

# Using neighbourhood vegetation information on cork oak growth and yield modelling

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FORESTRY ENGINEERING AND NATURAL RESOURCES

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**To my children Guilherme, Gustavo, Gonçalo,  
my natural regeneration**

*Life is divided into three terms - which was, which is, and which will be.*

*William Wordsworth*

## **Agradecimentos**

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## **Resumo Alargado**

O presente trabalho tendo por foco povoamentos de sobreiro, pretende contribuir para o conhecimento do efeito da competição no crescimento da árvore e da cortiça, através de duas abordagens: uma relativa ao efeito da vegetação no subcoberto, outra relativa ao impacto da competição intraespecífica. Para isso, foram analisados e modelados dados recolhidos ao nível local e ao nível regional, provenientes de diversos povoamentos localizadas na área de distribuição de sobreiro.

O conjunto de dados ao nível local tem por base um ensaio experimental, delineado em blocos causalizados, estabelecido com o objetivo de comparar dois tipos de gestão do subcoberto durante um período de descortiçamento de 9 anos. Neste ensaio foram recolhidas amostras de cortiça no início e final de dois ciclos de descortiçamento desfasados e analisados os anéis de crescimento. Numa primeira análise, considerando as amostras do ciclo de descortiçamento que acompanhou o período do ensaio, nenhum efeito foi encontrado no crescimento da cortiça ou em madeira, comparando as parcelas de sementeira periódica de tremocilha, com as parcelas sem remoção da vegetação arbustiva espontânea. Numa segunda abordagem, considerando o conjunto de anéis de crescimento provenientes de ambos os ciclos, foi analisada a interação da idade do anel de cortiça com a realização das operações de remoção de mato e sementeira de tremocilha. Nesta análise, e para as espécies arbustivas existentes, foram apresentados diferentes limites para idade dos anéis de cortiça associados à manutenção da vegetação do subcoberto ou à sementeira. Posteriormente, entre 2016 a 2019, um dos blocos do ensaio foi continuado excluindo agora a sementeira de tremocilha e comparando a manutenção com remoção do mato, este último com e sem fertilização N e P do solo. Para isso foi selecionado um conjunto de árvores por tratamento e monitorizado o acréscimo mensal em diâmetro e a variação sazonal do teor de nutrientes nas folhas jovens. Da análise destes dados foram encontradas nas folhas diferenças no teor de N e P, e também no acréscimo em diâmetro no tratamento com fertilização do solo.

Ao nível regional, foram recolhidos dados numa rede de parcelas permanentes localizadas na área de distribuição de sobreiro em Portugal, abrangendo povoamentos jovens e/ou não descortijados, e povoamentos adultos com ou sem produção de cortiça.

Para o conhecimento sobre a estrutura dos atuais povoamentos jovens de sobreiro focando no apoio das decisões de gestão, foi realizada uma análise aos dados provenientes de plantações jovens e povoamentos não descortijados, representativos das densidades existentes, que demonstrou estes se encontrarem longe de atingir a sua lotação máxima. No entanto, foram encontrados sinais de competição intraespecífica em povoamentos adultos

não descortiçados com elevada densidade, através da análise da taxa de crescimento relativo em diâmetro com a dimensão da árvore.

De acordo com os objetivos de gestão, a percentagem de coberto em povoamentos de sobreiro é normalmente usada como medida para definir o limite de densidade, embora o registo de raios de copa inventários florestais não seja usual por ser uma medição demorada. Utilizando o conjunto de dados regional foi desenvolvido um modelo para predição do diâmetro da copa sob duas abordagens, uma delas considerando o efeito das medições repetidas – modelos mistos. Em ambas as abordagens, foi incluído um índice de competição para explicar o efeito da posição das árvores na estrutura do povoamento. O modelo desenvolvido com uma abordagem alternativa aos modelos mistos, considerando efeitos fixos, foi aplicado usando os dados do inventário nacional. Como resultado, para um horizonte de dez anos, verificou-se uma diminuição da percentagem de coberto nos povoamentos de sobreiro em Portugal.

Os modelos de crescimento em diâmetro permitem a predição do crescimento do povoamento, podendo expressar não só a competição intraespecífica como a variabilidade no povoamento e a variabilidade regional. Utilizando os dados recolhidos em Portugal conjuntamente com dados recolhidos em Espanha, ambos provenientes de povoamentos adultos com produção de cortiça, foi desenvolvido um modelo de incremento em diâmetro aplicando duas metodologias: equações as diferenças independentes da idade e crescimento potencial do povoamento multiplicado por um modificador. O conjunto de dados da Península Ibérica permitiu testar a inclusão da variabilidade dos povoamentos associada às condições edafo-climáticas. Em ambos os modelos desenvolvidos, os índices de competição independentes da distância incluídos, expressaram uma correlação negativa com o incremento de diâmetro. Em relação às variáveis de clima e do solo, apenas a precipitação foi incluída no modelo obtido pela segunda metodologia, apresentando uma correlação positiva com crescimento em diâmetro. O modelo obtido pelo método das equações às diferenças revelou melhor predição de incremento diâmetro para ambos os países.

## **Resumo**

*O presente trabalho contribui com informação sobre competição, avaliando o impacto da vegetação vizinha e da sua densidade, no crescimento da árvore e da cortiça.*

*Para comparar o efeito na árvore da gestão do subcoberto, durante um ciclo de descortiçamento (9 anos), foram recolhidas amostras de cortiça, no início e final do ciclo, em árvores sujeitas a ciclos desfasados num ensaio específico. Primeiramente não foi encontrado efeito no crescimento anual da cortiça e no incremento em madeira entre árvores sujeitas a diferente gestão. Mas analisando a interação entre a idade do anel de cortiça e as operações realizadas, foram associados diferentes limites à manutenção dos arbustos e à sementeira de tremocilha. Este ensaio foi continuado para comparar a manutenção com a remoção dos arbustos, com ou sem fertilização NP do solo, monitorizando um conjunto de árvores selecionadas. Analisando o registo do incremento em diâmetro mensal e da variabilidade sazonal dos nutrientes das folhas, foram encontradas diferenças no tratamento com fertilização do solo.*

*Os dados recolhidos numa rede de parcelas permanentes localizadas na área de distribuição de sobreiro em Portugal, foram utilizados para analisar e modelar variáveis arbóreas. Abordando apenas dados de plantações jovens e povoamentos não descortçados, a relação entre a taxa de crescimento relativo em diâmetro com a dimensão da árvore mostrou sinais de competição nas árvores não descortçadas, em povoamentos adultos de elevada densidade. Foi desenvolvido um modelo predição do diâmetro da copa que aplicado aos dados do inventário florestal nacional, indicaram uma diminuição da percentagem de coberto, num horizonte de dez anos. Juntando a este conjunto, dados de parcelas espanholas, foi desenvolvido um modelo para o incremento em diâmetro, com a inclusão da variabilidade local associada ao clima e ao solo, abordando duas metodologias: equações às diferenças independentes da idade e potencial de crescimento multiplicando um modificador.*

**Palavras-chave:** *anel de crescimento da cortiça; acréscimo em diâmetro; modelos mistos; equações às diferenças; potencial de crescimento*

## **Abstract**

*The present work contributes to information regarding the competition on the tree and cork growth, by evaluating the neighbourhood vegetation and local tree density impact.*

*From a specific trial established to compare the effect on the tree of different understory management options, along a cork rotation cycle of 9 years, cork samples were taken at the beginning and at the end of the cycle on trees within lagged cycles. Former results revealed no effect on cork annual growth and wood increment for the trees growing under lupine periodical seeding. When analysing the interaction between cork ring age and understory operations, different thresholds were linked to the shrubs' maintenance and the lupine seeding. Later, this trial was monitored to compare the shrubs' maintenance versus removal with or without NP soil fertilization. On the set of selected trees, diameter increment was monthly monitored, as well as, leaves nutrients seasonal variability, and differences were found in the treatment with soil fertilization.*

*Data gathered from a Portuguese network of permanent plots across the cork oak species distribution area was used to model tree variables including the site characteristics. Focusing the analysis on young plantations and never debarked stands, the relationship of the diameter relative growth rate over tree dimension showed signs of inter-tree competition before the first cork extraction in older high-density stands. A crown width model developed with a fixed-effect approach was applied using national forest inventory datasets. Subsequently, a decrease in crown cover was identified in Portugal over ten years. Using the Portuguese dataset with a Spanish dataset, a diameter increment model was developed applying two methodologies: age-independent difference equations and potential growth times a modifier. This Iberian dataset allowed testing the inclusion of stand variability associated with climate and soil site conditions.*

