

## Climate effects on stem radial growth of *Quercus suber* L.: does tree size matter?

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The cork oak (*Quercus suber* L.) is periodically harvested for bark (cork) throughout its lifetime. Trees undergo physiological changes as they age which affect stem diameter growth and their sensitivity to climate. However, little is known about trees age- or size-related growth changes and it remains unclear if trees of different ages (sizes) have similar climate-growth relationships. In this study, we examined the increment in stem basal area of 47 randomly selected (large and small) cork oaks over a 12-year period to assess divergent climate-growth relationships. Our approach, using a machine learning algorithm on unlabelled data sets of basal area increments, successfully filtered out tree-clusters that suggested a size (age)-dependent growth response to climate. On average, the basal area increment was more than three times larger in larger-trees clusters compared with smaller-trees clusters. A large tree (diameter >75 cm) on average added 105 cm<sup>2</sup> y<sup>-1</sup> to its basal area against 25 cm<sup>2</sup> y<sup>-1</sup> in a small tree (diameter <35 cm). Additionally, in smaller-trees, cork harvesting intensified the negative impact of drought on tree growth, and worsened post-drought recovery. These findings highlight the need to consider biological growth trends for accurate predictions of trees responses to drought.

### Introduction

Woodlands composed of Mediterranean evergreen cork oak (*Quercus suber* L.) in southwestern Iberia are among the most vulnerable forest ecosystems in temperate regions to climate change impacts. These woodlands are located in a critical area that is a climate change ‘hot spot’, where precipitation is expected to decrease during the warm season and peak temperatures are expected to rise during summer season (Giorgi and Lionello, 2008).

*Quercus suber* L. has developed drought-avoidance strategies to cope with summer drought stress (Cherubini *et al.*, 2003; Kurz-Besson *et al.*, 2006; David *et al.*, 2007), and the structure of cork oak woodlands, particularly tree density, has been managed by farmers to promote ecohydrological sustainability over longer time periods (Joffre *et al.*, 1999). Despite these mechanisms, the predicted increase in the frequency and severity of meteorological droughts in southern Europe during summer (Spinoni *et al.*, 2017) is likely to influence cork oak growth patterns and the functional processes that will eventually alter the

carbon budgets of these woodlands (Johnson and Curtis, 2001; Tenhunen *et al.*, 2009).

Despite the faint wood-rings in cork oak (Leal *et al.*, 2008) it is possible to evaluate the growth response to climate using cork-ring chronologies in dendrochronological analyses. The thick bark (cork) has distinct boundaries in its annual rings (Natividade, 1950), and effectively encodes a strong climate signal (Costa *et al.*, 2016; Oliveira *et al.*, 2016; Ghalem *et al.*, 2018). These dendrochronological analyses commonly have a sampling design with a biased selection of trees, for example, focusing on dominant, large and presumably old trees and/or selecting cross-datable tree (cork)-ring chronologies that share a similar growth pattern. Neither the complex (intra- and inter-annual) variations in stem radial growth response over long-term periods at tree-level nor important tree-specific traits, such as stem diameter size have been considered in existing studies (Rieger *et al.*, 2017).

In this study, we explicitly included large and small trees to assess size-related differences in trees diameter growth responses to climate (Dobbertin, 2005; De Luis *et al.*, 2009; Johnson and Abrams, 2009) and, thereby, understand the cork

oak growth dynamics, under the superimposed effect of cork harvesting.

Three issues were examined: (1) What is the influence of tree size on radial growth? (2) To what extent is this relationship drought-driven?; (3) Which trees (small or large) are more resilient and responsive in their radial growth patterns to drought? We hypothesized that, similarly to other temperate forests, in cork oak woodlands: (1) the basal area increment (BAI) would continuously increase with tree size (and aging) (Oliveira *et al.*, 1994; Luyssaert *et al.*, 2008; Stephenson *et al.*, 2014), and (2) large trees would be much more resilient and responsive to drought events than small trees, in accordance to Costa *et al.* (2003). Previous findings, that smaller trees cannot withstand climate variability as efficiently as larger trees, may have implications for conservation strategies of cork oak woodlands in a changing climate context, and should be taken into consideration in adopting proper and sustainable forest management.

We used a novel approach based on an unsupervised machine learning algorithm (MLA) in order to group together trees in clusters according to similarities/distinctions in the data sets regarding long-term BAI. This approach is complementary to commonly used dendrochronological approaches to detect tree-specific growth trends and contributes to new developments in our understanding of cork oak growth climate sensitivity, which varies over time.

## Materials and methods

### Study area

The study was conducted at a permanent plot named Carro Quebrado (38.83°N, -8.81°W, 20 m a.s.l.), which has an area of 15 ha in a cork oak woodland at a state-owned farm (Companhia das Lezírias, S.A.) (Figure 1). Carro Quebrado is located in the southwestern part of the Portuguese mainland in the Tagus Basin.

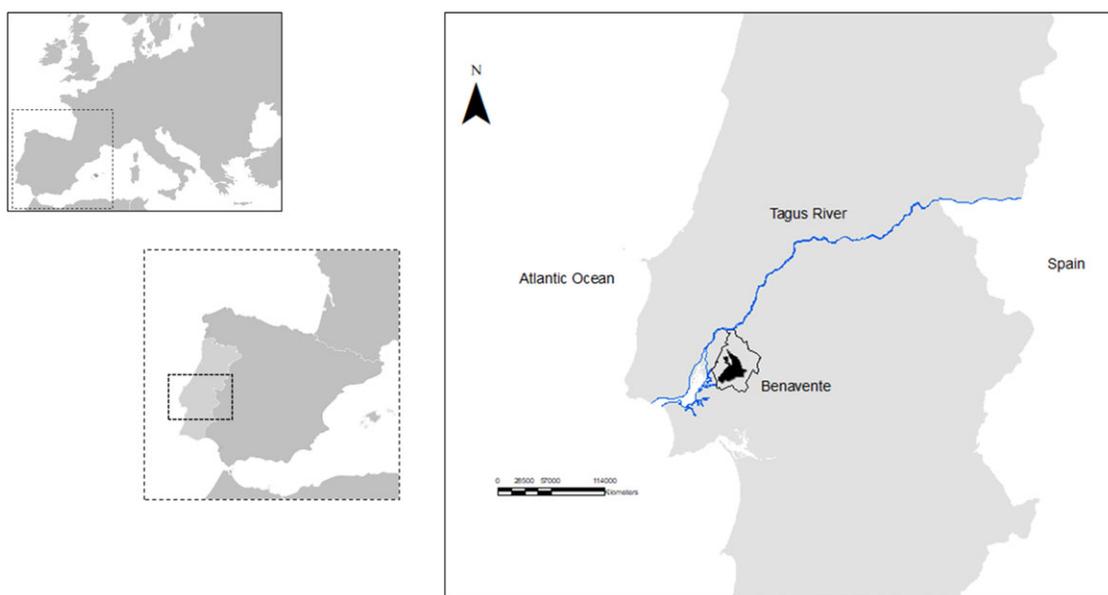
The climate of the study region is of Mediterranean type and has been classified as warm temperate climate according to Köppen's climate classification (Kottek *et al.*, 2006). The highest temperature (T) in this area occur during summer, when precipitation (P) is lowest, and the dry period ( $P < 2T$ ) extends from May to September. The mean annual temperature is 15.3°C and the mean annual precipitation, concentrated on the winter season, is 578 mm. July is the warmest month, with an average temperature of 21°C and the coldest is January, with a mean temperature of 9°C.

