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Original article

Influence of climate on the seasonality of radial growth of cork oak during a cork production cycle

Augusta Costa*, Helena Pereira and Ângelo Oliveira

Centro de Estudos Florestais, Departamento de Engenharia Florestal,
Instituto Superior de Agronomia, 1349-017 Lisboa, Portugal

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Abstract – The radial growth of mature cork oaks (*Quercus suber* L.) was studied during a 9-year production cycle using monthly dendrometer measurements and cork ring widths. The mean tree radial increase was 5.1 mm yr^{-1} and the cork increment accounting for 3.8 mm yr^{-1}. The radial growth curves for cork, wood and stem were very similar, showing a decreasing trend along the production cycle. Cork increment was always the largest fraction of tree growth (on average 74%) and showed less inter-annual variations as compared to wood. Tree radial growth presented a clear within-the-year seasonal pattern, extending from March to October, with a maximum in June-July. The overall pattern of monthly growth distribution was similar among the years of the production cycle, but some inter-annual variations occurred with 1–2 month shifts or monthly growth rate decreases, related to climatic factors. Early spring growth was enhanced by winter rain, autumn growth by high summer rain and June increments by high temperatures during this month.

cork oak / diameter growth / cork growth / climatic fluctuations / dendroclimatology

Résumé – Influence du climat sur la variabilité saisonnière de la croissance radiale du chêne-liège au cours d'un cycle de production de liège. La croissance radiale de chênes-liège (*Quercus suber* L.) adultes en pleine production a été suivie pendant un cycle de production de 9 ans par des mesures mensuelles de dendromètres et par la mesure des cernes du liège. L'accroissement annuel des arbres a été de 5,1 mm an^{-1}, dont 3,8 mm an^{-1} de liège. Les courbes de croissance du liège, du bois et de la tige ont montré une même tendance à la diminution de la croissance au cours du cycle. Le liège, qui correspond à la fraction majeure de l'accroissement de l'arbre (en moyenne 74 %), a montré une variation interannuelle de croissance moindre que le bois. La croissance soumise à une variation saisonnière marquée, s'étend de mars à octobre, avec un maximum en juin-juillet. La distribution de la croissance a été similaire toutes les années, parfois avec des déphasages de 1 à 2 mois ou avec une diminution de l'accroissement résultant de variations interannuelles de précipitation ou de température. La croissance au début du printemps a été favorisée par les pluies d'hiver, la croissance en automne par les pluies d'été et les accroissements en juin par une température moyenne plus élevée pendant ce mois.

chêne-liège / croissance radiale / croissance du liège / influences climatiques / dendroclimatologie

* Correspondence and reprints
Tel.: 351 21 3634662; fax: 351 21 3645000; e-mail: augustac@isa.utl.pt

1. INTRODUCTION

In temperate regions, the elongation and radial growth of the stem of woody plants are periodical and clearly correlated with the climatic changes in seasons [9, 24]. In the western Mediterranean basin and adjacent Atlantic areas, cork oak (*Quercus suber* L.) grows from spring to late autumn and then enters a period of winter rest that extends to the following spring [3]. Climatic conditions, as well as water and nutrient availability, are important growth factors and cambium activity tends to last until environmental conditions remain adequate [13, 23].

The study of phenological events among some Mediterranean shrub and tree species showed that cork oak presents the longest radial growth period [21] extending from early spring to early winter [8, 16] and continuous throughout the hot and dry summer [3, 14]. The tree has a dimorphic root distribution, with shallow lateral and deep tap roots, similar to holm oak (*Quercus rotundifolia* Lam.), which is able to transport water from deep aquifers to maintain growth during the period of high water demand when radiation is high [5, 12].

The activity of the vascular cambium and the factors influencing this activity, in relation to wood production, have been intensively studied (see [23]), but much less is known about the functioning of the cork cambium or phellogen.