**Key-words** *cork ring increment; wood diameter increment; mixed model; difference equation; potential growth*

## **Preamble**

The present thesis is a compilation of scientific articles conducted under the PhD theme: *Using neighbourhood vegetation information on cork oak growth and yield modelling*. Some of the articles have already been published and others are ready for the process of submission. Chapter I explains the motivation and the tasks carried out for accomplishing these articles, which are organized in two chapters following the PhD underlying research hypotheses:

<b>Chapter</b>	<b>Title</b>
----------------	--------------

- |       |   |
|-------|---|
| II    | <u>How does the neighbourhood vegetation affect the tree and cork growth?</u>   |
| II.1  | Faias SP, Paulo JA, Palma JHN, Tomé M, 2018. Understory effect on tree and cork growth in cork oak woodlands.<br><i>Published in Forest Systems</i>   |
| II.2  | Faias SP, Paulo JA, Firmino PN, Tomé M, 2019. Drivers for annual cork growth under two understory management alternatives on a Podzolic cork oak stand.<br><i>Published in Forests</i>  |
| II.3  | Faias SP, Paulo JA, Firmino PN, Moreno G, Tomé M. Intra-annual tree diameter increment and seasonal leaves nutrient variation in cork oak species under three understory management alternatives in Podzol soils.<br><i>Working paper</i>   |
| III   | <u>What is the impact of local tree density on tree growth in cork oak stands?</u>  |
| III.1 | Paulo JA, Faias SP, Ventura-Giroux C, Tomé M, 2016. Estimation of stand crown cover using a generalized crown diameter model: application for the analysis of Portuguese cork oak stands stocking evolution.<br><i>Published in iForest</i> |
| III.2 | Faias SP, Paulo JA, Tomé M, 2019. Inter-tree competition analysis in cork oak plantations as a support tool for management in Portugal.<br><i>Published in New Forests</i>  |
| III.3 | Faias SP, Paulo JA, Firmino PN, Sánchez-González M, Tomé M. Tree diameter increment for cork oak productive stands in the Iberian Peninsula.<br><i>Ready for submission</i>   |

The present studies required from the PhD candidate several visits to the field to collect data on permanent plots established in cork oak stands. Each article's summary information is presented in the first page of the corresponding subchapter.

The articles in Chapter II focused on the analysis of data collected at a specific trial, established to compare different understory management alternatives in a cork oak stand, which required plenty of fieldwork and laboratory time to handle cork samples.

The articles in Chapter II and the article in subchapter III.1 all used a mixed model approach.

The articles in Chapter III used a dataset collected on ForChange's (CEF-ISA/ULisboa) network of permanent plots, located across the cork oak species distribution area in Portugal. Concerning the first article in Chapter III, the study initiated by its first author had a valuable contribution collaboration from the PhD candidate in data analysis and manuscript writing.

The article in subchapter III.3 was based on a single Iberian dataset, which is a compilation of information at tree level from cork oak sites located across Portugal (PT) and Spain (ES). This study is the result of a 6-month PhD internship in INIA-CIFOR, Madrid – Spain, supervised by the Spanish co-author.

Chapter IV summarizes and links the outcomes of the six scientific articles, and finalizes with the final remarks. However, the discussion of these articles results is left to each subchapter.

The PhD candidate presented the following studies at international conferences:

Faias SP, Paulo JA, Tomé M, 2017. Competition pattern in young cork oak stands. IFORS, 17-21 July Quebec (Canada). Oral communication

Faias SP, Paulo JA, Tomé M, 2017. Tree diameter growth model for cork oak stands in Portugal. International congress on cork oak trees and woodlands: Conservation, Management, Products and Challenges for the Future, 25-26 May Sassari (Italy). Oral communication

Faias SP, Paulo JA, Tomé M, 2017. Competition pattern in young cork oak stands. International congress on cork oak trees and woodlands: Conservation, Management, Products and Challenges for the Future, 25-26 May Sassari (Italy). Oral communications

Faias SP, Paulo JA, Palma JHN, Tomé M, 2016. Is cork growth affected by different understory management options: lupine pasture versus shrubs encroachment? World Congress Silvo-Pastoral Systems 2016, 27-30 September, Evora (Portugal). Poster

During the PhD period, the PhD candidate participated in other projects resulting in the following publications:

**Title**

Correia AC, Faias SP, Ruiz-Peinado R, Chianucci F, Cutini A, Fontes L, Manetti MC, Montero G, Soares P, Tomé M, 2018. Generalized biomass equations for Stone pine (*Pinus pinea* L.) across the Mediterranean basin, *Forest Ecology and Management* 429:425-436, <https://doi.org/10.1016/j.foreco.2018.07.037>

Demertzi M, Paulo JA, Faias SP, Arroja L, Dias AC, 2018. Evaluating the carbon footprint of the cork sector with a dynamic approach including biogenic carbon flows. *The International Journal of Life Cycle Assessment*: 1-12  
<http://dx.doi.org/10.1007/s11367-017-1406-8>.

Guerra-Hernández J, González-Ferreiro E, Monleón JV, Faias SP, Tomé M, Díaz-Varela AR, 2017. Use of Multi-Temporal UAV-Derived Imagery for Estimating Individual Tree Growth in *Pinus pinea* Stands. *Forests* 8(8):300. <http://dx.doi.org/10.3390/f8080300>

Reyer C, Bathgate S, Blennow K, Borges JG, Bugmann H, Delzon S, Faias SP, Garcia-Gonzalo J, Gardiner B, Gonzalez-Olabarria JR, Gracia C, Guerra J, Kellomäki S, Kramer K, Lexer MJ, Lindner M, van der Maaten E, Maroschek M, Muys B, Nicoll B, Palahi M, Palma JHN, Paulo JA, Peltola H, Pukkala T, Rammer W, Ray D, Sabaté S, Schelhaas M, Seidl R, Temperli C, Tomé M, Yousefpour R, Zimmermann NE, Hanewinkel M, 2017. Are forest disturbances amplifying or canceling out climate change-induced productivity changes in European forests?" *Environmental Research Letters* 12(3):034027. <https://doi.org/10.1088/1748-9326/aa5ef1>

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**I. INTRODUCTION**

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In Portugal, cork oak (*Quercus suber* L.) is the main forest tree species of the traditional system called *Montado*, most often managed in combination with agriculture or pastoral activities. This system is characterized by low density of trees about 66 trees/ha (AFN 2010). The cork oak forest area is the second most important forest coverage, representing 23% of the forest area (ICNF 2013). Cork is the main economic production that is extracted at a minimum interval of 9 years, according to the national legislation. The economic return depends on cork price and market fluctuations, emphasizing the importance of the multifunctional management and the impact of forest management on tree and cork growth. Thus, an analysis of competition status in cork oak stands may contribute with knowledge that could be expressed in tools to support management decision.

Competition is defined as an interaction between individuals that shared a required resource with limited supply, which may lead to a reduction in growth, reproduction and/or survival (Begon *et al.* 1986). Competition may be a key process but facilitation processes also occur (e.g. Callaway 1995). In fact, the presence of shrubs may be positive for soil functions, as it reduces soil surface temperature and increases soil water content and nutrient content beneath shrub canopies. Despite the negative effects of competition for water and light among species, according to some authors (e.g. Gómez-Rey *et al.* 2013, Marañón *et al.* 2009, Moreno & Obrador 2007). Burkhart & Tomé (2012) made the state-of-the-art on how to take into account local competition in tree growth modelling, describing traditional competition measures and, identifying new indices with a more mechanistic methodology. When comparing growth models that include distance-dependent against distance-independent indices, an improvement in precision would be expected. However, some studies did not find a clear improvement (e.g. Soares & Tomé 1999). This can be explained by the knowledge gap in plant-to-plant interactions that makes the development of biologically consistent competition indices a challenge. Paulo *et al.* (2002) explored the effect of intraspecific competition in cork oak stands focusing on tree diameter and crown width, and presented a list of distance-dependent competition indices that significantly correlated with those variables. Other factors such as climate and cork age have proven to affect cork oak growth patterns. Throughout a cork growth rotation cycle a negative correlation with cork age was observed (Pereira 2007). In the Mediterranean area, cork oak grows from spring to autumn (April-October) followed by a dormancy period during winter (e.g. Costa *et al.* 2003). Some previous studies focusing on the impact of climate on cork growth have shown a positive correlation with precipitation, indicating a climatic influence on cork growth distribution (e.g. Caritat *et al.* 2000, Oliveira *et al.* 2016). Sánchez-González *et al.* (2006) attest that in the Mediterranean area, competition for water and soil nutrients may be more relevant than competition for light.

The present work aimed to contribute to improve the knowledge about plant-to-plant interactions in the *Montado* ecosystem, assessing the effect of the neighbourhood vegetation, on the cork growth and on the tree growth, considering the stages of tree life cycle. This research intends to answer two questions that may be relevant to support management decisions:

- (i) How does the neighbourhood understory affect the tree and cork growth?
- (ii) What is the impact of local tree density on tree growth in cork oak stands?