The study area is a flat and gently undulating area (slope typically less than 1 per cent), and the predominant soils are Haplic Arenosols (AR), which allows cork oaks to develop deep roots (Costa *et al.*, 2008). It is located in the Tagus alluvium aquifer, which is unconfined and shallow and reaches a depth of 70 m. Here, the groundwater levels respond quickly to rainfall, mainly during the recharge period between October/November and March/April, and water table depth has a negative impact on tree, and in particular on cork growth (Mendes *et al.*, 2016).

During the study period (2000–2012), the groundwater table in the dry summer period (between June and September) at the Carro Quebrado study area was on average 2.5 m deep. There were two severe droughts in this period, one in April–September 2005 and other one in May–August 2009, however, the groundwater levels fell below 3.5 m in depth only in 2005 (Mendes *et al.*, 2016).

### Tree measurements

We installed manual band dendrometers (D1 Dendrometer, with 0.05\* $\pi$  cm resolution, UMS, Munich, Germany) on 47 randomly selected cork oaks in June 2000. Dendrometers measure the inter- and intra-annual tree stem diameter increment changes associated with climate variability (Bormann and Kozłowski, 1962). All trees were adult, under full cork production (mature trees in the third–fourth cork harvesting cycle), managed under low harvesting pressure (Oliveira and Costa, 2012), and with a harvesting coefficient (HC) lower than 2 (Table 1). Trees, over their lifetimes, achieve large stem diameters (reaching 70–80 cm diameter at breast height), with thick branches and large crown canopies (Costa *et al.*, 2008) and, by including small and large



**Figure 1** Location of the study area, in the state-owned farm Companhia das Lezírias, S.A., at Tagus Basin (in dark grey), within Benavente municipality (border in solid black) in central Portugal.

**Table 1** Dendrometric variables of the 47 cork oaks in the study area Carro Quebrado. Variables were measured during the first cork harvesting in June 2000

Tree variables	Acronym	Description	Mean $\pm$ standard deviation	Median	IQR (Q25)	Min-Max
<b>Size</b>						
Diameter over cork	Dbh <sub>c</sub>	Stem diameter at breast height over cork before cork harvesting (cm)	53.7 $\pm$ 12.76	53.5	21.4 (41.9)	33.2–85.4
Diameter under cork	Dbh <sub>w</sub>	Stem diameter at breast height after cork harvesting (cm)	46.5 $\pm$ 12.22	46.5	20.2 (35.3)	28.8–76.7
Stem height	Hs	Stem height (m)	2.3 $\pm$ 0.89	2.3	1.3 (1.7)	1.0–5.0
Crown diameter	Cr	Average crown diameter (m)	15.4 $\pm$ 3.98	15.3	6.6 (11.7)	9.8–25.3
<b>Harvesting pressure</b>						
Harvesting coefficient	HC	Maximum harvesting height (m) to perimeter at breast height over cork (m) ratio	1.8 $\pm$ 0.36	1.8	0.5 (1.6)	1.1–2.9
Stripped surface	SS	Total, stem and branches, cork harvested surface (m <sup>2</sup> )	6.6 $\pm$ 4.59	5.5	5.0 (3.5)	1.4–24.3
Harvesting intensity	HI	Harvested surface (m <sup>2</sup> ) to stem sectional area at breast height over cork (m <sup>2</sup> ) ratio	26.7 $\pm$ 10.42	24.2	12.6 (19.9)	5.4–50.0

trees in this study, we aimed to detect individually tree responses to environmental parameters that vary annually such as precipitation and temperature.

The band dendrometers were wrapped around the tree stems after cork harvest, which ensured close contact, and were fastened with a spring mechanism that allowed the tape to expand during tree growth. Stem diameter increment was measured in monthly intervals, over 12 years, from July 2000 to June 2012. Monthly stem diameter increment was determined by calculating the difference between the stem diameter values over two consecutive months. Additionally, we calculated annual stem diameter increments in each biological year (October<sub>(-1)</sub>–September), in each wet semester (October<sub>(-1)</sub>–March), and in each dry semester (April–September). Monthly, seasonal and annual stem diameter data collected (in cm) were converted to stem basal area increments (BAI, cm<sup>2</sup>) for each tree, assuming a circular outline of the stem cross section:

$$BAI = \frac{\pi}{4} \times (Dbh_{t=0} + \Delta_{Dbh})^2 - \frac{\pi}{4} \times (Dbh_{t=0})^2 \quad (1)$$

with  $Dbh_{t=0}$  being the stem diameter at breast height (in cm) measured with a band dendrometer at time  $t = 0$  and;  $\Delta_{Dbh}$  being the stem diameter increment at breast height (in cm) calculated between the two consecutive measurements. The time-interval between two consecutive stem diameter measurements was a 1-month period for the monthly BAI, a 6-month period for the seasonal BAI and a 12-month period for the annual BAI. When examining tree radial growth trends and responses, BAI is preferable because from a physiological perspective it is a better indicator of tree growth. BAI depends partially on the initial stem diameter and intuitively, for the same stem diameter increment, trees will have different BAIs, if they differ in the initial stem diameter (West, 1980).

In this study, negative monthly BAIs were assumed to be caused by stem diameter measurement errors and were excluded from the analysis. However, trees with zero increments were retained for analysis because we interpreted this as cessation of stem radial growth. Potential outliers were identified using the plot level means and standard deviations of individual tree diameter increments and were excluded from analysis if they had values that were greater than 3-standard deviations from the mean. The total number of outliers represented less than 0.05 per cent of the total measurements.

## Data analysis

### Wavelet feature extraction

Unsupervised learning is a common type of MLA that is usually applied to time series data sets, when there is a lack of knowledge regarding their structure and there are no training samples. The goal is to find patterns in the data sets, above and beyond what would be considered purely unstructured (non-growth pattern information) noise in the data series, through a pattern dimensionality reduction and data clustering (Ghahramani, 2004). The dimensionality reduction in this study was based on the feature extraction technique, discrete wavelet transform (DWT). This method extracts a set of new features from the original features through functional mapping (Guyon and Elisseeff, 2006; Zhang et al., 2006) and compresses the time series, keeping and emphasizing only growth trend information, while discarding noise and removing correlations. These methods improve subsequent clustering algorithms as optimally separating clusters that contain trees with similar BAI patterns, while the dissimilarity between tree-clusters is as high as possible (Mörchen, 2003).

DWT measures the dissimilarity between BAI time series data and separates it into different frequencies, at different scales (Montero and Vilar, 2014). This method separates (and extracts) the features from the first wavelet coefficients, which correspond to the low-frequency portion of the signal (equivalently, large scales) from the features which are noise, in the high-frequency portion of the signal (equivalently, small scales) (Zhang et al., 2006, Chaovalit et al., 2011).