In cork oak, the phellogen produces, during a growing season, a large number of cork cells outwards and one or two layers of inner phelloderm cells [11,19]. One of the most interesting aspects of cork oak is that, after the removal of cork and the death of the exposed phellogen, a new cork cambium is formed in the mature and already completely differentiated cells of the phloem that become again undifferentiated meristematic cells [11, 26]. This characteristic allows the sustainable production of cork during the tree life, by periodically removing the cork layer when its thickness is adequate for industrial processing. In the major production regions, the period between two consecutive cork extractions is 9 years in general.

The seasonal pattern of cork oak radial growth and the general decrease of yearly radial increments during a 9-year production cycle, were described previously for mature trees in full cork production [3, 4]. In this paper, we discriminate the cork from the wood component within the total tree radial growth and its interannual variation during the production cycle, and we study the monthly variation of cork oak growth and the influence of rainfall and temperature on growth.

2. MATERIALS AND METHODS

2.1. Study area

The study area is located in a cork-oak stand in the estate of Companhia das Lezírias, at Porto Alto (Benavente), in the western central part of Portugal (38º 46' N, 8º 45' W). The area is flat (10–20 m a.s.l.) and the climate is of Mediterranean type with Atlantic influences, the highest temperatures occurring in summer when precipitation is lowest (*figure 1*).

The annual rainfall averaged 595 mm and the mean annual temperature was 17.6 ºC for the period under study (June 1991–June 2000). The climatic data (monthly rainfall and mean temperature) refer to the weather stations of Vila Franca de Xira, located approx. 11 km NW of the site, and of Sto Estevão, located in the study area, and were provided by INAG (National Water Institute).

The soils are regossols (FAO) slightly acidic, poorly developed, and low in nutrients. A study of the soil profile made at this site [18] showed a sandy layer (10–11 m of coarse sand and gravel) of high permeability and low water storage capacity and a deeper clay layer where soil water capacity may be attained in wet periods due to the relatively slow water drainage.

The stand is a typical "montado" with trees exploited for cork production and the herbaceous layer used for grazing, with some pasture improvement. The density of the stand around the sampling point is low, about 78 trees per ha, and the stand structure shows 5% of young trees that still did not enter into the cork production cycle.

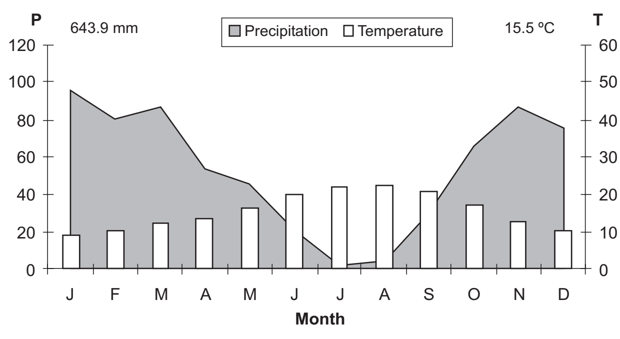

Figure 1. Mean annual patterns of temperature and precipitation for the period 1960–1991 for the study area (total annual precipitation and mean annual temperature are indicated on the graph).

2.2. Measurements

During cork extraction in June 1991, 50 trees were randomly selected and dendrometer bands were installed at breast height (1.3 m) in November 1991, on the stripped stem of the cork-oak trees. Measurements were made monthly during nine years until June 2000, when cork extraction was made again. This period includes eight complete years of cork growth, from 1992 to 1999.

At the time of cork extraction in June 2000, the tree's health was evaluated and only the trees without stem injuries, crown damage, low branching or other anomalies were kept for the study, to avoid the introduction of uncontrolled variability factors. The dendrometric characteristics of the 25 trees kept in the analysis are summarized in *table I*.

The average over bark circumference was 1.6 m, corresponding to mature cork oaks under full exploitation. The cork stripping coefficient, calculated as the ratio of the maximum height of stripping to the circumference at breast height, was on average 1.9, a moderate value that is below the legally authorized value of 2.5.

The cork stripping surface was calculated as the surface of a cylinder using the circumference at breast height and the maximum height of cork stripping. The crown area was determined as the horizontal projection area of a circle with an average radius calculated from four determinations in the North-South and East-West directions.