### **I.1. Evaluation of the neighbourhood effect on tree and cork growth**

The literature review did not show many studies focusing on the effect of local vegetation on tree and cork growth in cork oak woodlands. The comparative study of Caritat *et al.* (1999) for cork oak trees growing with or without shrubs showed no substantial effects of shrubs presence on radial growth, but significant differences were found in relation to apical elongation that was higher in the absence of shrubs. This increment on shoot growth can be explained by the decrease in plant competition and by the nutrient contribution from grazing. Martín *et al.* (2014) assessed the effects of climate, competition, topography, and initial stem diameter on stem girth increment in holm oak trees and concluded that tree initial size and competition can explain the growth response to climate. The same authors even suggest silvicultural management practices as a form to mitigate climate effects by reducing competition, especially in dense forests. On a follow-up study assessing the impacts of understory and soil management practices on holm oak growth, no significant effects were found (Martín *et al.* 2015). However, cork oak trees in stands invaded by shrubs when affected by extreme drought events evidenced high vulnerability to hydraulic failure (Caldeira *et al.* 2015).

To complement the existing studies, the research carried out under the scope of this PhD was mostly based on data from an understory management trial established in 2003, in an uneven aged cork oak stand located on a private property near Montargil village, on the Tagus basin. The experimental trial implemented as a complete randomized block design, followed by the ForChange Group since its establishment, tested different understory management alternatives comparing a periodical lupine seeding with spontaneous shrubs species maintenance. A sub-set of trees within the trial had consecutive cork samples taken at debarking years from 2003 to 2012 and from 2006 (prior to this PhD research was initiated) to 2015 (the last at PhD candidate responsibility). Under the PhD work, the cork rings were visually marked and their width measured using the image analysis software ImageJ (Ferreira & Rasband 2010; Schneider *et al.* 2012). Two studies were conducted based on the collected

cork samples. The first study (Faias *et al.* 2018, subchapter II.1 of this manuscript) used this data along one cork rotation of 9 years (2003 and 2012) for comparing the tree radial growth and the cork annual growth response under the two understory management alternatives. The second study (Faias *et al.* 2019 in subchapter II.2) focused on the cork samples from 2006, 2012 and 2015 in order to analyse the impact on understory operations at the beginning or at the middle of the cork rotation cycle. This study analysed the effect of potential drivers on cork annual growth: intraspecific competition, assessed by tree level distance-dependent indices, and interspecific competition, assessed by variables characterizing the understory management. On both studies, the differences between understory management alternatives were assessed by fitting linear mixed models, due to the nested structure of the data, trees inside plots and plots inside blocks.

The debarked trees from one block of *Montargil* trial were continuously monitored between 2016 and 2019, when three different understory treatments were applied. The previous plot with no vegetation control was maintained in the same place. Two other treatments were performed incorporating the understory removed into the soil, in the plot with previous lupine seeding, and adding another plot with NP fertilization. Trees were selected on each plot to monthly monitorize their diameter increment with band dendrometers. For assessing the effect of the treatments on the nutrient uptake by trees, leaves were seasonally sampled in the monitored trees, and their specific leaf area (SLA) and N, P and K contents were assessed. In this study, described in subchapter II.3, a parametric approach to identify seasonal variation patterns in SLA and nutrient leaf content under the different understory management alternatives and debarking ages. A linear mixed model was also developed for the diameter increment, considering simultaneously the management alternatives and temporal correlations.

## **I.2. Evaluation of local density effect on tree growth**

Competition influences not only tree growth patterns but also the stand structure. Perry (1985) describes the competition process in forest stands focusing its impact on the evolution of stand structure and on the relationship between individual tree relative growth rate and tree size. This relationship is a decreasing exponential in young stands before competition onsets, levelling out at the start of asymmetric competition and following an increasing trend when small trees become totally dominated by the large trees. These growth patterns were observed for eucalyptus stands in Soares & Tomé (1996). Sánchez-González *et al.* (2006) support that tree size reflects the effect of past competition, expressed through the inclusion of symmetric stand density variables in the tree diameter increment models indicating that. Del Rio *et al.*

(2014) studied the symmetry/asymmetry pattern of competition in mixed stands using competition indices formulated with all the trees or only those larger than the subject tree

Data from the network of cork oak permanent plots maintained by ForChange research group were used to (CEF-ISA/ULisboa) for the studies described in subchapters III.2 and III.3. The network covers the area of cork oak distribution in Portugal and comprises plots in juvenile stands, undebarked mature stands and mature debarked stands.

The study described in subchapter III.2 followed the methodology proposed by Perry (1985) to analyze the impact of competition on stand structure using repeated measurements from juvenile stands and undebarked mature stands. Stand structure was analyzed by computing the coefficients of asymmetry, skewness and kurtosis of the tree diameter distributions, as well as, the Gini coefficient that gives information of stand variability. Additionally, was assessed the relationship between the individual tree relative growth rate (RGR) over tree size, concerning the tree diameter.

The repeated measurements from mature debarked stands were used to perform two studies. One related to tree crown width modelling (Paulo *et al.* 2016 in subchapter III.1) and another to the tree diameter increment modelling described in subchapter III.3. Additionally to tree size, both studies focused on the inclusion of competition measures, which were evaluated by testing the significance of distance-independent competition indices.

The study in subchapter III.1 aimed to develop a tree crown diameter model over a large range of tree dimensions. Due to the nested structure of the data analyzed – trees within stands – a mixed model approach was conducted and compared to fixed-effect model fitted with the ordinary least squares method. Several candidate model from the list proposed by Paulo *et al.* (2011) were tested.

The later study aimed to develop an Iberian model for tree diameter increment. For that reason the Portuguese dataset was combined with a shared dataset from INIA-CIFOR network, with measurements on plots across the cork oak species area in Spain. Two approaches to predict diameter growth were compared: an aged independent difference equation method, a potential growth function multiplied by a modifier exponential function bounded between 0 and 1 to express inter-tree competition. The Richards growth function, formulated as an age-independent difference equation, was indicated by previous authors (Almeida *et al.* 2010, Tomé *et al.* 2006, Sánchez-González *et al.* 2005) to be the most appropriate for cork oak. The Richards function was used to develop the age-independent difference equation and potential growth equation.

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**II. How does the neighbourhood vegetation affect the tree and cork growth?**

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**Title**                    **II.1. Understory effect on tree and cork growth in cork oak woodlands**

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## Understory effect on tree and cork growth in cork oak woodlands

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### Abstract

**Aim of study:** Cork oak is one of the main forest tree species in Portugal that typically occurs in *montado*, where operational practices oriented to the tree, crop or animal management may influence several of the ecosystem components. This study aimed at contributing to fulfil the a lack of knowledge on the effect of these practices on the cork and wood growth, by comparing the wood diameter growth and the annual cork increment under two different understory management options.

**Material and methods:** An experimental trial implemented on an uneven-aged cork oak pure stand during a cork rotation period of 9 years, was established with the specific goal of comparing understory management options: a yellow lupine pasture *versus* spontaneous vegetation. Cork samples were taken at the beginning and end of the period and were used to measure cork thickness and annual cork rings. The differences between treatments were assessed performing a non-parametric test and a more robust approach using linear mixed model. Precipitation and treatment levels were jointly considered on the analysis.

**Main results:** A slight effect was found on the cork thickness regarding the treatment with lupine application. However, no distinct effect was found, regarding wood and the annual cork increment pattern. Additionally, annual cork ring width showed a positive correlation with precipitation and a negative correlation with ring age.

**Research highlights:** The results of this study indicate no distinct pattern regarding the annual cork and wood increment when comparing the understory effect of yellow lupine pasture *versus* spontaneous vegetation.

**Additional keywords:** *Quercus suber*, cork thickness; cork ring; lupine; shrubs; linear mixed model.

**Abbreviations used:** AIC (Akaike information criterion); Cc (crown cover percentage); du (diameter at breast height under cork); dug (quadratic diameter at breast height under cork); idu (wood diameter increment); KW (Kruskal-Wallis); M (percentage of dead trees); MSE (mean square error); N (number of trees per hectare); NUR (no understory removal); OM (organic matter); RUL (understory removal with lupine seeding); *rw* (annual cork ring width).

**Authors' contributions:** Conception, design and implementation of the trial: MT and JAP. Data collection and analysis: SPF and JAP. Drafting of the paper: SPF and JAP. Revision of the intellectual content: MT and JHNP. All authors read and approved the final manuscript.