The feature extraction algorithm using orthogonal wavelet (Haar Wavelet Transform) (Zhang et al., 2006; Montero and Vilar, 2014) was applied to estimate BAI time series dissimilarities and feature dimensionality selection and reduction. This selection proposed an efficient reduction of data into a lower dimensional model, while preserving the properties of the original data. The algorithm works as follow:

Consider a set of time series  $\{X_t^{(1)}, \dots, X_t^{(m)}\}$  located in a scale  $J = \log_2(T)$ . Denoted by  $H_j(X_t^{(i)}) = \{A_j^{(i)}, D_j^{(i)}, D_{j+1}^{(i)}, \dots, D_{J-1}^{(i)}\}$ , the coefficients corresponding to the DWT of  $X_t^{(i)}$  at the scale  $j$ . The  $A_j^{(i)}$  are named Approximation coefficients and represent the smooth behaviour (low-frequency) of the data. The  $D_k^{(i)}$ ,  $k = j, j + 1, \dots, J - 1$  are called the Detail coefficients and they represent the high-frequency nature of the data. As feature vector, Zhang et al. (2006) proposed to keep all the Approximation coefficients,  $A_j^{(i)}$  within a specific scale  $j_s$  corresponding to the highest scale that satisfies:

$$\sum_{i=1}^m E(D_{j*}^{(i)}) < \sum_{i=1}^m E(D_{j*-1}^{(i)}) \quad (2)$$

where  $E(Z) = \sum_{k=1}^s z_k^2$  represents the energy associated with a vector  $Z \in \mathbb{R}^s$ . Since the sum of the squared errors (SSE) between  $X_T^{(i)}$  and the reconstructed approximation series  $\hat{X}_T^{(i)}$  is given by the following equation:

$$SSE(X_T^{(i)}, \hat{X}_T^{(i)}) = E(X_T^{(i)}) - E(A_j^{(i)}) = \sum_{k=j}^{J-1} (D_k^{(i)}) \quad (3)$$

By following equation (2), the Detail coefficients within a specific scale  $j_*$  are removed and there is a tradeoff between lower dimensionality and lower SSE.

### Clustering with k-medoids algorithm

In this study, the clustering analysis is based on the  $k$ -medoids algorithm, an adaptation of the  $k$ -means algorithm in which the cluster centre of  $k$ -medoids is defined as the object that has the smallest sum of distances from other objects in the cluster (Boeva, 2014). The algorithm begins by initializing a set of  $k$  clusters centres, where,  $k$  is preliminarily determined. Next, each object of the dataset is distributed to the cluster that has the centre that is nearest, and the cluster centroid is recalculated. This step is repeated until the objects inside each cluster become as close as possible to the centre and, no further object reassignment can take place (Boeva, 2014; Montero and Vilar, 2014).

### Silhouette plot

The partition around medoids (PAM) algorithm creates clusters by accepting a dissimilarity matrix and then minimizing the sum of dissimilarities, rather than forming a sum of squared Euclidean distances as it is commonly done by other algorithms. Once dissimilarities are minimized in a graphical display, the silhouette plot is used to help in the selection of the clusters (Maechler et al., 2017).

In the silhouette plot (Rousseeuw, 1987), each cluster is represented by a silhouette that is obtained by the  $k$ -medoids algorithm (Maechler

et al., 2017). The silhouette width of an observation  $i$ ,  $s(i)$ , is obtained by combining  $a(i)$  and  $b(i)$ , according to the following equation:

$$s(i) = \frac{b(i) - a(i)}{\max\{a(i), b(i)\}} \quad [-1, 1] \quad (4)$$

where  $a(i)$  denotes the average distance between the  $i$ th observation and all other observations in the cluster to which  $i$  belongs and  $b(i)$  denotes the minimum average distance between the  $i$ th observation and observations in other clusters. The cluster for which this minimum is attained is called the neighbour of object  $i$ . When  $s(i)$  is close to 1, it implies  $a(i)$  is much smaller than  $b(i)$ , and  $i$  is well assigned to the cluster. Observations with  $s(i)$  around zero tend to lie between clusters, and those with negative  $s(i)$  are likely placed in the wrong cluster. For a given partition of the  $n$  observations into  $K \in \mathbb{K} \mathbb{N}$  clusters, the overall average silhouette width,  $\overline{s(i)}$ , is as follows:

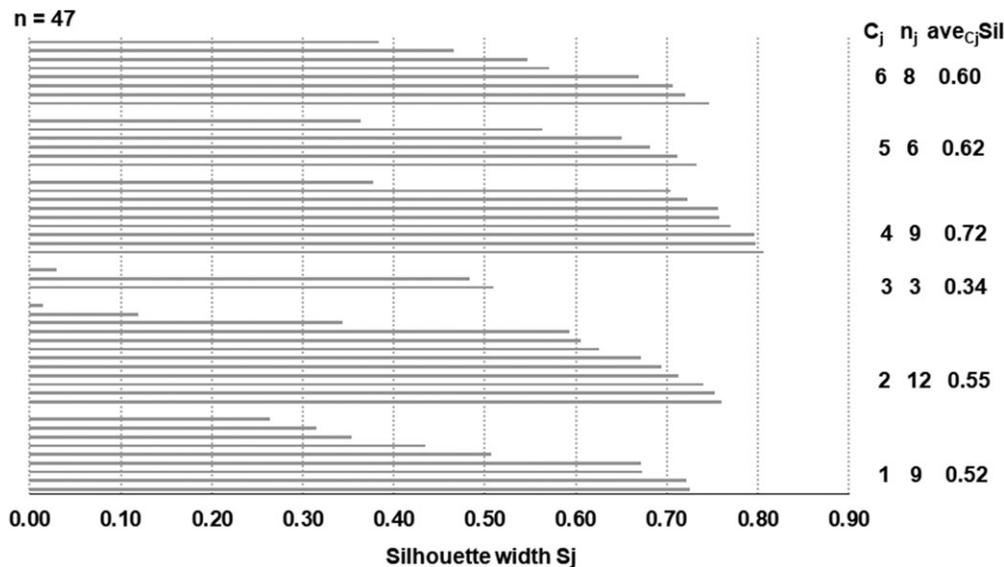
$$\overline{s(i)} = \frac{1}{n} \sum_{i=1}^n s(i) \quad (5)$$

The classification of the overall average silhouette width  $\overline{s(i)}$  (Spector, 2011), representing the strength of group membership, range between: (1) 0.71 and 1.0, meaning a strong structure; (2) between 0.51 and 0.70, meaning a reasonable structure; and (3) 0.26 and 0.50, meaning a weak (artificial) structure and; <0.25, meaning no substantial structure. A strong structure of the silhouette plot means that each tree is well placed in the cluster it is in and shares its monthly BAI trend with the trees in the same cluster, but reveals a contrasting trend with trees in neighbouring clusters.

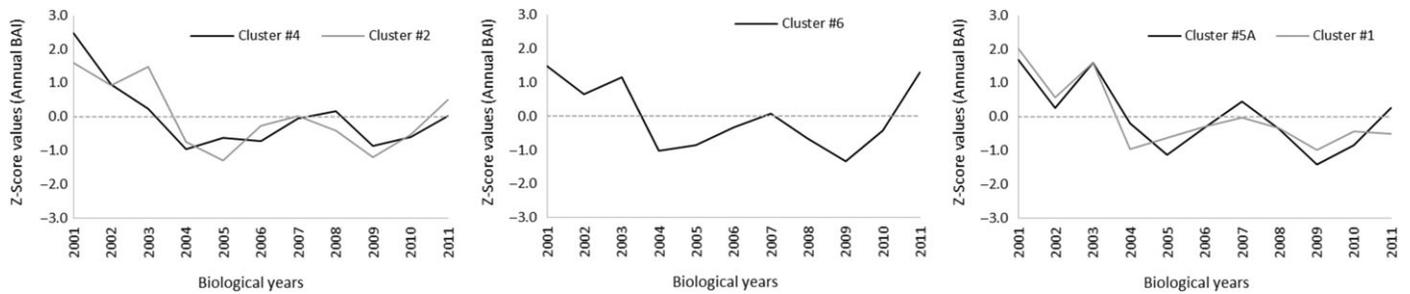
## Results

### Clusters analysis

The clusters analysis grouped the 47 trees according to the monthly BAI-dissimilarity matrix and yielded six main clusters. The silhouette plot (Figure 2) shows an average silhouette width of 0.58, between 0.51 and 0.70, which indicates a reasonable structure.