A 20×20 cm^2 cork sample was taken from each tree at 1.30 m height during the cork extraction in 2000. The samples were boiled during 1 hour in water at 100 °C and dried in open air until equilibrium.

Table I. Dendrometric characteristics of the 25 sampled cork oak trees at the time of cork harvest in June, 2000.

Dendrometric variables	Mean ± standard deviation
Total tree height (m)	11.5 ± 2.4
Circumference at breast height (m)	1.6 ± 0.4
Crown area (m^2)	86.9 ± 44.0
Maximum height of cork stripping (m)	3.1 ± 1.0
Cork stripping surface (m^2)	5.6 ± 3.1
Cork stripping coefficient	1.9 ± 0.4
Cork green weight (kg/tree)	66 ± 42
Cork thickness (mm)	33.0 ± 6.5

The total cork plank thickness was measured in a middle point of the transverse cork section. The annual growth of cork was measured with an image analysis system as previously described by [20] after marking the annual rings with a thin pen on 3 positions (at 1/3, mid and 2/3 of the transverse section length of each cork plank). These measurements were used to calculate the mean annual radial growth of cork for each of the complete 8 years of cork growth.

Wood growth for each of these 8 years was estimated by subtracting the measured cork growth from the tree annual radial increment obtained from the dendrometer bands measurements. In this estimate, we considered that the phloem and the pheloderm contributed negligibly to the radial increase so that the tree radial growth can be considered as the sum of wood and cork increments only.

2.3. Data analysis

The within-the-year distribution of the tree radial growth was analyzed on a monthly basis, using monthly relative growths calculated as a percentage of the total annual growth.

The influence of rainfall and temperature of specific months on the within-the-year distribution of growth was studied by using a dendrochronological approach [9, 24]. For data standardization, a monthly growth index (MGI) was calculated for each month by dividing the measured value of the relative diameter growth for a given year (in % of the total annual diameter growth) by the mean relative diameter growth for the 8 years. A correlation analysis was then performed between the monthly growth indices and the precipitation of different months (i.e. current and previous months up to the 4th previous month) as well as with the mean monthly temperature (i.e. current and previous months).

3. RESULTS

3.1. Annual tree diameter growth vs. cork growth

The total tree diameter increase in the 9-year production cycle, from cork harvest to cork harvest, ranged from 5.7 cm to 11.7 cm, with an average of 8.0 cm. The production cycle period comprises 8 complete years of growth (1992 to 1999) and two incomplete years when the cork extraction was carried out (1991 and 2000).

These two “half years”, as they are called in cork oak forestry, represent on average 7.3% of the total diameter increase in the production cycle. They will not be further discussed in this paper, which deals only with the 8 complete years of growth.

Tree diameter growth showed an inter-annual variation within the cycle with larger increments in the first years than in the last years (*figure 2*). In spite of the intra-tree variation, the growth pattern was similar in all cases.

Considering only the growth of cork, the accumulated radial increment of cork during the 8 years of the production cycle ranged between 23 mm and 40 mm among individual trees, with an average of 30.0 mm, which corresponds to a mean annual radial growth of 3.8 mm yr^{-1}. The annual growth rate of cork was not constant and it showed also a decreasing trend along the production cycle (*figure* 2) with a mean radial growth of 4.5 mm yr^{-1} and 3.0 mm yr^{-1} during the first and the last four years respectively.

Second degree polynomial curves could be adjusted to the annual diameter increase and to the annual cork growth during the production cycle (*figure 2*) with good correlation coefficients.

Diameter increase

$$y = 0.0013x^2 - 0.121x + 1.5274 \qquad (R^2 = 0.67) \qquad (1)$$

Cork growth

$$y = -0.0252x^2 - 0.1585x + 5.1094 \qquad (R^2 = 0.93) \qquad (2)$$

where y is the tree diameter increment (in cm) (1) or cork growth (in mm) (2), and x the time (in years) after the year of cork extraction. Linear correlations also showed similar determination coefficients (0.70 and 0.91, respectively) but the distribution of residues was better for the polynomial models.