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### Introduction

Cork oak (*Quercus suber*) is a Mediterranean species covering a worldwide area of 2,139,942 ha (APCOR, 2016), from which the tree bark (cork) is extracted and used as raw material of an industry that is responsible for a total value of exportations of 1,430 million € (APCOR, 2016). In Portugal, a country responsible for supplying 49.6% of the world cork production (APCOR, 2016), this tree plays a key role mostly in the southern rural areas. It is the main forest species present in the traditional silvopastoral system called *montado*, which is characterized by tree densities

around 66 trees/ha, according to the last published official data (AFN, 2010).

In *montado*, management practices are oriented not only for cork extraction purposes, but also for grazing or crop production, which may have influence on several ecosystem components (e.g. Pinto-Correia *et al.*, 2011; Paulo *et al.*, 2016a). Under a silvopastoral management, it is a common practice to periodically install a legume rich pasture in the understory, such as *Lupinus luteus*, with the expectation of improving soil fertility and decrease the need of external input for animal forrage (e.g. Callaway, 1995; Teixeira *et al.*, 2011). When animals are not present, the spontaneous

vegetation is periodically mechanically removed, reducing the fuel component to avoid fire hazard. These mechanization processes, have been referred to have a negative impact on soil compactation and affect the tree roots development contributing to the tree decline (e.g. Dinis *et al.*, 2015).

It is expected that interspecific competition between the trees and the understory influences tree growth patterns, along with intraspecific competition and stand structure, depending on the species, environment and management conditions. In Mediterranean cork oak stands, Sánchez-González *et al.* (2006) found out that tree diameter growth is negatively influenced by increasing stand density, however Paulo *et al.* (2016b) did not find the same pattern. Regarding the competition between trees and the understory species in the neighbourhood, diverse relationships should be considered. The presence of understory may be positive for some soil functions as it contributes to the nutrient content (Moreno & Obrador, 2007), and may influence tree natural regeneration (Pulido & Díaz, 2005). The *Cistus* species is a common spontaneous species in the cork oak woodland understory, that is reported to promote different soil C/N ratios (Gómez-Rey *et al.*, 2013). According to Correia *et al.* (2014), the *Cistus salvifolius* species success relates to a high shadow tolerance and a fast water uptake in short precipitation events. Caldeira *et al.* (2015) experimental results with *Cistus ladanifer* indicate that this species is more tolerant to low soil water potential and dry soil conditions than cork oak trees.

Several studies focus on the prediction of cork growth evolution (e.g. Sánchez-González *et al.*, 2007; Almeida *et al.*, 2010; Paulo *et al.*, 2016b); however, few studies are available when focusing the effect of competition between trees and understory species. This is even more evident when considering the cork oak species, where both the effect on tree wood growth and on cork growth are of interest. Caritat *et al.* (1999) indicated that there is no significant effect of shrubs presence on cork tree radial growth, although apical elongation was higher in the absence of shrubs. Similar results were found by Martín *et al.* (2015) for the holm oak species, since no significant effects were found on tree growth when comparing understory and soil management practices. Thus, no results were found when considering cork and wood differentiation growth.

To increase our understanding on the effects of the understory on the cork and tree growth, this study focuses not only in wood diameter growth, but also in the cork annual growth. The research addresses the following question: do trees have a similar increment pattern regarding wood and cork, when growing under two different understory management options?

## Material and methods

### Trial description

The experimental trial was located in Portugal Center, near the Montargil village (39°3.242'N, 8°10.588'W) and implemented in 2003, in an uneven-aged mature cork oak stand. The stand was characterized by an average of 101 trees/ha, where the major percentage of trees have already been debarked. There were two different cork rotation cycles within the stand: from 2003 to 2012 and from 2006 to 2015, the years in which cork stripping was performed. The understory layer, composed by spontaneous vegetation dominated by the *Cistus salvifolius*, alongside with sparsely distributed *Rosmarinus officinalis* and *Ulex airensis*, was characterized by a phytomass of 0.35 kg/m<sup>3</sup> at the age of 4 years. From 1994 to 2003 the understory was mechanically removed with an interval of 3 to 4 years. Accessing the digital cartography available at the Portuguese Agency for the Environment website (<http://sniamb.apambiente.pt/webatlas/>) soils were classified as Podzols, according to the IUSS Working Group WRB (2006). Plot determination of pH and organic matter percentage (OM) was done in 2009 (Table 1).

The trial focused on the comparison of two different understory management options, from now on designated as treatments, implemented as a complete randomized block design. Each block consisted of two quadrangular plots with 2 ha, allowing the delimitation of a 20 m border to ensure no impact of non-treated areas on the trees used for the experiment. The first treatment consisted in the maintenance of spontaneous understory vegetation during the complete cork debarking rotation period (NUR, no understory removal). The second treatment consisted on the periodical removal of the understory with incorporation of organic matter into the soil, followed by the seeding of *Lupinus luteus* (RUL, understory removal with lupine seeding). This treatment was repeated along the cork debarking rotation period in 2003, 2007 and 2009. After each application, visual assessment on the success of the lupine germination rate was made in the field.

### Tree measurements

Measurements of tree diameter at breast height after debarking (*du*) were carried out at each debarking year, in 2003 and 2012, for all the trees inside the plots after being debarked. The wood diameter increment (*idu*) was computed as the difference between the diameter at breast height under cork (*du*) from the debarked trees measured in 2012 and 2003 ( $n_{\text{block1}} = 302$ ;  $n_{\text{block2}} = 229$ ). The stand characteristics were computed at the beginning and

at the end of the period, namely: number of trees per hectare (N); the quadratic diameter at breast height under cork (dug) and crown cover percentage (Cc) (Table 1).

### Cork samples collected

In 2003 and 2012, cork samples with approximately 20 cm × 20 cm, were taken at breast height from the debarked trees. Samples from 2003 cover the cork growth period between 1994 and 2003, when the understorey was mechanically removed with an interval of 3 to 4 years. Samples from 2012 cover the cork growth period between 2003 and 2012, when the understorey management was differentiated by the treatments implementation. All samples were boiled during 1 hour in water at 100°C and atmospheric pressure, and left to air-dry in well ventilated conditions until equilibrium. The aim is to decrease internal tensions, caused by the cellular corrugation during cork growth, that are particularly important in the radial direction where cork thickness is measured (Pereira, 2007). Cork thickness before and after boiling was measured on each cork sample using a digital caliper ( $n_{\text{block1}} = 94$ ;  $n_{\text{block2}} = 57$ ). Annual cork growth rings, a total of 8 complete rings, were measured, after been visually identified on at least two positions, using the image analysis software *ImageJ* (Ferreira & Rasband, 2010; Schneider *et al.*, 2012). This procedure was carried out only in the trees having the cork samples in both debarking years where the rings were unmistakable marked ( $n_{\text{Block1}} = 75$ ;  $n_{\text{Block2}} = 51$ ).

### Climate data

According to the known relationship between annual cork growth and precipitation (*e.g.* Caritat *et al.*, 2000; Paulo *et al.*, 2016b), values of monthly precipitation for

the 1994 to 2012 period were gathered from the nearest meteorological station in Montargil, available at the network SNIRH - Sistema Nacional de Informação de Recursos Hídricos ([www.snirh.pt](http://www.snirh.pt)).

### Data analysis

As a first step, the cork thickness, the annual cork ring width and the wood diameter increment measurements were used for a preliminary graphical analysis. The empirical distributions of the cork thickness and of the annual cork ring width were compared among treatments and separately for each block. The hypotheses to test were: 1) the distributions were not significantly different in 2003; 2) the distributions became significantly different in 2012, after the treatments application. The hypotheses were tested using the non-parametric statistical test of Kruskal-Wallis (McDonald, 2014), separately for the cork samples of 2003 (previous to the trial establishment) and for the cork samples of 2012 (subject to the trial treatments: RUL and NUR). The annual cork ring width was tested for each ring year. These analyses were evaluated ( $\alpha = 0.05$ ), with the PROC NPAR1WAY procedure of the SAS 9.3 (SAS Inst., 2011).

### Modelling approach

Although the trial was established following a complete randomized block design, due to the nested structure of the data, trees inside plots and plots inside blocks, the data analysis was carried out using a mixed modelling approach. This parametric approach is particularly suitable for data referring to growth curves since it considers not only the nested structure of the data, but also the correlation from the repeated measures taken on the same individuals (*e.g.* Pinheiro

**Table 1.** Plot characterization by block, inventory year and treatment, where RUL is the treatment with understorey removal and lupine pasture and NUR is the treatment with spontaneous understorey vegetation maintenance.

Block	Treatment	Year	dug	N	Cc (%)	M (%)	pH	OM (%)
1	RUL	2003	27.5	132	55	1	5.5	1.82
		2012	28.6	131	58			
	NUR	2003	27.9	127	53	12	6.1	1.47
		2012	28.1	114	49			
2	RUL	2003	36.1	86	53	22	5.6	1.45
		2012	37.6	71	46			
	NUR	2003	33.6	100	55	11	5.7	1.37
		2012	35.7	91	56			

dug, quadratic diameter at breast height under cork (cm); N, number of trees/ha; Cc, crown cover percentage; M, percentage of dead trees; OM, organic matter percentage.