**Figure 2** Silhouette plot output for the 47 cork oaks basal area increment data collection (from July 2000 until June 2012). Six clusters ( $j$ ) were filtered out, each cluster with a distinct number of trees ( $n_j$ ) and with distinct average silhouette score ( $ave_{C_j} S_{ij}$ ).



**Figure 3** Z-score values of average yearly BAI for tree-clusters considering the 11 biological years of the study period (2001–2011). Tree-clusters grouped in: Cluster #4 and Cluster #2 (with the smaller trees); Cluster #6; and Cluster #5A and Cluster #1 (with the larger trees).

**Table 2** Characteristics of 47 cork oaks grouped in the five Clusters #1, #2, #5A, #4 and #6. Descriptive statistics of stem radial growth for each cluster: diameter and basal area increments in the 12 years study period (from July 2000 until June 2012). Extreme clusters are highlighted: Cluster #4, with the smaller trees and Cluster #5A, with the larger trees

Tree variables	Cluster #1 (9 trees)	Cluster #2 (11 trees)	Cluster #4 (10 trees)	Cluster #6 (8 trees)	Cluster #5A (9 trees)
<b>Size</b>					
Dbh <sub>c</sub> (cm)	59.5 ± 4.65	46.8 ± 6.72	39.1 ± 5.29	54.2 ± 6.96	72.2 ± 5.52
Dbh <sub>w</sub> (cm)	51.6 ± 5.20	40.3 ± 7.36	33.6 ± 4.73	45.8 ± 7.50	64.2 ± 6.74
Cr (m)	17.0 ± 1.72	13.3 ± 2.43	11.3 ± 1.46	15.2 ± 2.58	21.2 ± 2.22
<b>Harvesting pressure</b>					
HC	1.9 ± 0.33	1.7 ± 0.48	1.8 ± 0.17	1.9 ± 0.52	1.8 ± 0.19
SS (m <sup>2</sup> )	8.5 ± 3.71	4.4 ± 1.99	3.1 ± 1.22	6.0 ± 4.27	11.7 ± 5.42
HI	30.0 ± 10.81	24.9 ± 8.82	26.7 ± 11.40	27.4 ± 12.89	24.6 ± 14.23
<b>Annual basal area increment (cm<sup>2</sup> y<sup>-1</sup>)</b>					
Mean ± Standard deviation	78.5 ± 19.97	48.9 ± 12.29	31.4 ± 10.73	66.3 ± 14.06	103.5 ± 24.76
Median	74.5	48.9	27.5	66.1	99.3
IQR (Q25)	16.2 (67.5)	13.3 (38.9)	10.3 (24.7)	20.0 (53.3)	30.8 (85.9)
Min–Max	54.6–115.9	35.0–72.3	18.9–56.5	51.6–91.9	71.3–144.0
<b>Total basal area increment (m<sup>2</sup>)</b>					
Mean ± standard deviation	0.94 ± 0.05	0.59 ± 0.05	0.38 ± 0.07	0.80 ± 0.04	1.24 ± 0.15
Median	0.9	0.6	0.4	0.8	1.2
IQR (Q25)	0.0 (0.9)	0.1 (0.6)	0.1 (0.3)	0.1 (0.8)	0.2 (1.1)
Min–Max	0.8–1.0	0.5–0.7	0.3–0.5	0.7–0.8	1.1–1.5
<b>Annual diameter increment (cm y<sup>-1</sup>)</b>					
Mean ± standard deviation	0.97 ± 0.27	0.76 ± 0.21	0.60 ± 0.23	0.96 ± 0.27	1.02 ± 0.27
Median	0.9	0.7	0.5	0.9	1.0
IQR (Q25)	0.2 (0.8)	0.3 (0.6)	0.3 (0.4)	0.2 (0.8)	1.0 (0.8)
Min–Max	0.7–1.5	0.6–1.2	0.3–1.1	0.7–1.6	0.7–1.5
<b>Total diameter increment (cm)</b>					
Mean ± standard deviation	11.59 ± 0.74	9.15 ± 1.40	7.18 ± 0.94	11.50 ± 1.94	12.23 ± 1.40
Median	11.8	9.2	7.1	11.2	11.9
IQR (Q25)	0.8 (11.4)	1.8 (8.2)	0.8 (6.9)	3.1 (9.8)	1.3 (11.5)
Min–Max	10.2–12.45	7.5–12.3	5.3–8.4	9.3–14.5	10.5–15.2

In this silhouette plot, each of the clusters #1, #2, #5 and #6 contained at least 6 trees ( $n_j \geq 6$ ) and each had a reasonable structure, with an average silhouette width ( $ave_{C_j} S_{il}$ ) between 0.51 and 0.70 (Figure 2). Cluster #4, with nine trees, had the best assigned trees and showed a strong structure, with an  $ave_{C_4} S_{il} C_4 = 0.72$  (between 0.71 and 1.00). Cluster #3 had the worst results, with the smallest number of trees ( $n_3 = 3$ ), and the lowest average silhouette score ( $ave_{C_3} S_{il} C_3 = 0.34$ ),

between 0.26 and 0.50, which indicates a weak structure (Figure 2).

Considering the Cluster #3 output in the silhouette plot, the final clustering was manually improved. Thus, all the trees from Cluster #3 were reassigned to the nearest-neighbour cluster ( $Cl_{t_{neighbor}}$ ), Cluster #5 (Table S1, Supplementary Material). Clusters #5 and #3 were eliminated, Cluster #5, initially with 6 trees, originate a new Cluster #5A (based on Cluster #5 plus

Cluster #3) with nine trees. Moreover, one tree in Cluster #2 (CL48) had the lowest silhouette score, near 0 ( $Sil_{width} = 0.01$ ) (Table S1, Supplementary Material), and shared temporal BAI behaviour with the neighbour cluster (Cluster #4). This tree was thus reassigned in the later cluster that resumed 10 trees. The Cluster #2 initially with 12 trees, ended with 11 trees.

The improved final silhouette plot filtered out five main clusters (Table 2), which were sorted by increasing annual average BAI for the 12 years and were: Cluster #4 (10 trees), with the lowest yearly average of  $BAI_{(2000-2012)}$  of  $31.4 \text{ cm}^2 \text{ y}^{-1}$ ; Cluster #2 (11 trees) with  $BAI_{(2000-2012)}$  of  $48.9 \text{ cm}^2 \text{ y}^{-1}$ ; Cluster #6 (8 trees) with  $BAI_{(2000-2012)}$  of  $66.3 \text{ cm}^2 \text{ y}^{-1}$ ; Cluster #1 (9 trees) with  $BAI_{(2000-2012)}$  of  $78.5 \text{ cm}^2 \text{ y}^{-1}$ ; and Cluster #5A (9 trees), with the highest yearly average  $BAI_{(2000-2012)}$  of  $103.5 \text{ cm}^2 \text{ y}^{-1}$ .

Each tree that had a  $Dbh_c > 75 \text{ cm}$  (selected from the trees belonging to Cluster #5A that presented an overall average of  $103.5 \text{ cm}^2 \text{ y}^{-1}$ , Table 2) annually added more than  $105 \text{ cm}^2 \text{ y}^{-1}$  to their basal area (corresponding to a mean annual diameter increment of  $1.0 \text{ cm y}^{-1}$ ). In addition, each tree that had a  $Dbh_c < 35 \text{ cm}$  (selected from the trees belonging to Cluster #4 that presented an overall average of  $31.4 \text{ cm}^2 \text{ y}^{-1}$ , Table 2) added less than  $25 \text{ cm}^2 \text{ y}^{-1}$  (corresponding to a mean annual diameter increment of  $0.6 \text{ cm y}^{-1}$ ).

