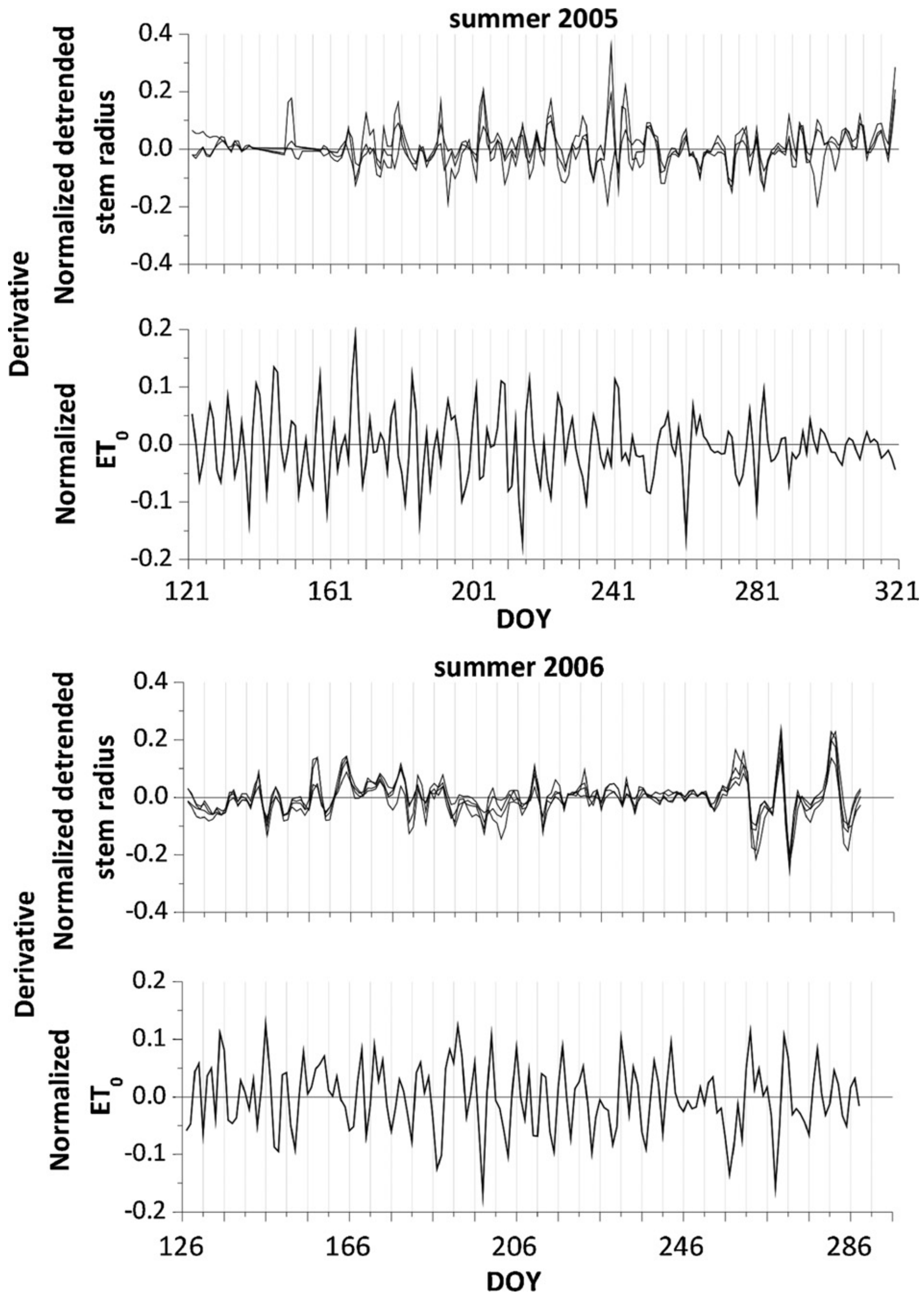


Fig. 5. Normalized detrended derivative values of stem radius in the four olive tree cultivars and ET_0 in summer 2005–2006. The standardisation was carried out using the equivalent derivative of stem radius and minimum air temperature, and the relative value range between −1 and 1.

Differences in sensitivity to environmental variables between cultivars were not observed; however, stem radius variations resulted in agreement with seasonal climatic patterns. All cultivars showed positive radial growth anomalies defined in the range of normal growth patterns (Neuwirth et al., 2007), regardless of the season (spring or summer) or year (2005 or 2006). Significant pointer days were not observed for the absence of remarkable environmental conditions.