& Bates, 2000), specifically the eight complete rings of each cork sample.

For the cork annual growth, a linear mixed model was developed using the samples from 2012. The development of this model was preceded by the selection of the precipitation variable that was best related to the variable cork annual growth. The potential variables were retrieved from the list presented by Caritat *et al.* (2000) and were computed between October 1<sup>st</sup> of the year before the growth period and September 30<sup>th</sup> of the growth period year. This process was performed by fitting the following fixed base model:

$$rw_i = \beta_0 + \beta_1 t_i + \beta_2 P_i + \varepsilon_i, \quad [1]$$

where  $rw$  is annual cork ring width (mm) of the tree  $i$ ;  $t$  is the cork age;  $P$  is the volume of precipitation for a specific period;  $\beta_0, \beta_1, \beta_2$  are the fixed effects parameters and  $\varepsilon_i$  is the error term.

The selected precipitation variable was the one that resulted in the lower value of the mean square error (MSE) and Akaike information criterion (AIC). The fitting of the linear mixed model was then carried out by adding to the base model (Eq. [1]), a dummy variable concerning the treatment with lupine (RUL), a variable regarding the interaction between the cork age and the treatment, and the plot's random effects.

Additionally, a linear mixed model was developed for the tree wood diameter increment that included variables of the initial tree diameter, the dummy variable concerning the treatment with lupine (RUL), and the plot's random effects. The tree wood diameter increment, was assessed between the two consecutive cork extractions, performing 9 years growth. The dataset considered for fitting included all the debarked trees measured in 2003 and 2012.

All models were fitted using the procedure PROC MIXED of the software SAS 9.3 (SAS Inst., 2011). The variance components were used for the covariance structure. The RANDOM statement was applied to specify the random effects associated to the plot levels. The random effect parameter was tested in all the fixed parameters, and the selection criteria for its inclusion in the model was the lowest AIC value. For each developed model, the significance of the parameters estimates were evaluated considering  $\alpha = 0.05$ .

## Results

### Treatment effect in cork growth

There was a clear decrease in the cork thickness measured after boiling, assessing the 2003 and 2012 subset samples observed in both blocks (Fig. 1). The

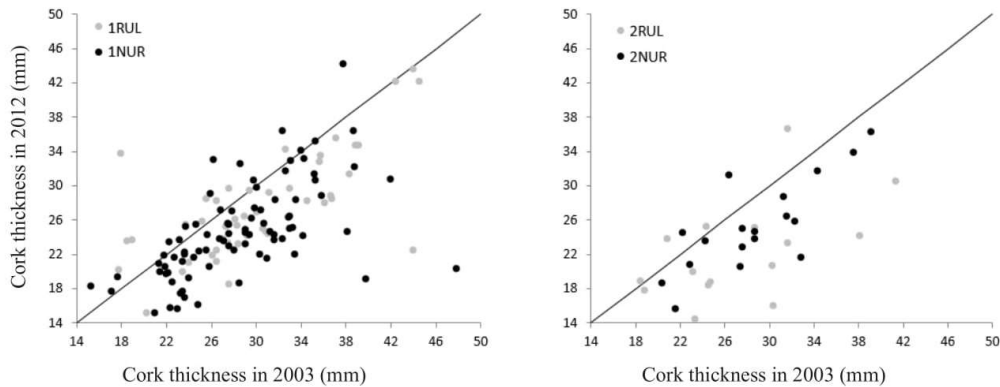
Kruskal-Wallis (KW) results performed for the cork thickness empirical distribution for the 2003 samples presented no significant difference between treatments in both blocks ( $p=0.2246$  in block 1;  $p=0.5388$  in block 2). This confirms that at the beginning of the trial the plots were similar. The KW test results obtained for the cork thickness, using the 2012 samples, indicate a significant difference between NUR and RUL treatments in block 1 ( $p=0.0007$ , mean RUL = 27.62, mean NUR = 23.15), but no significant difference in block 2 ( $p=0.2995$ , mean RUL = 24.45, mean NUR = 26.37).

When visualizing the annual cork ring width of each treatment (Fig. 2), no similar pattern was found in either blocks, for each subset of cork samples, 2003 and 2012. Regarding the KW test results for the annual cork ring width using the 2003 samples, no significant difference was found between the two blocks (results not presented), confirming once more that both blocks were similar before the trial establishment. While, the KW test results for the annual cork ring mean width using the 2012 samples showed significant differences between NUR and RUL treatments on block 1 for the years: 2004, 2005 and 2009, all corresponding to the year of lupine seeding or the following year (Table 2). The only exception in block 1 was the year 2007 (Table 2), however the lupine seeding in this year was applied under unsuitable precipitation and soil humidity conditions, resulting in a low germination rate of the lupine during the following year. The KW test results or the annual cork ring width of block 2 were not the same when comparing NUR and RUL treatments, only in 2010 the annual cork ring distribution was different between the treatments (Table 2).

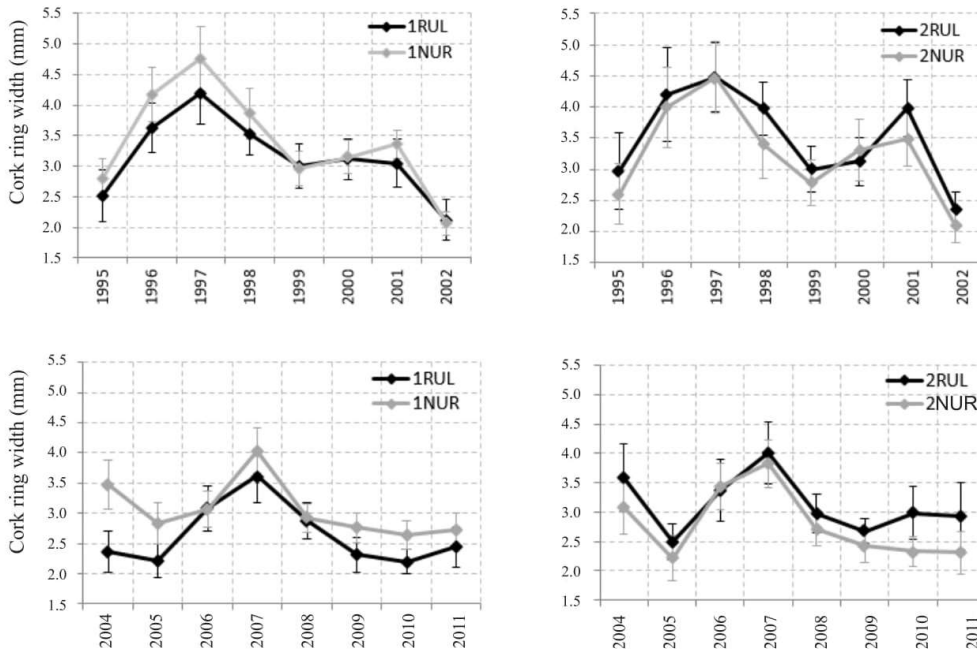
Regarding the annual cork ring width model, the precipitation variable included was the one selected according to the MSE and AIC lower values: the annual precipitation for the period between October 1<sup>st</sup> of the year before the growth period and September 30<sup>th</sup> of the growth period year (Table 3). For this model, the random effect was more significant when added only to the intercept parameter, since it was not possible to obtain convergence with more than one random effect. Thus, the full random effect model defined was:

$$rw_{2012_{ij}} = (\beta_0 + \mu_{0_j}) + \beta_1 t_i + \beta_2 P_i + \beta_3 RUL_j + \beta_4 (t_i \times RUL_j) + \varepsilon_{ij}, \quad [2]$$

where  $rw$  is the annual cork ring width of the tree  $i$ ;  $t$  is the cork age;  $P$  is the volume of precipitation for a given period;  $RUL$  is the variable regarding the treatment with lupine;  $\beta_0, \beta_1, \beta_2, \beta_3$  are the fixed effects parameters;  $\mu_{0_j}$  is the random effect associated to plot  $j$  and  $\varepsilon_{ij}$  is the error term.



**Figure 1.** Relationship between the cork thickness in both debarking years, 2012 and 2003. Block 1 on the left and block 2 on the right. RUL is for the treatment with understory removal and lupine pasture; NUR is for the treatment with spontaneous understory vegetation maintenance.



**Figure 2.** Annual cork ring mean width during 8 complete years of cork production for each subset of cork samples, 2003 (top) and 2012 (bottom), by treatment for each block. Block 1 on the left and block 2 on the right. RUL is for the treatment with understory removal and lupine pasture; NUR is for the treatment with spontaneous understory vegetation maintenance.