### Inter- and intra-annual stem radial growth pattern

The inter-annual BAI variations found in tree-clusters indicated that cork harvesting is the primary factor that influences trees stem radial growth pattern. All the tree-clusters shared similar values for the highest yearly BAI in the first post-harvesting year (in the biological year of 2001, from October<sub>(2000)</sub> to September<sub>(2001)</sub>), which makes this year a positive pointer year for stem radial growth (Figure 3). In this positive pointer year, the yearly BAI z-scores of all tree-clusters were superior to the mean value by  $\sim 1.0$  standard deviations. Noticeably, Cluster #4, with the smaller trees and with the lowest yearly BAI average, reached a z-score of 2.47 in the year 2001. This later value was larger than 2.0 standard deviations, which means that 2001's BAI for trees in Cluster #4 was significantly different (higher) than the mean value.

The occurrence of drought years (2005 and 2009) negatively influenced radial stem growth. In all tree-clusters, we found lower values of annual BAI in the biological year of 2009 (between October<sub>(2008)</sub> and September<sub>(2009)</sub>) which makes this a negative pointer year for radial growth. In this year, the yearly BAI z-scores were inferior to the mean value by around  $-1.0$  standard deviations (ranging between  $-0.86$  in Cluster #4 and  $-1.41$  in Cluster #5A) (Figure 3). In the biological year of 2005 (between October<sub>(2004)</sub> and September<sub>(2005)</sub>), we also found negative z-score values in all tree-clusters, which ranged between  $-0.64$ , in Cluster #4 and  $-1.31$ , in Cluster #2. The drought year of 2005 was considered a negative pointer year for tree radial growth, similar to the drought year of 2009.

The biological year of 2004 (between October<sub>(2003)</sub> and September<sub>(2004)</sub>) that immediately preceded the drought year 2005 was not considered a negative pointer year. All tree-clusters, with the exception of Clusters #5A and #2, had relatively lower negative average BAI z-scores than in the year 2005. Z-score values were also lower than the mean value by

$\sim -1.0$  standard deviations in 2004, which may indicate a cork-harvesting effect legacy in radial growth, rather than one unique response to a sequence of dry months. Coincidentally, Clusters #4 and #1 were the only clusters that were highly responsive to cork harvesting in the positive pointer year of 2001 (with z-score  $\geq 2.0$ ), which may allow these clusters to show a strong cork harvesting legacy (Figure 3).

The monthly BAI that was found for the five tree-clusters revealed a similar intra-annual growth pattern. This growth pattern comprised a sole growing season that extended from March until October, with a seasonal (summer) peak BAI in the months between May and July. The cessation of stem radial growth is effective during the winter months, between December and February (Figure 4).

The intra-annual growth patterns revealed differences between tree-clusters in the magnitude of BAI values, which increased from smaller trees to larger trees. In addition, in smaller trees the majority of monthly BAI values fell below the mean BAI values, as recorded in Clusters #4 and #2, and in larger trees, the majority of monthly BAI values were above mean BAI values, as recorded in Clusters #5A and #1 (Figure 4).

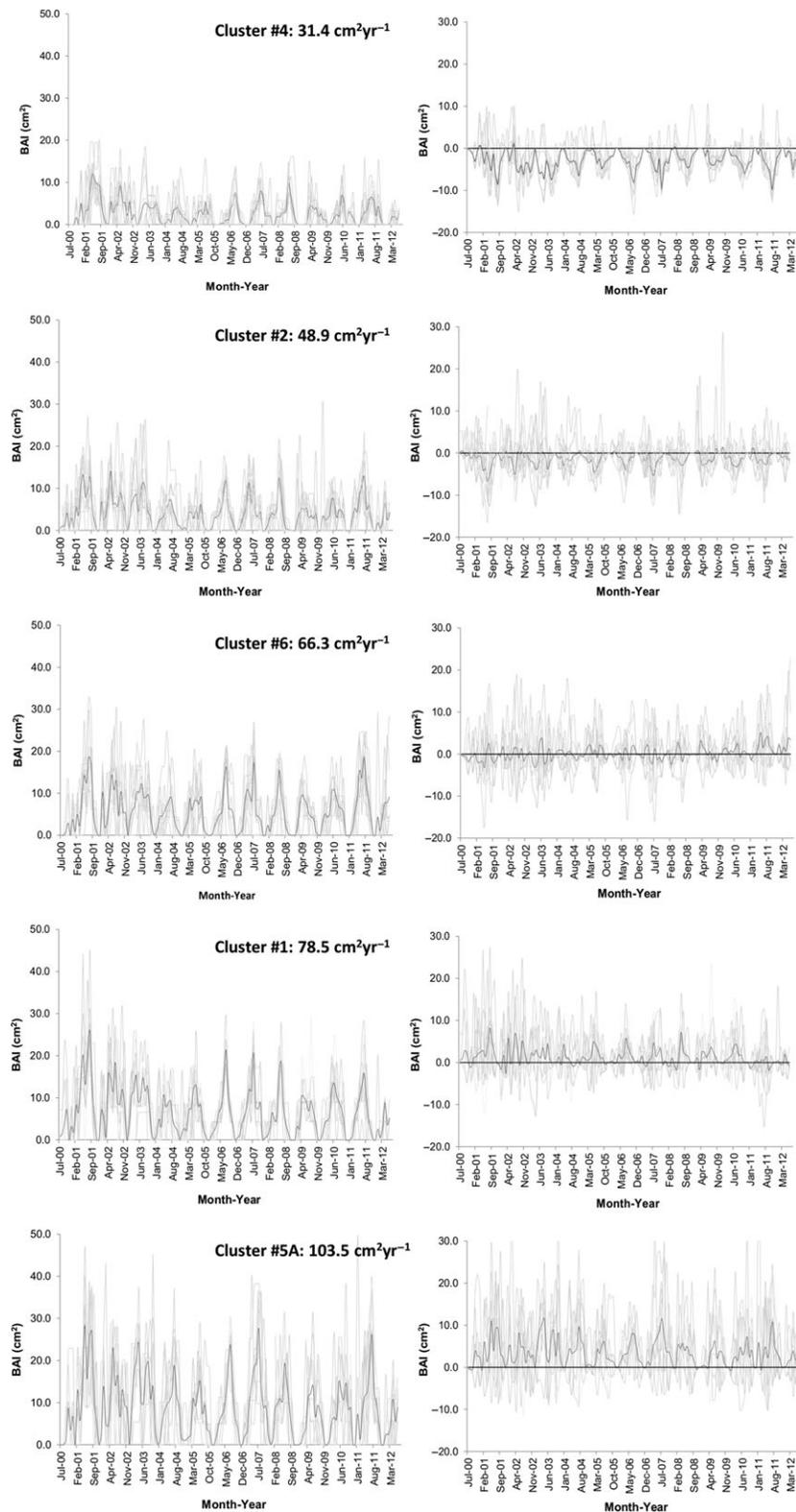
Noticeably, in Cluster #6 the monthly BAI in the peak of the growing season (in July) increased over the 12 years study period, and in 2011 was at its highest (Figure 4). This monthly growth pattern in the year 2011 resulted in a yearly BAI z-score value of 1.30, comparable with the one in the positive pointer year of 2001 of 1.49 (Figure 3). This average BAI growth pattern likely contributed to differentiating this cluster's response in the (*k*-medoids) clustering analysis.