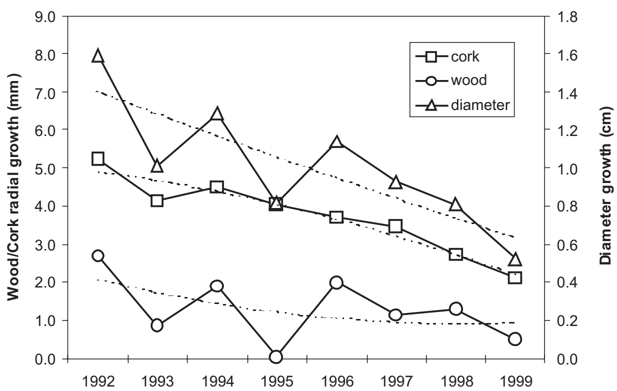

Figure 2. Mean annual radial increments of cork and wood and mean tree diameter growth for the cork oaks studied during eight complete years of the cork production cycle (1992–1999). The dashed lines represent quadratic best-fit models.

Wood growth was estimated to vary between 0.1–0.5 mm yr^{-1} (1995 and 1999) and 2.0–2.7 mm yr^{-1} (1996 and 1992), with an average radial increment of 1.3 mm yr^{-1} in the cork production cycle.

The annual variation of wood growth followed closely the variation of tree diameter growth, e.g. during 1993, 1995 and 1999, increment values were under the values predicted by the models (*figure 2*).

3.2. Monthly tree diameter growth

The within-the-year seasonal pattern of tree growth was similar for the 8 years of the production cycle. Between November and February, monthly diameter growth was almost null (less than 2% of the total annual diameter growth). The onset of diameter growth occurred in March and the maximum growth rate was attained in June and July. Growth continued throughout the summer, and the growth accumulated from June to August represented on average 50% of the annual growth (*figure 3*).

The annual growth increments of cork oak trees may be divided into three phases (*figure 4*): an early phase corresponding to the early spring growth (March and April), a main phase from May to August where the main part of growth takes place and a late phase in Autumn (September and October). These three phases represent on average 18.2%, 63.9% and 17.8% of total growth, respectively. During the last years of the production cycle, the fraction of the annual increment occurring in the late phase in autumn increased, in the 8th year accounting for 36.9% of the total annual growth.

In spite of the overall similar pattern of growth distribution within the year, some inter-annual variations were observed, corresponding either to 1–2 month shifts or to the occurrence of a decrease of the monthly growth rate. This is exemplified in *figure 5*: in May 1992 there was a decrease of the annual growth rate; in 1993 the onset of growth was delayed one month to April; the period of the maximum growth occurred in June–July, April–May and in May respectively in 1992, 1993 and 1999.

3.3. Influence of precipitation and temperature

The relative monthly diameter growth (in % of the total annual diameter growth) showed a negative and

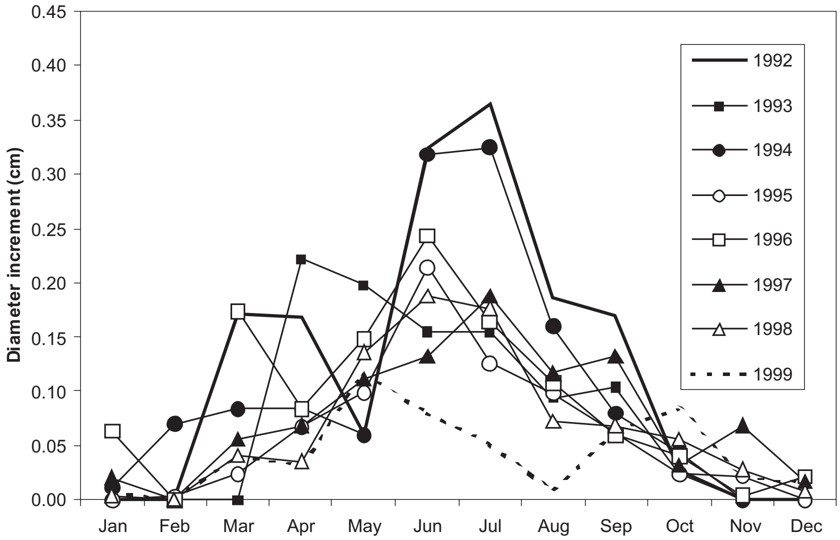

Figure 3. Monthly diameter increments of cork oaks during the 8 years of the production cycle (1992–1999).