For the full fitted model (Eq. 2), the parameters estimates for  $P$  and  $t$  were statistical significant and showing a positive correlation with precipitation and a negative correlation with ring age (Table 4). The treatment with lupine (RUL) was not significant, while the interaction between the cork age and the

RUL treatment was significant. However, when excluding the RUL variable, this interaction was also not statistical significant. The random effects term were not significantly different from zero for any of the plots. Thus, the final random effect model only included precipitation and cork ring age (Table 4),

**Table 2.** Comparison of the annual cork ring width (mm) distribution using the Kruskal-Wallis test (KW) for the 2012 sample.

Year	Lupine seeding	Rain (mm)	1 <sup>st</sup> Block			2 <sup>nd</sup> Block		
			RUL mean	NUR Mean	<i>p</i> -value	RUL mean	NUR mean	<i>p</i> -value
2003	Yes	614.8	2.12	1.68	–	1.83	2.19	–
2004	No	449.1	3.31	2.31	0.0006	3.04	3.24	0.7345
2005	No	251.1	2.79	2.20	0.0154	2.25	2.72	0.0705
2006	No	500.8	3.11	3.02	0.7405	3.47	3.25	0.3965
2007	Yes	844.9	4.03	3.56	0.1023	3.81	3.79	0.7919
2008	No	427.5	2.96	2.79	0.4629	2.73	2.98	0.3758
2009	Yes	396.9	2.75	2.25	0.0081	2.45	2.77	0.3707
2010	No	623.6	2.55	2.23	0.1059	2.35	2.89	0.0288
2011	No	587.3	2.73	2.37	0.0562	2.25	2.68	0.2870
2012	No	806.5	1.08	1.01	–	1.11	1.00	–

RUL= understory removal with lupine seeding. NUR= no understory removal.

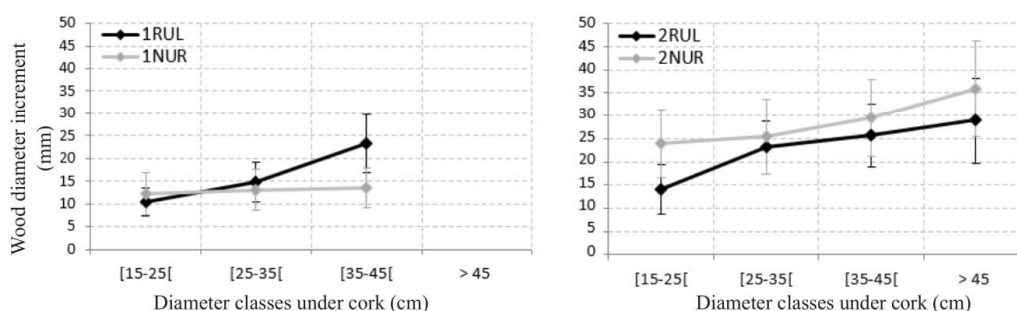
which is an indication that the treatments are not different concerning their influence in annual cork ring increment.

#### Treatment effect in tree wood diameter increment

The wood mean diameter increment plot with diameter classes showed no similar pattern on the treatments by block (Fig. 3). For the wood mean diameter increment model, the random effect was also more significant when added to the intercept parameter. The full random effect model defined was:

$$idu_{ij} = (\beta_0 + \mu_{0j}) + \beta_1 du_{2003i} + \beta_2 RUL_j + \varepsilon_{ij}, \quad [3]$$

where  $idu$  is the wood diameter increment (mm) for the debarking period of tree  $i$ ;  $du_{2003}$  is the tree diameter under cork measured in 2003;  $RUL$  is the variable regarding the treatment with lupine;  $\beta_0, \beta_1, \beta_2$  are the fixed parameters;  $\mu_0$  is the random effect associated to plot  $j$  and  $\varepsilon_{ij}$  is the error term.



**Figure 3.** Wood diameter mean increment (mm), between 2003 and 2012, by diameter at breast height class (under cork) for each treatment. Block 1 on the left and block 2 on the right. RUL is for the treatment with understory removal and lupine pasture; NUR is for the treatment with spontaneous understory vegetation maintenance.

**Table 3.** Selection of the period of precipitation to be considered in the model, its respective mean square error (MSE) and Akaike information criterion (AIC) for the cork growth models fitted with fixed effects.

Precipitation variable (defined by the period considered)	Model	
	MSE	AIC
March <sub>(t)</sub> to June <sub>(t)</sub>	1.9712	5422.8
March <sub>(t)</sub> to May <sub>(t)</sub>	2.5306	5806.0
March <sub>(t)</sub> to September <sub>(t)</sub>	1.8495	5326.2
January <sub>(t)</sub> to June <sub>(t)</sub>	2.0706	5500.0
January <sub>(t)</sub> to September <sub>(t)</sub>	2.0444	5480.5
June <sub>(t)</sub> to September <sub>(t)</sub>	2.3202	5673.4
October <sub>(t-1)</sub> to September <sub>(t)</sub>	1.7569	5249.6
October <sub>(t-1)</sub> to June <sub>(t)</sub>	1.8590	5336.1
October <sub>(t-1)</sub> to December <sub>(t-1)</sub>	2.1945	5589.8

t: year of the growth period

of cork thickness and cork ring width under two distinct understorey management regimes. This is one of the study main features, since it allowed to characterize the annual cork growth rates and distributions previous to the treatments application, demonstrating that not only management was similar along the four different plots, but also that the cork annual growth presented equal distributions among the four plots.

Cork thickness decreased from the 2003 to the 2012 samples, irrespective of the treatment, which may be the result of a decrease of total precipitation within the second debarking period, and in line with the existing literature on the relationship between annual cork growth and climate conditions (e.g. Caritat *et al.*, 2000). The fitted model for the annual cork ring width showed a positive correlation with precipitation, as shown in several other studies (e.g. Paulo *et al.*, 2016b; Oliveira *et al.*, 2016). Regarding the cork ring age, a negative correlation was obtained, as expected from known studies (e.g. Costa *et al.*, 2002; Pereira, 2007; Oliveira *et al.*, 2016), that showed a decrease of the annual cork width trend along the cork debarking period. The inclusion of precipitation and cork age variables in the fitted baseline model for annual cork growth, allowed to isolate the treatment effect, as well as, the plot and block random effects.

No difference was found between the two understorey treatments regarding their influence in annual cork width or wood diameter increment, in line with Caritat *et al.* (1999) related study, in which the results for a sample of 10 trees by treatment did not show significant

differences between the treatments. Nevertheless, it was also observed that plots in both blocks did not present a similar response to the treatments. One block presented a small positive effect of the understorey removal treatment, with an increase of less than 1 mm on the mean annual cork growth, when the lupine was applied or in the following year, whereas in the other block a small effect was detected only in one year. Looking at the annual response of the tree to the treatments, it was observed that although the lupine installation may favour cork increment one or two years after application, this effect could also be inexistent in years when unfavourable conditions prevailed. The increments lower than 1 mm are not expected to have an impact in the cork price and the resulting farm income (Paulo & Tomé, 2017). This varying effect suggests that site characteristics, such as soil and stand structure, may influence the impact of different management options, but that these may also be related to annual climate conditions (Sánchez-González *et al.*, 2007).

Mechanical operations such as the ones carried out for understorey removal, may affect the tree roots development, contribute to the tree decline (e.g. David *et al.*, 2013), or limit cork oak regeneration (e.g. Arosa *et al.*, 2017). These operations being frequently performed may slow the full recovery of understorey composition and structure as evidence in Santana *et al.* (2011). We recommend that management plans should be frequently reviewed, at the stand scale, regarding the conditions, the management goals such as the cork and cattle production, the tree regeneration, the fire hazard reduction and the biodiversity conservation, following an adaptive management strategy (e.g. Aronson *et al.*, 2009).

## Conclusion

The data used for this study, were collected from a trial established with the specific goal to contribute for understanding the effects of the understorey on the cork and tree growth. The study outcome indicates no effect, for this site, regarding cork or wood increment pattern, when comparing the understorey effect of yellow lupine pasture *versus* spontaneous vegetation. The cork thickness variability between trees and the individual tree response to annual climate conditions is more determinant to the final cork thickness than the management alternatives considered in this research. Nevertheless, the differences found across the two blocks suggest that site characteristics should be explored in further research. The follow-up monitoring of this trial and the establishment of

**Table 4.** Parameters estimates for the annual cork ring width (*rw*) random fitted models from Eq. [2] ( $AIC_{Full} = 2184$ ;  $AIC_{Final} = 2182$ ).