### Annual and seasonal response to cork harvesting

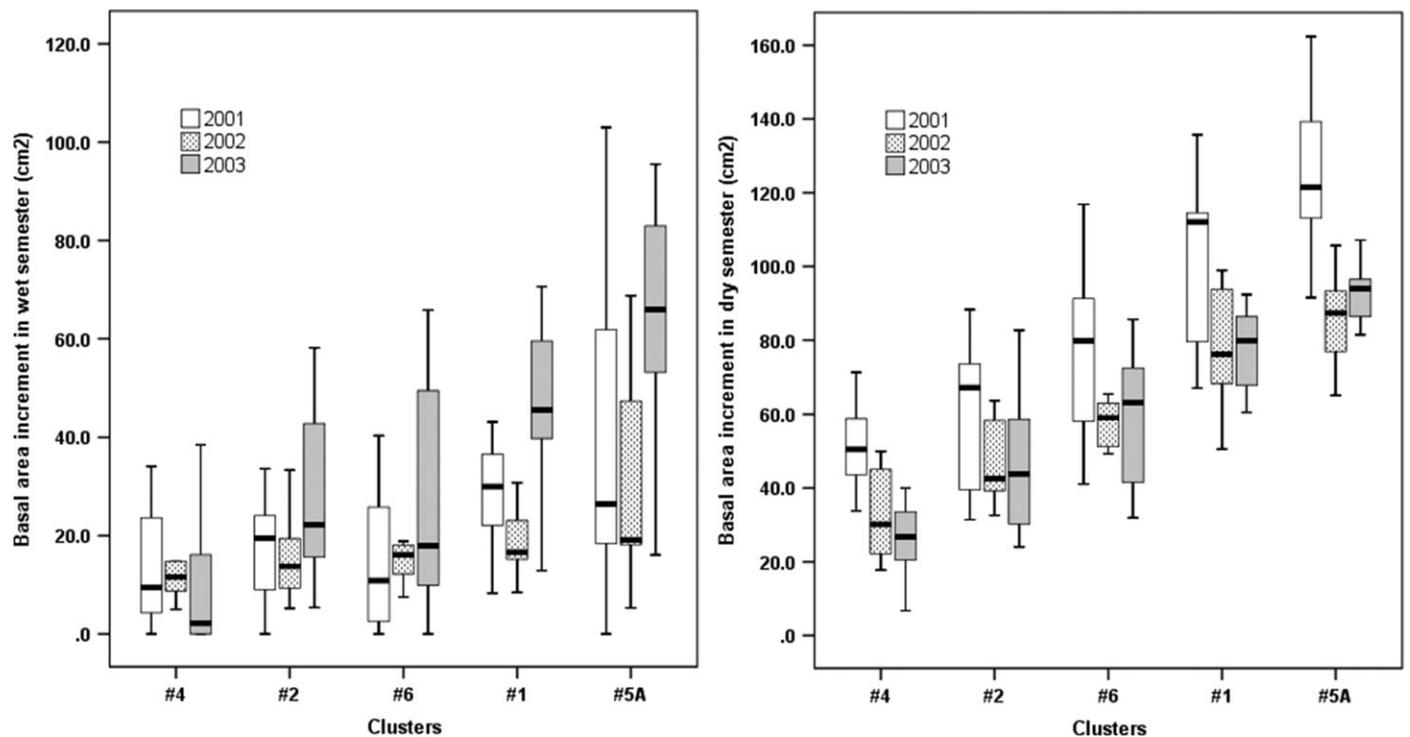
In the biological positive pointer year of 2001 (first post-harvesting year), the maximum annual BAIs were similarly achieved by all tree-clusters, that ranged in mean values between  $67.3 \text{ cm}^2 \text{ y}^{-1}$  (in smaller trees of Cluster #4) and  $159.1 \text{ cm}^2 \text{ y}^{-1}$  (in larger trees of Cluster #5A). Following the positive pointer year of 2001, during the biological year of 2002 (second post-harvesting year), all tree-clusters abruptly altered and reduced their BAIs (Figure 5). This reduction was proportionally less pronounced in the larger trees when compared with the smaller trees. In one extreme, Cluster #5A (with the larger trees) had an average reduced BAI of 25 per cent and reached a BAI of  $116.6 \text{ cm}^2 \text{ y}^{-1}$  in 2002 (corresponding to a  $\Delta BAI$  of  $\sim 42 \text{ cm}^2$ ). In the other extreme, Cluster #4 (with the smaller trees) had an average reduced BAI of 31 per cent and reached a BAI of  $46.3 \text{ cm}^2 \text{ y}^{-1}$  in 2002 (corresponding to a  $\Delta BAI$  of  $\sim 21 \text{ cm}^2$ ).

In the year 2003 (third post-harvesting year), all the tree-clusters appeared to resume their normal radial growth, with the exception of Cluster #4 (Figure 5). Trees in Cluster #4 distinctly and continuously decreased their yearly BAI between 2001 and 2003 (Figure 5) and also in the year 2004. In this later year (2004), Cluster #4 achieved the lowest annual average BAI ( $20.3 \text{ cm}^2 \text{ y}^{-1}$ ), which corresponded to the cluster's lowest z-score value of  $-0.96$  (Figure 3).

It seemed that trees in Cluster #4 were not able to resume their growth in response to cork harvesting before the year 2005. This is in contrast to the other tree-clusters, which recovered their growth in the year 2003. At the extreme, in the year



**Figure 4** Intra-annual (monthly) basal area increment,  $BAI_{(2000-2012)}$  (in  $cm^2$ ) of the 47 cork oaks discriminated by clusters. Grey lines are for each tree and black lines are for trees average per cluster. Left column is for BAI absolute values (in  $cm^2$ ) and right column is for below (negative) and above (positive) the average BAI (in  $cm^2$ ).



**Figure 5** Seasonal BAI (in  $\text{cm}^2$ ) in the post-harvesting year of 2001 and in the 2 years following (2002 and 2003). BAI in the wet semester (October<sub>(-1)</sub>–March) (left) and BAI in the dry semester (April–September) (right). Multiple boxplots (median, box: interquartile range: IQR =  $Q_{75\text{percent}} - Q_{25\text{percent}}$ , whiskers: minimum and maximum).

2003, the larger trees in the Clusters #5 A and #1 resumed their BAI and achieved  $156$  and  $119 \text{ cm}^2 \text{ y}^{-1}$ , respectively.

The variation (increasing trend) of yearly BAI from 2002 to 2003 in all tree-clusters, with the exception of Cluster #4, is related to a pronounced increase in the BAI within the wet semester of 2003 (Figure 5). Notably, in Clusters #1 and #5A trees resumed their growth in the third post-harvest year by extending and intensifying their growth rates within the wet semester, either in the autumn of the previous the growing season (October<sub>(-1)</sub> and November<sub>(-1)</sub>) or in March during the onset of the growing season.

In the 2003 biological year, Cluster #4, in contrast to all other clusters, showed a steady decrease in BAI during the dry semester (which includes the summer growth peak, in the May–July period) and in the wet semester (which includes the onset of the growing season in February and March) (Figure 5), when it reached a minimum average monthly BAI of  $3.3 \text{ cm}^2 \text{ month}^{-1}$ .