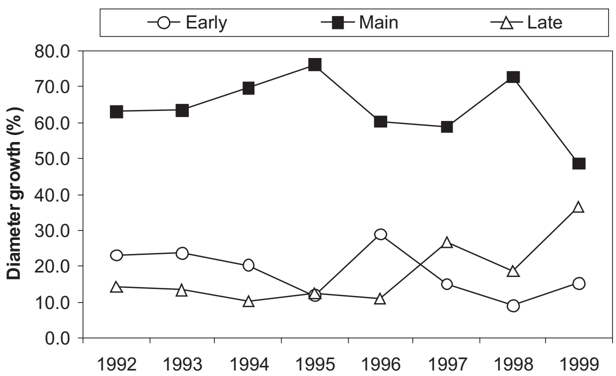

Figure 4. Distribution of the annual diameter growth (% of annual growth) of cork oak by periods: early growth (Jan-Apr), main growth (May-Aug) and late growth (Sep-Dec).

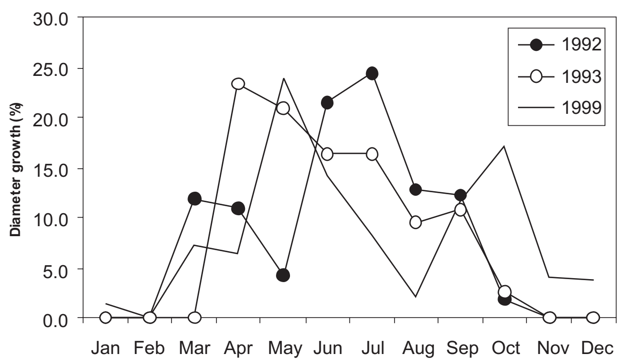

Figure 5. Monthly diameter growth (% of annual growth) of cork oaks during three years of the production cycle (1992, 1993 and 1999).

statistically significant correlation with the rainfall of the current month (r = –0.67*) in the 8-year production cycle.

The influence of the rainfall of specific months on the monthly variation of tree diameter growth was studied using a correlation analysis between the monthly growth index (MGI) and the rainfall for different preceding months. The correlation coefficients are shown in *table II* and the highest values obtained are discussed below.

The growth index of March was positively correlated with the January precipitation (r = 0.78*) (*figure 6*). On the contrary, the relative growth in July was negatively correlated with precipitation in spring (March, r = –0.71*). Positive correlations were obtained between the growth index of September and the precipitation of August (r = 0.84**) (*figure 7*) and the growth index of October and the precipitation of September (r = 0.81**).

As regards temperature, the monthly mean temperature showed a statistically very significant positive correlation with the monthly relative growth (r = 0.84**) in the 8-year production cycle. High radial growth rates

Table II. Correlation coefficients between monthly growth index (MGI) and monthly precipitation for the period 1992–1999.

Monthly precipitation	Monthly growth index (MGI)							
	Mar	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Preceding year								
Oct	–0.17							
Nov	0.04	–0.50						
Dec	0.24	–0.14						
Current year								
Jan	**0.78***	–0.33	–0.05					
Feb	0.02	–0.27	–0.50	0.68				
Mar	0.25	–0.01	0.67	–0.11	**–0.71***			
Apr		0.40	0.35	–0.66	–0.11	–0.35		
May			–0.19	–0.36	0.15	0.08	–0.08	
Jun				–0.21	0.49	0.33	0.61	–0.32
Jul					0.15	0.26	0.57	–0.15
Aug						–0.30	**0.84****	0.38
Sep							0.29	**0.81****
Oct								0.33

* *P* value of 0.95.
** *P* value of 0.99.