	Full model				Final model			
	Estimate	<i>p</i> -value	Lower	Upper	Estimate	<i>p</i> -value	Lower	Upper
<b>Fixed</b>								
$\beta_0$	2.1913	0.0119	1.1518	3.2308	2.3635	0.0007	1.8358	2.8911
$\beta_{1tc}$	-0.1016	<0.0001	-0.1434	-0.0598	-0.1290	<0.0001	-0.1613	-0.0967
$\beta_{2Pr}$	0.0024	<0.0001	0.0019	0.0028	0.0024	<0.0001	0.0019	0.0028
$\beta_{3RUL}$	0.3915	0.2306	-0.2491	1.0321	–	–	–	–
$\beta_{4tc \times RUL}$	-0.0625	0.0443	-0.1235	-0.0016	–	–	–	–
<b>Random</b>								
$\mu_{011}$	0.1229	0.5316	-0.2627	0.5086	0.1403	0.2668	-0.1076	0.3882
$\mu_{012}$	-0.1229	0.5316	-0.5086	0.2627	-0.0955	0.4402	-0.3382	0.1472
$\mu_{021}$	-0.227	0.2469	-0.6115	0.1576	-0.2424	0.0447	-0.4790	-0.0058
$\mu_{022}$	0.227	0.2469	-0.1576	0.6115	0.1975	0.1220	-0.0529	0.4479
<b>Cov. Parm</b>								
intercept $\mu_0$	0.0718	–	0.01827	4.6625	0.04713	–	0.01389	1.0591
Residual	0.9566	–	0.8673	1.0604	0.9604	–	0.8708	1.0646

**Table 5.** Parameters estimates for the wood diameter increment (*idu*) linear mixed fitted models from Eq. [3] ( $AIC_{Full} = 1884$ ;  $AIC_{Final} = 1892$ ).

	Full model				Final model			
	Estimate	<i>p</i> -value	Lower	Upper	Estimate	<i>p</i> -value	Lower	Upper
<b>Fixed</b>								
$\beta_0$	1.1489	0.1476	-0.9956	3.2933	–	–	–	–
$\beta_{1du_{2003}}$	0.0207	0.0185	0.0035	0.0379	0.0287	0.007	0.01	0.0438
$\beta_{2RUL}$	0.0274	0.9631	-1.1358	1.1906	–	–	–	–
<b>Random</b>								
$\mu_{011}$	-0.3198	0.4471	-1.1456	0.5060	0.6044	0.016	0.1131	1.0957
$\mu_{012}$	0.3198	0.4471	-0.5060	1.1456	1.2090	<0.0001	0.6107	1.8074
$\mu_{021}$	-0.4662	0.2643	-1.2857	0.3534	0.4248	0.0917	-0.0691	0.9186
$\mu_{022}$	0.4662	0.2643	-0.3534	1.2857	1.3574	<0.0001	0.8178	1.8970
<b>Cov. Parm</b>								
intercept $\mu_0$	0.3352	–	0.0872	18.019	1.0354	–	0.3004	25.716
Residual	1.9551	–	1.7388	2.2147	1.9580	–	1.741	2.2185

similar trials is needed in order to clarify the long-term tree response in consecutive cork debarking periods and in different environmental and structural stand characteristics.

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**Title**                    **II.2. Drivers for annual cork growth under two understory management alternatives on a Podzolic cork oak stand**

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Article

# Drivers for Annual Cork Growth under Two Understory Management Alternatives on a Podzolic Cork Oak Stand

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**Abstract:** Understory management practices and stand density characteristics allow one to distinguish a cork oak traditional silvopastoral system (known as a *montado*) from a cork oak forest system. Although understanding the manner in which different management practices affect cork growth is imperative, there are still only a few outputs from experimental research that contribute to this knowledge. The effect of potential drivers on annual cork growth was analyzed using a linear mixed model approach. Two dimensions of drivers were considered: intraspecific competition, assessed by tree level distance-dependent indices; and interspecific competition, assessed by variables characterizing understory management. The present dataset was collected from an experimental trial established on a cork oak stand in Podzolic soil on the Tagus river basin, covering two different cork growth cycles over the period from 2003 to 2015. The adjusted models considered two understory management alternatives: spontaneous shrubs maintenance and forage application. In both models, annual precipitation displayed a positive effect on annual cork growth, as expected. However, no significant effect of intraspecific competition was found. Additionally, there was a positive effect on annual cork growth associated with the spontaneous shrubs growth and a negative effect associated with lupine presence; both effects linked to different cork ring ages' thresholds. The study main contributions are the following: (i) the introduction of the interaction between cork growth cycle stage and understory management practices, only possible with cork sample collections from different cork rotation cycles; (ii) the finding that there was no significant effect of intraspecific competition on cork growth.

**Keywords:** *Quercus suber* L.; *montado*; distance-dependent competition index; cork ring; shrubs; lupine

## 1. Introduction

Cork oak (*Quercus suber* L.) is an important species in the Mediterranean forest, as it provides raw material suitable for cork stoppers and other high value manufactured products. This species mainly occurs in a traditional silvopastoral system called a *montado*, characterized by low density and sparse trees. The species also occurs in a forest system with higher tree density, usually dominated by spontaneous vegetation. The Portuguese National Forest Inventory characterizes cork oak stands by an average density of around 66 trees per hectare [1], making no distinction between these two systems: *montado* and cork oak forest. Since there is no clear definition of a tree density threshold to differentiate between these two systems, they can only be distinguished by their management practices and production aims: the first is oriented for cork production, crop production and/or grazing; the second focuses mainly on cork production.

In a *montado*, the standard understory management implies mechanization practices, which may influence several ecosystem components, such as tree regeneration, soil biota, soil compaction, and/or root development (e.g., [2–5]). These practices have several aims: facilitate access to trees during the debarking operation; reduce phytovolume of a specific native or invasive shrub species; reduce fire hazard; allow permanent and improved pastures to increase forage availability for the livestock; contribute to soil fertility (e.g., [6–9]).

There are still few studies focusing on the impact of stand density and management practices on cork growth; namely, there is a clear lack of knowledge, when considering simultaneously the effect of intraspecific and interspecific competition. Caritat et al. [10] also looked for tree radial growth under distinct understory management alternatives, but did not separate wood and cork growth. Paulo et al. [11] explored the effect of intraspecific competition using distance-dependent tree competition indices, but focused on tree diameter and crown variables. Sánchez-González et al. [12] developed a total cork thickness model considering relative tree dimension variables and one single distance-independent competition index, but did not test the interaction with alternative management options. Faias et al. [13] compared the annual cork pattern growing under two distinct understory management alternatives along one cork debarking rotation cycle of 9 years, but did not consider tree intraspecific competition effect.

The dataset in this study is an extended version from the one used by Faias et al. [13], with additional cork samples extracted in the same trial from a different cork growth cycle, covering the period from 2006 to 2015. Tree coordinates, as well as understory evolution information, were also collected for the present study. This extended dataset allows us to explore not only the effect of both intra- and interspecific competition drivers on cork's annual growth, but also its interaction with the ring age due to the existence of cork samples from two different cork debarking rotation cycles. The study intends to answer the following questions that are relevant to support management decisions, such as deciding the best timing to remove the understory: (i) Is there an impact of intraspecific competition on cork growth?; (ii) What is the impact of understory (interspecific competition) management practices on cork growth?; (iii) What is the interaction between cork age and understory management?

## 2. Materials and Methods

### 2.1. Study Area and Trial Description

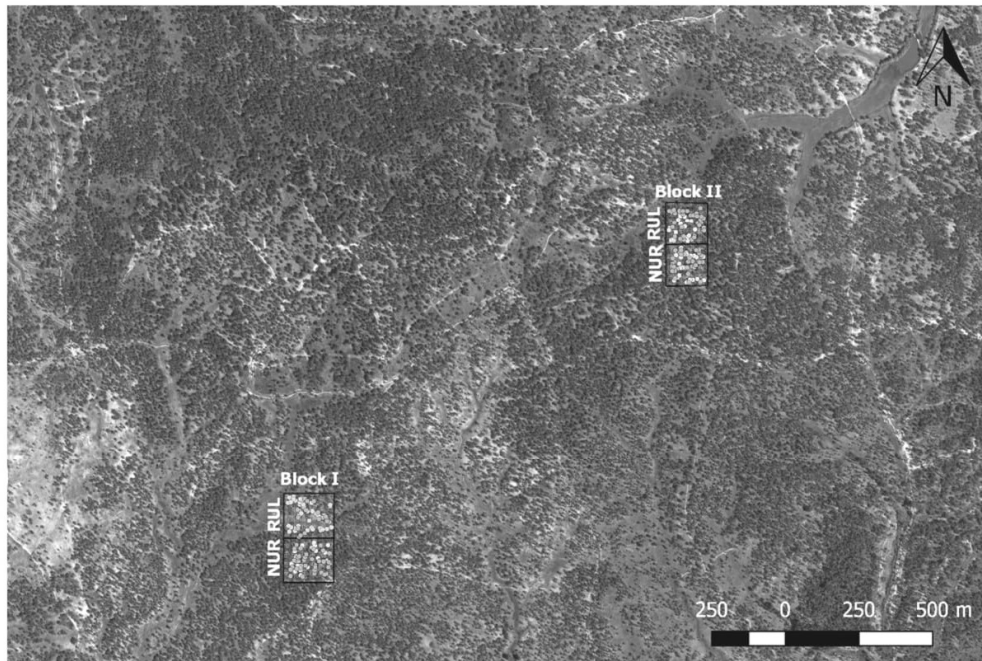
An experimental trial to compare two understory management alternatives was implemented, as a complete randomized design with two blocks, in uneven-aged cork oak stands near Montargil village (39°3.24' N, 8°10.58' W). Each block contains two quadrangular plots, with 2 hectares each, including a 20-m border to ensure no impact of non-treated areas on the monitored trees (Figure 1).