#### Annual and seasonal response to drought periods

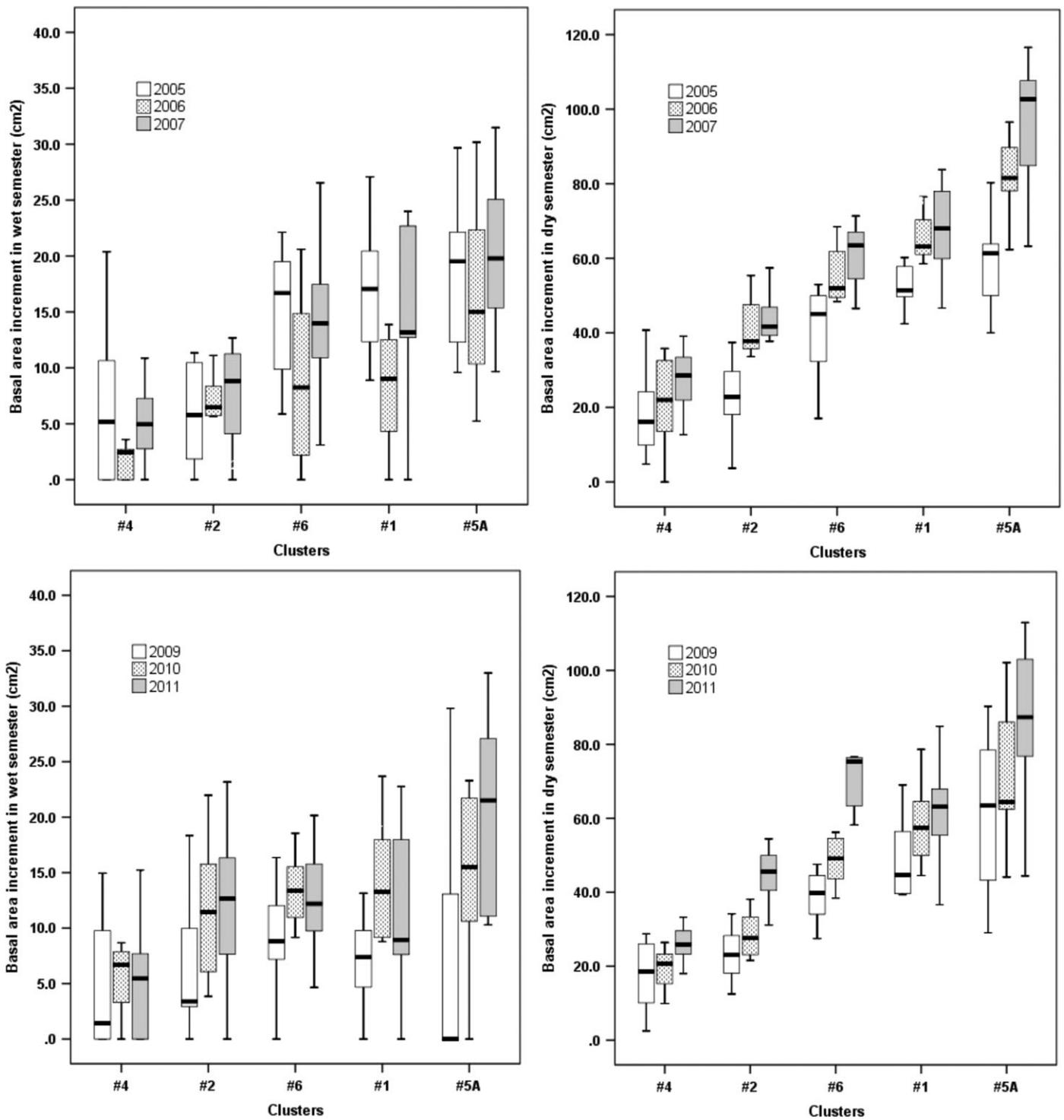
In the 2005 and 2009 negative pointer years, the minimum annual BAIs were similarly achieved by all tree-clusters (Figure 6). The yearly average BAI growth ranged between  $24.7$  and  $21.5 \text{ cm}^2 \text{ y}^{-1}$  in Cluster #4 to  $76.0$  and  $67.6 \text{ cm}^2 \text{ y}^{-1}$  in Cluster #5 A, in the 2005 and 2009 years, respectively.

Following the 2005 negative pointer year, during 2006 and 2007, all the tree-clusters resumed their stem radial growth (Figure 6). This growth recovery was proportionally more pronounced in the larger trees when compared with the smaller

trees. At one extreme, the larger trees in Cluster #5 A nearly doubled their average BAI, achieving  $122.5 \text{ cm}^2 \text{ y}^{-1}$  in 2007. At the other extreme, smaller trees in Cluster #4 reached a mean BAI of  $32.7 \text{ cm}^2 \text{ y}^{-1}$  in the year 2007, which was an increase of 33 per cent.

From smaller- to larger-trees clusters, the increasingly high annual BAI growth recovery, in response to the drought year of 2005, was made at the expense of proportionally higher BAI growth during the dry semester. This is in contrast to the trees response to cork harvesting (Figures 5 and 6). Moreover, from smaller to larger trees, the dry semester BAI growth seemed to increasingly compensate for the relatively lower BAI growth during the wet semester (Figure 6). While in the larger trees of Cluster #5A, the dry semester  $\Delta\text{BAI}$  represented an increase of  $\sim 80$  per cent of the initial dry semester BAI, which allowed the growth recovery from the drought in 2007. In the smaller trees of Cluster #4, the dry semester  $\Delta\text{BAI}$  corresponded to an increase of  $\sim 50$  per cent of the initial BAI and impeded an effective growth rebound in the year 2007.

Following the drought year of 2009, a consistent growth rebound effect was noticed in all the tree-clusters which resumed their radial growth in the year 2011, two years after the negative pointer year. Similarly to the growth rebound following the drought year of 2005, this was based primarily on a dry semester BAI increase (Figure 6). However, larger trees in Cluster #5A showed a more limited growth recovery from the drought of 2009 than from the drought of 2005, as  $\Delta\text{BAI}$  in the dry semester was only 50 per cent of the initial (in 2009) BAI. In contrast, the smaller trees of Cluster #4 were much more



**Figure 6** Seasonal BAI (in  $\text{cm}^2$ ) in the: 2005 negative pointer year and in the 2 years following (2006 and 2007) (Top row) and; 2009 negative pointer year and in the 2 years following (2010 and 2011) (Bottom row). BAI in the wet semester (October<sub>(-1)</sub>-March) (left) and BAI in the dry semester (April-September) (right). Multiple boxplots (median, box: interquartile range, IQR =  $Q_{75\text{percent}} - Q_{25\text{percent}}$ , whiskers: minimum and maximum).

responsive to the 2009 drought and increased their dry semester BAI by 65 per cent of the initial dry semester BAI (Figure 6). In the extreme, Clusters #2 and #6 stand out as tree-clusters that were highly responsive to the 2009 drought year. The later tree-cluster roughly doubled their BAI growth in the dry semester, from  $39.0 \text{ cm}^2 \text{ y}^{-1}$  in 2009 to  $76.4 \text{ cm}^2 \text{ y}^{-1}$  in 2011.

## Discussion

In this study, by sampling trees with variable sizes, from small (young) to large (old) trees, instead of selected cross-datable (even-aged) trees, we observed divergent patterns of BAI, corresponding to the findings of Rieger *et al.* (2017). Our new methodological approach allowed the removal of non-growth pattern information (noise) and reductions to the dimensionality that usually prevail in the heavy structure of BAI data sets, and focused on dominant (low frequency) growth pattern changes (Långkvist *et al.*, 2014). This was similar to detrending and standardization procedures in the cork-ring data, to maximize and keep the large-scale wavelengths in the final master chronologies (Costa *et al.*, 2015). Also, our methodology identified growth patterns in the unlabelled BAI time-series, and organized data sets into clusters. The easy-to-obtain monthly BAI data allowed a better interpretability of trees growth primarily because the BAI was found to be a robust measure of long-term growth patterns and trends for distinct tree size (age) classes (Johnson and Abrams, 2009).