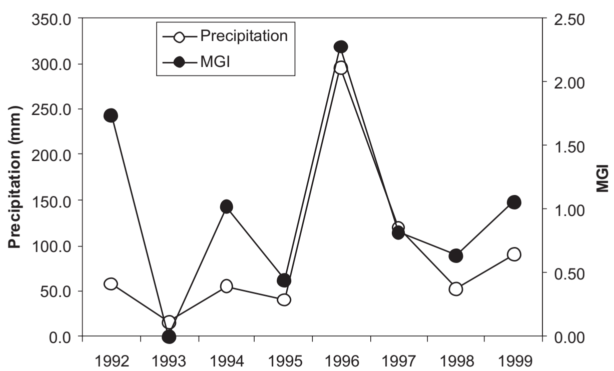

Figure 6. Variation of the monthly growth index (MGI) of March compared to variation of precipitation in January during the eight years of the production cycle.

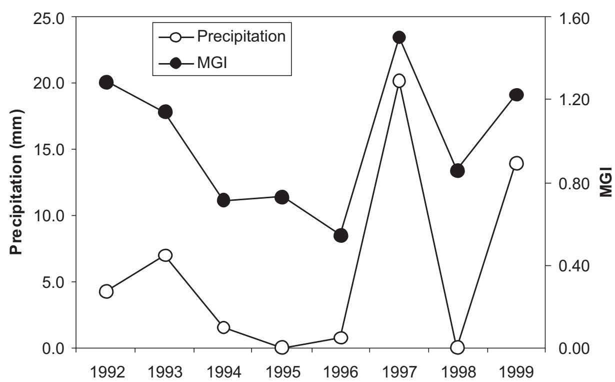

Figure 7. Variation of the monthly growth index (MGI) of September compared to variation of precipitation in August during the eight years of the production cycle.

corresponded with warm months, with a maximum in June, the warmest month. This was also revealed by the correlation analysis (*table III*), which showed that temperature and the monthly growth index in June were positively correlated ($r = 0.72$*). Moreover a negative correlation was observed between the monthly growth index of April and the temperature in March ($r = –0.71$*).

Table III. Correlation coefficients between monthly growth index (MGI) and monthly temperatures for the period 1992–1999.

Monthly temperature	Monthly growth index (MGI)							
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Jan	0.21	–0.14	–0.17					
Feb		–0.32	–0.48	–0.38				
Mar			–0.06	**–0.71***	–0.23			
Apr				–0.45	0.21	–0.29		
May					–0.36	0.48	0.06	
Jun						**0.72***	0.37	0.50
Jul							0.51	0.27
Aug								–0.05

* *P* value of 0.95.

4. DISCUSSION

4.1. Tree diameter growth vs. cork growth

The values obtained for cork growth were similar to those referred previously for other important production regions (3.8–4.3 mm yr^{-1}) [7]. The decreasing trend of cork ring width along the production cycle (*figure 2*) is also a well-known feature resulting from the enhanced activity of the traumatic phellogen formed after cork extraction in the immediately subsequent years.

Regarding wood growth in adult cork oaks under cork production, there are very few values available in the literature. A wood growth rate of 2 mm yr^{-1} was previously reported for young trees [15] as well as values ranging from 1 to 4 mm for wood rings in trees under cork production [10].

Along the 8 years of the production cycle, cork and stem showed a similar variation pattern of radial growth (*figure 2*), as expectable since cork represents a large part of the total cork oak radial increment [3] (on average 74% of total growth). The adjusted equations followed previously described models for cork growth [4, 6, 14].

However, in 1993, 1995 and 1999 the increments were smaller than predicted by the growth models, the deviations being more pronounced in tree diameter than in cork. It is known that climatic effects decrease tree radial growth, as reported for oaks [22] and for cork oaks, for which a lower than average rainfall in the previous winter and cold spring temperatures decreased tree growth of the current year [4].