Minimum air temperature induced winter shrinkage (Figs. 1 and 2), while VPD, SMD and ET_0 patterns were pioneering in the definition of the onset of moderate induction process in early spring and intrinsic radial growth later in the season (Figs. 1, 4 and 5). Seasonal course of local climate was regular, considering long term records for the area, which represented a regular signal explaining the relationship between environmental conditions and cambial activity. Indeed, air temperature, ET_0, VPD and SMD provided information of critical environmental values at many stages of plant development (Heide and Prestud, 2005; Badeck et al., 2004), useful to expand the application of point dendrometers and stem radius variations in stress physiology of woody plants.

4.2. Stem radius shrinkage during winter

Stem shrinkage in winter reflected a direct sensitivity to low temperature following the seasonal course (Fig. 3). Air temperature showed a weaving and cyclic course during the winter, with negative thermal excursions. The night time shrinkage and daytime swelling of the stem are primarily dependent on temperature (Zweifel and Häsler, 2000; Turcotte et al., 2009). Stem shrinkage events occurred when temperatures suddenly dropped below 0 °C, in all cultivars showing highly similar time series and significant response to low temperatures. Indeed, the analysis of correspondence between stem shrinkage and air temperature did not reveal different sensitivity to freezing air temperature amongst cultivars, which showed similar shrinkage and swelling of stem during dormancy. In alpine conifers, a sharp stem radius changes in winter (frost shrinkage and thaw expansion) are caused by changes of turgor in the elastic bark cells (cambium, phloem, and parenchyma) in the same way as the diurnal radius fluctuations in summer (Zweifel and Häsler, 2000). However, only small fluctuations in wood size are reported at moderate temperatures (Dobbs and Scott, 1971; Molz and Klepper, 1973; Siau, 1984), which are mainly driven by changes in relative humidity (Gall et al., 2002).

When temperatures fall below the freezing point of sap, the reduction in the bark cell volume associated with the loss of intracellular water produces tissue shrinkage (Améglio et al., 2001), which produces the contraction phase. The swelling of the stem, as a result of hydrating cells, creates the expansion phase, which restores the tree to a physiologically active state specifying the range of stem size that allows water transport in the xylem and gas exchange of the canopy (Zweifel and Häsler, 2000). The stem radial swelling after winter shrinkage is also modulated by tissue elasticity (Améglio et al., 2001). Zweifel and Häsler (2000) suggested that the morphological structure of the xylem plays an important role in efficient radial water transport during freezing periods. Améglio et al. (2001) found that the magnitude of stem shrinkage in response to freezing temperatures is proportional to stem diameter. The onset of wood formation corresponds to the rise in air and soil temperature, which is consistent with this experiment. However, the analysis of stem radius variation and its coordination with seasonal climatic trend needs additional functional and structural insights (Cocozza et al., 2009).

Wider stem shrinkage-recovery phases were observed in winter 2005–2006 than in previous year, in all cultivars. The two winter seasons were characterized by similar minimum temperature peaks, −5.6 °C and −6.6 °C in the first and second monitoring year, respectively. However, the number and the amplitude of thermal excursion events, as wave span between maximum and minimum temperature peaks, shaped differences in stem shrinkage cycles between the two winter seasons. Indeed, winter 2005–2006 showed wide thermal fluctuations tallied by stem radius variations, while limited thermal excursion events in winter 2004–2005 corresponded to relatively narrow stem radius variations. It may be hypothesized that the amplitude of thermal fluctuations defines the correspondence of radial variations with temperature peaks.

The derivative approach was useful for a clearer definition and description of stem radius variations related to meteorological data. No tissue damage under low temperatures was detected, and each stem shrinkage event was followed by recovery, as shown by derivative functions with negative values (stem shrinkage phase) followed by positive values (stem recovery phase). Therefore, stem radius variations were entirely reversible under freeze-thaw cycles, suggesting acclimation of these olive tree genotypes to local environmental conditions. A general correspondence of stem shrinkage peaks, namely radius sensitivity, with low winter temperatures was, therefore, confirmed for this Mediterranean species, suggesting that point dendrometers could be consistently used to define sensitivity thresholds of stem radius variations to low air temperatures.