Our findings demonstrate that radial growth patterns changed across clusters and revealed how strongly radial growth is determined by tree size. On average, the overall increment of stem basal area was more than three times higher in large trees: in the order of the  $1242.0 \text{ cm}^2$  ( $103.5 \text{ cm}^2 \text{ y}^{-1}$ ) against  $376.8 \text{ cm}^2$  ( $31.4 \text{ cm}^2 \text{ y}^{-1}$ ) in small trees. Our results are in accordance with the results found in a previous study by Oliveira *et al.* (1994) which reported BAIs for cork oak that ranged between  $14.8$  and  $57.2 \text{ cm}^2 \text{ y}^{-1}$  in trees with stem diameters reaching 50 cm. Moreover, previous results on radial growth of other oak species (Johnson and Abrams, 2009) showed that trees increased their basal area and only plateaued in their radial growth if they were 200+ years old. Furthermore, the results are in line with other studies, which tested whether tree growth rates are size-related (Mencuccini *et al.*, 2005; De Luis *et al.*, 2009; Stephenson *et al.*, 2014). These results, which confirm our first hypothesis, may contradict general physiological growth models because trees continuously increase their BAI throughout their life.

In our study, the lower BAI rates found in the small trees should represent proportionally lower tree respiration rates and/or less carbon diverted to radial growth because trees are growing in a common environment, with common biophysical and climate conditions and under similar superimposed effect of cork harvesting. These results are in accordance to previous findings on the variations over time in a trees responsiveness to cork harvest (Costa *et al.*, 2015). According to previous authors trees in younger stages (corresponding to the smaller trees in our study), displayed lower mean cork-ring widths, and consequently, lower annual radial increments. Aging, older trees (which should correspond to larger trees in our study), were increasingly resilient to cork harvesting (over time) in their radial

cork growth, until the trees reached a radial growth break point, at the age of 120+ years old.

In response to cork harvesting, trees transfer their reserves from the non-conducting phloem tissues, which are close to the zone where the phellogen is formed. This transfer indicates the use of energy stored for the support of the regeneration process of cork layers (Oliveira and Costa, 2012). The loss of cork in younger tree stages may constitute a considerable sink of carbon reserves and photoassimilates, which competes with tree growth (Spiecker *et al.*, 1996) and reproduction efforts (Chapin *et al.*, 1990). Eventually, cork loss will be followed by a proportionally large decline in vegetative (secondary, radial) growth. Moreover, cork harvest is also a water-related loss process (Oliveira *et al.*, 1992). Larger trees, rather than smaller trees, probably take advantage of their deep roots to extend and intensify their radial growth during late autumn, and also in winter, when warmer temperatures may stimulate cambial and phellogen activity (Tessier *et al.* 1994; Costa *et al.*, 2016). This may be one explanation for the fact that larger trees manage to rebound their radial growth in the two years following the positive pointer year, in contrast to smaller trees that slowly rebound their radial growth rates in the first five years after the cork harvesting only (e.g. Clusters #4 and #2).

According to our results, drought-driven growth sensitivity is related to tree-size. Additionally, the larger trees were more resilient and responsive to drought events than smaller trees, which confirms our second hypothesis. In the 2-year drought legacy period, similar to the drought legacy period found for other trees species (Anderegg *et al.*, 2015), the larger trees when compared with smaller trees responded better to drought events because of intra-seasonal strategies that allowed them to immediately take advantage of favourable climate conditions. In fact, these (large) trees intensified and extended radial growth in the dry semester, which occurred between the onset of the growing season till the end of summer and before the full depletion of soil moisture (Ghalem *et al.*, 2018). In addition, these trees extended their vegetative growth period until early autumn by reaching the groundwater, even at its deepest depths (Mendes *et al.*, 2016).

Our findings add important details regarding the growth of larger (older) trees and their ability to continuously increasing their radial stem diameter. Growth of larger trees results in larger BAIs and, eventually, in the fixing of large amounts of carbon after cork harvesting. Thus, large trees actively contributed to the net accumulation of aboveground carbon in the forest ecosystems, especially in uneven-aged cork oak woodlands. These trees, so far assumed as simply senescent carbon reservoirs, contained the majority of biomass and have major ecological functions, and may determine the role of cork oak woodlands as a potential carbon sink in a changing climate. In fact, large cork oaks are key ecological features, assuming a similar role to scattered trees in other savannah-type ecosystems (Manning *et al.*, 2006).

The carbon stock for cork oak woodlands has been reported to range between  $100$  and  $200 \text{ g cm}^{-2} \text{ y}^{-1}$  (Pereira *et al.*, 2007), similarly to other Mediterranean savannahs-like forest ecosystems that have large scattered-trees (Baldocchi *et al.*, 2004). In cork oak woodlands in the southwestern region of Portugal, trees with a  $\text{Dbh}_c \geq 57 \text{ cm}$  were considered at the end of their exploitation lifetime (Natividade, 1950) and only represented

~20 per cent of the living trees, but should be responsible for fixing ~55–110 g cm<sup>-2</sup> y<sup>-1</sup>, while the smaller trees, with a Dbh<sub>c</sub> < 32 cm, at the onset of its lifetime exploitation for cork, represented ~70 per cent, although should only be fixing ~45–90 g cm<sup>-2</sup> y<sup>-1</sup>.

In the light of previous findings, the introduction of new large afforestation areas with cork oak in southern Portugal (Costa *et al.*, 2014) remains a fragile strategy to mitigate global warming given the lower responsiveness of growth patterns to climate in the smaller trees, under conditions of cork harvesting. As Luysaert *et al.* (2008) and Stephenson *et al.* (2014) reported for temperate forests, young forests (as new afforestation areas) are less conspicuous sinks for CO<sub>2</sub>, when compared with old-growth forests. Specifically, adaptive cork oak woodlands conservation strategies should also include the preservation of larger (older) trees in uneven aged woodlands, because these larger trees increasingly and continuously recycle carbon and effectively contribute to the carbon budget pool and to climate change mitigation in the long term.

## Conclusion

Our findings highlight that under the superimposed effect of cork harvesting, BAI of cork oak continuously increases with tree size and that larger trees grow more and are more responsive and resilient to climate fluctuations. These findings, already reported for other tree species but previously undocumented for cork oak, support the idea that individual tree growth can continue to increase with tree size. These data highlight that understanding tree growth dynamics is important when assessing the role of cork oak woodlands as a potential carbon sink under climate change. Also, our findings underline the fact that large trees play a disproportionately important role in uneven aged cork oak woodlands, significantly influencing biomass production (including cork), carbon cycles, and the ecological functioning of cork oak woodlands.

Conservation strategies for cork oak woodlands growing in regions with temperate Mediterranean climate should target the conservation of the largest trees and should promote adequate forestry management that focuses on drought mitigation effects, especially in the smaller (younger) trees that are newly harvested for their cork in the recent afforestation areas.

## Supplementary data

Supplementary data are available at *Forestry* online.

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## Conflict of interest statement

The authors declare that they have no conflict of interest.

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## Author contribution

A.C. conceived the study and provided data. A.C. and M.P.M. performed the analyses. M.P.M. performed the Machine Learning Algorithm approach. All authors contributed to the writing of the article.

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