It is however noteworthy that the tree growth decrease in 1993, 1995 and 1999 was mostly due to a decrease of wood growth and much less to a decrease in cork growth; in fact, for these three years, more than 90% of the total tree growth corresponded to cork. The influence of rainfall on wood ring width was previously reported for cork oaks using a dendrochronological approach [15] as well as on cork growth, although the variations of cork ring width with the climatic factors were not always clear [1, 2, 6]. This suggests that the activity of the phellogen and therefore the resulting cork growth are less sensitive to climatic influences than the activity of the cambium and the resulting wood increments.

4.2. Monthly tree diameter growth

Tree growth was continuous from March to October, through the dry and hottest period of the year. The deep root system of this species [14] contributes to secure the water uptake from the soil to maintain transpiration and tree growth [5] since it is known that cork oak stem growth only stops, or decreases to very low values, when summer drought becomes too severe [16].

Nevertheless, growth in August decreased sharply compared to July, in agreement with previous findings

[8, 16], and it was followed in September by either a slight increase of the growth rate or by a reduction in the decrease of the growth rate (*figure 3*).

The three phases in the annual growth (early, main and late phase) represent the different growth rates within a year that were reported by [8, 16]. The increase in the proportion represented by the late autumn growth in the last years of the production cycle from about 15% to 37% of the annual growth is explained by a reduction in the growth rate during the early and main growth phases. The decreasing trend of the diameter growth curve seems therefore to derive from the decrease of spring and summer growth, suggesting that the enhanced activity of the phellogen in the years after cork stripping is more focused in these periods. This growth seasonality is very much similar to the one described by [16] when the tree is not affected by the stripping stress.

However, in spite of the overall similar pattern of growth distribution within the year, some variation occurs between the different years (*figure 5*) suggesting that growth may be delayed or reduced in relation to climate or other external factors [2, 4].

4.3. Influence of precipitation and temperature

In general, there were no significant correlations between relative monthly growth and the current or previous month precipitation, the only exceptions being the positive correlations between the growth index of September and October and the precipitation of August and September, respectively (*table II*). These positive correlations show that summer rainfall may be used immediately during the dry growth period, taking advantage of the warm temperature and of the still large photoperiod. It can be seen also that the monthly growth index of September is positively correlated (even if not statistically significant) with June and July rainfall (*table II*). Late growth of cork oak therefore seems to be favoured by precipitation occurring during the preceding summer months as discussed by [25].

Most of the tree growth occurs in late spring and summer when temperatures are warm and rainfall reaches its minimum but the relative growth in July is negatively correlated with precipitation in spring (March). This has been already observed [17, 25] and explained by an increased root development in early spring in detriment of above ground growth. A similar explanation could be applied to the present results. Moreover the rainfall in the previous winter (January) induces a stem diameter increase [2, 4, 16]. These results suggest that a medium to long-term strategy is involved in the water uptake for cork oak growth, both in relation to the beginning (March) and to the main period (June–July) of tree growth.

In this region, with a low drainage clay layer underneath the sandy soil [18], the cork oaks have the possibility to use the water stored in deep soil for growth during the dry summer months as the upper horizons dry quickly. This is the reason why the correlations between growth and precipitation were rather weak in this region when compared with the Extremadura region [2] where strong climate links between precipitation and cork growth were reported.

Temperature, on the contrary, showed a relative strong link to growth in the 8 years of the production cycle as also found by [2]. Spring growth was negatively correlated to the temperature in the current or in the previous month (*table III*). This probably results from the fact that the promotion by higher temperatures of phenological events such as leaf burst and branch elongation in early spring [8, 17] will shift radial growth to later stages in the season.

5. CONCLUSIONS

During a cork production cycle of mature cork oaks, the annual total tree diameter growth and the cork increments showed similar pattern curves with a decreasing trend along successive years. Cork represented the largest fraction of the tree radial growth and showed a less pronounced inter-annual variation as compared to wood.

Tree growth showed a clear within-the-year seasonal pattern with a maximum in June–July. Climatic factors influenced the monthly distribution of growth. Early spring growth was enhanced by winter rain, whereas autumn growth was increased by high summer rain and June increments by high temperatures during that month.

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