Stem shrinkage in olive trees did not show a genotype-specific thermal threshold. By contrast, Cocozza et al. (2009) identified specific thermal threshold in poplar clones. Comparison between effects of low temperature in poplar clones vs. olive tree cultivars might be inappropriate, as well as between the two experimental sites, which differ in temperature and precipitation patterns. Indeed, olive tree is well known for its hard, heavy and dense wood, which contrasts with that of poplar. However, these observations confirm the need to provide site- and plant-specific indications to define the short-term response of stem sensitivity to environmental conditions, necessary for predicting the long-term impact of climate change on tree growth. Dormancy release in olive trees is mainly due to chilling, with a weak-compensating effect by combination of maximum and minimum temperatures (De Melo-Abreu et al., 2004). The application of linear variable transducer sensors was a useful and non-invasive tool to test cold acclimation of olive trees in field conditions, which was confirmed a species with low chilling requirement for stem dormancy release (Rallo and Martin, 1991).

4.3. Radial fluctuation patterns in the growing season

The monitoring of stem radius variations showed regular radial growth trends in the four olive tree cultivars. The relation of SDI with environmental variables might be conveniently bounded to define season lengthening. The increase of air temperature in spring triggered the induction phase of radial growth development; temperature is, in fact, important for its effect on the initiation of vegetation period (Orlandi et al., 2010); besides, decreasing air temperature in autumn defined the end of growing period (Table 1). Thus, stage III had identical CDD in the four cultivars, for both years, being defined by the arrival and the conclusion of winter season.

Nevertheless, air temperature and stem radius time series did not show a clear coincidence, as observed in winter season. During the growing season, instead, VPD, SMD and ET_0 influenced the radial growth phases. In other experiments, air temperature was found to be unrelated to radial growth rate of olive trees (Cuevas et al., 2010). In this study, the four cultivars responded in synchrony to climatic factors, although small differences between trees were observed, in the onset and conclusion of each stage (Table 1). Indeed, SDI indicates the timing of xylogenesis (e.g., Deslauriers et al., 2003); at the present study site, SDI was recorded from March to December, in 2005, and from March to October, in 2006. The stage I of growth was set at the beginning of the season from mid March to mid April (Table 1), being characterized by slight shrinkage events with SDI below 1 mm. The stage II was set from mid April to early July, except for Canino in 2006 and Cipressino in 2005, for which the end of stage II was set in mid June and late July, respectively. The stage II was defined by an important inflexion of stem radial increment, up to 5 mm in both years, with small differences between cultivars, and by a positive and significant correlation with ET_0 (Table 2). The stage III of growth was set from early July to mid November, expect for Canino in 2006 and Cipressino in 2005, as mentioned before. In 2006, the end of stage III was set in late October, in coincidence with the stop of monitoring period. The stage III was characterized by SDI up to 9 mm in 2005 and up to 2 mm in 2006, showing a negative correlation with ET_0 (Table 2). Nevertheless, in the considered olive tree cultivars, climatic pressure overwhelmed genetic variation.

Different dynamics of SDI emerged between years, with higher SDI values in 2005 than 2006, suggesting inter-annual dynamics of stem radius variation due to variable xylem production and specific thermal limits. Evidences of threshold temperatures for xylogenesis have been found for trees at their ecological limit, namely altitudinal (Rossi et al., 2007). Canino showed the highest SDI, probably related to absolute higher radial growth rates than others cultivars. Cumulative degree-days based on temperature thresholds were quite similar for 2005 and 2006, at the site study. Heat units could be used to quantify phenological phases of radial growth, which progressed as a function of air temperature from the end of winter (phase of stem shrinkage). The different CDD required by each cultivar probably defines genotype-specific heat needs prior to evolve in the succeeding stage of stem growth.

The increase in ET_0 during the growing season drove stem shrinkage, as evidenced by the opposite derivative values. The decrease in stem radius derivative function matched the increase in ET_0 derivative function, in spring and summer, depicting cambial activity. The relationship between SDI and ET_0 may be explained by the association between MDS and daily tree transpiration (Moreno et al., 2006). Michelakis (1997) showed that MDS in olive trees was highly correlated to evaporation rate. Herzog et al. (1995) and Deslauriers et al. (2007b) observed that transpiration rate and VPD influence MDS in alpine conifers, the correlations being dependent also on the duration of stem radius and contraction phases. Impacts of changing environmental conditions on timing and duration of the growing season have been assessed by long-term plant phenological observations (Rutishauser et al., 2007), which may be further refined by monitoring stem radius variations. In olive trees, stem physiological parameters determined through dendrometers and sap flow sensors respond to variations in plant water status, soil moisture availability and evaporative demand (e.g., Tognetti et al., 2004, 2005). However, MDS has been found to be relatively more sensitive to seasonal water availability than plant transpiration rate (Remorini and Massai, 2003; Ortuño et al., 2006a, b; Conejero et al., 2007), affecting plant water status albeit supplied in modest amount (Tognetti et al., 2007). Indeed, stem growth may not provide an independent measure of plant water status (Intrigliolo and Castel, 2007), particularly in alternate-bearing species such as the olive tree (Tognetti et al., 2009), which observed a small increase in MDS during drought periods, while unclear differences were recorded between different irrigation treatments.

The regression analysis indicated a linear relation between SDI and ET_0, defining three definite stem developmental stages within the growing season. The stage I probably corresponded to the "induction signal" (onset of growth), recording the increase of air temperature essential for meristem reactivation and for shifting to successive stages. Stem radius increased from one morning to the next in the stage II (growth period), following high evaporative demand. The stage III was defined by SDI decreasing with increasing evaporative demand (slow expansion). Values of SDI were high in stage III for 2005 and in stage II for 2006, although similar ET_0 ranges characterized the two growing seasons. By contrast, low SDI values were observed in stage II for 2005 and in stage III for 2006. Therefore, the range of SDI values could not be indicative of consecutive growth stages. Patterns of stem development did not separate these olive tree cultivars from one another clearly, and confirmed that little genetic differentiation occurs among cultivars in terms of stem phenology. Indeed, the four olive tree cultivars showed little variation in the duration of the three stem developmental stages, and the statistical analysis did not support differences in cultivar sensitivity to local climate. The study approach may be conveniently applied in the definition of specific requirements for succeeding phenological growth stages, when planning appropriate management practices for modern olive tree growing (Sanz-Cortés et al., 2002).

5. Conclusion

In conclusion, this study provides a simple mathematical approach describing stem radius variations and complements the analysis of data matrix obtained using continuous high-resolution dendrometers (Deslauriers et al., 2007a, b; Giovannelli et al., 2007), in order to synchronize the stem radius variation with seasonal climatic course. On this model species for Mediterranean-type environments, we distinguished the timing of transition from the dormant winter state to the active growth stage and till the slow expansion phase (see Cherubini et al., 2003), saving living tissues from cold and drought damages. The approach provides new insights of shrinkage-swelling phenomena in olive trees, related to dehydration and hydration cycles, which are difficult to detect with stem radius variation alone. The ability to switch quickly between inactive to active stages would enable the olive tree to restart physiological processes and to cope with erratic climatic conditions of the Mediterranean region. Despite a long history of research into the physiological pathways that underlie Mediterranean plant life cycle, we are still learning how multiple environmental influences interact with endogenous cues to predict biological events. By incorporating information on standardized stem radius oscillation, phenological observations and ecophysiological studies could contribute to better explain how olive trees respond to global warming (Orlandi et al., 2010).

The use of stem radius variation to extrapolate supplementary information on how trees use water and to schedule irrigation in modern tree plantations (e.g., Moriana and Fereres, 2002; Conejero et al., 2010; Egea et al., 2010) and to determine the timing of growth initiation (e.g., Downes et al., 1999; Deslauriers et al., 2003; Turcotte et al., 2009) requires expert interpretation (Fernández and Cuevas, 2010). The analysis of raw data and derivative values allowed an increase in the sensitivity of the investigative approaches applied to describe the response of olive tree cultivars to environmental conditions. This approach transforms the dendrometer signal in a physiological signal, which may complement the monitoring of the progression of radial growth and phenological stages in threatened Mediterranean ecosystems (García-Mozo et al., 2010). Further investigations are needed to combine objective data processing of stem radius dynamics with stem radius variation-derived drought indices for automatic irrigation scheduling, by reducing plant-to-plant variability and improving their sensitivity; in particular, when implemented with other plant water stress indicators (e.g., sap flow, spectral reflectance, infrared thermometry).

Acknowledgements

We thank Susanna Marchi (AEDIT srl) for kindly supplying of quality-controlled meteorological data and to Graziano Sani for technical assistance during the experiment and plant management. This work was in part funded by ARSIA Toscana – Project "Valorizzazione del germoplasma di pero ed olivo per la produzione di legno (PEROLIVO)".

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