Soils were classified as Podzols, according to the IUSS (International Union of Soil Sciences) Working Group [14], available at the Portuguese Agency for the Environment website (<http://sniamb.apambiente.pt/webatlas/>). Soil samples, with pH 5.5 to 6.1 and organic matter percentage of 1.5% to 1.8%, indicated similarity between plots. Monthly precipitation was gathered from the nearest available meteorological station at the SNIRH (Sistema Nacional de Informação de Recursos Hídricos; [www.snirh.pt](http://www.snirh.pt)) network for the period included in the dataset (Table 1).

Between 2003 and 2012, two different understory management operations were performed in one plot randomly selected in each block (Figure 1): (i) periodic removal of the spontaneous shrubs species, with incorporation of organic matter into the soil, followed by the seeding of *Lupinus luteus* L. (RUL—understory removal with lupine); (ii) spontaneous shrubs species maintenance, during a cork debarking rotation cycle of 9 years (NUR—no understory removal). The lupine presence was confirmed by visual assessment in the field until 2009, and after its first application in 2003 the need for seeding again was identified in 2007 and 2009 (Table 1). In 2007, lupine seeding had a low germination rate, due to unsuitable environmental conditions.

**Table 1.** Yearly operations calendar carried out for each understory management alternative, with corresponding annual precipitation, computed from October of the year before the growth period to September of the growth period year, shrubs height (HShrubs) estimation with equation 3, and cork ring ages for each cork year sampling. RUL represents the understory removal followed by lupine seeding and NUR represents the maintenance of spontaneous understory vegetation.

Period	Precipitation (mm)	Debarking	Cork Ring Age				RUL				NUR			
			2006	2012	2015	2015	Install	LSeeding	PLupine	Removal	Shrubs	TShrubs	HShrubs	
2002/03	614.8	Yes	6				Yes	0	0	Yes	0	0	0	0.166
2003/04	449.1		7	1				1	1		0	0	1	0.399
2004/05	251.1		8	2				0	1		1	1	2	0.594
2005/06	500.8	Yes		3				0	0		1	1	3	0.751
2006/07	844.9			4	1		Yes	0	0		1	1	4	0.872
2007/08	427.5			5	2			1	1		1	1	5	0.955
2008/09	396.9			6	3		Yes	0	0		1	1	6	1.002
2009/10	623.6			7	4			1	1		1	1	7	1.011
2010/11	587.3			8	5			0	1		1	1	8	0.982
2011/12	329.4	Yes			6			0	0	Yes	0	0	0	0.166
2012/13	798.0				7			0	0		0	0	1	0.399
2013/14	924.7				8			0	0		1	1	2	0.594
2014/15	439.7	Yes		—				—	—		—	—	—	—



**Figure 1.** Sampling design and its organization into blocks and plots with tree distribution differentiated by cork rotation cycle—lighter circles are trees debarked in 2003 and 2012, darker circles are trees debarked in 2006 and 2015—where RUL represents the understory removal followed by periodic lupine seeding and NUR represents the maintenance of spontaneous understory vegetation.

## 2.2. Understory Evaluation

Stand understory layer was composed of spontaneous shrubs species dominated by *Cistus salvifolius* L. (25%), alongside with sparsely distributed *Ulex airensis* M.D. Esp.Santo, Cubas, Lousa, C.Pardo & J.C.Costa (15%), *Lavandula pedunculata* (Mill.) Cav. (10%), and *Calluna vulgaris* (L.) Hull (5%). Until 2003, the understory was mechanically removed with a forestry mulcher, in the complete stands area, with an interval of 3 to 4 years. In order to assess understory evolution with time, since 2012, for each of this shrub species, additional measurements of shrub height (m) were performed—a minimum of two samples per species—in the following years after clearing (TShrubs): 2, 4, 6 and more than 9 years in a similar neighboring stand. These measurements were used to develop a simple quadratic model, dependent of TShrubs, as in Navarro et al. [15], allowing the estimation of shrub height in intermediate years.

## 2.3. Tree and Cork Measurements

One important feature of the trial that allowed the present study to go forward in comparison to the one used by Faias et al. [13] was the presence of two different cork rotation periods within the stand understory management period: 2003 to 2012 and 2006 to 2015 (Figure 1). This detail allows the interaction between cork ring age with understory removal and periodic lupine application to be studied. The diameter at breast height without cork (du) of each debarked tree was measured at each debarking year. Mean stand density between 2003 and 2015 had a slight trees per hectare variation, from 130 to 120 on block 1 and 93 to 74 on block II. Individual tree coordinates were taken, considering the Cartesian coordinate system, in order to allow the computation of distance-dependent competition indices.

Cork samples, approximately 20 cm × 20 cm, were taken at breast height from the debarked trees in 2003, 2006, 2012, and 2015. The samples were boiled for 1 h in water at 100 °C and atmospheric pressure, and were polished with a belt sander machine (FAI™ Modelo LCU, Paredes, Portugal). Cork rings were marked on a vertical axis in samples where rings were unmistakably identified. Annual cork growth or cork ring width (rw) was measured for the eight complete rings after digital scanning, using the image analysis software ImageJ [16,17]. These measurements include different cork ring ages within the same period (Table 1), having a range of mean values between 1.5–4.5 in 2006 (n = 98 samples), 2.1–3.9 in 2012 (n = 114 samples), and 1.7–4.7 in 2015 (n = 101 samples). Cork samples from 2003 were used only in the previous study from Faias et al. [13], as a baseline to characterize both stands before the trial establishment.

2.4. Annual Cork Growth Modeling

Due to the nested structure of the data—trees inside plots and plots inside blocks—the data analysis was carried out using a linear mixed modelling approach [18]. Comparing the large number of cork ring measurements to the number of repeated cork rings measured, with the same age at the same tree, in different cork samples (from 2006 and 2015), an absence of serial correlation was assumed, as in Paulo et al. [19].

The first step for the model development was the definition of a tree distance-depending intraspecific competition index (CI) more correlated with cork ring width. The indices tested were those that were demonstrated by Paulo et al. [11] to be significantly correlated with tree diameter (Table 2). The competitors were selected from a 20-m circle around the subject tree. These indices were fitted, one at a time, using the complete dataset with the following equation:

$$rw_{ijk} = (\mu_{0jk} + \beta_0) + \beta_1 CI_i + \varepsilon_{ijk} \tag{1}$$

where rw is the cork ring width (mm) for tree i within plot j and block k; CI is a competition index;  $\beta_0$ ,  $\beta_1$  are the fixed effects parameters;  $\mu_{0jk}$  is the random effect; and  $\varepsilon_{ijk}$  is the error term.

**Table 2.** List of competition indices tested, respective parameter estimates ( $\beta_1$ ), significance (p-value), and Akaike information criterion (AIC) values, where ij is the distance between subject tree i and its competitor tree j; du is the diameter at breast height under cork; Nc is the number of competitors.

Competition Indices	$\beta_1$	p-Value	AIC
(CI2) Number of competitors, within 20 m, with $du_j > du_i$	−0.04182	0.011	5996.4
(CI5) Size ratio: $\frac{du_i}{du_i + \sum_{j=1}^{Nc} du_j}$	3.09800	0.245	5991.2
(CI7) Distance to nearest tree, with $du_j > du_i$	0.00100	0.745	6006.0
(CI9) Size ratio proportional to distance: $\sum_{j=1}^{Nc} \frac{du_j}{du_i} \times \frac{1}{D_{ij}}$	−0.13700	0.118	5996.9

Hyperbolic cork ring age (tc) and annual precipitation (Pr) were explanatory variables included in the model, due to the known decreasing pattern of the annual cork growth with cork age and the positive correlation with annual precipitation (e.g., [20–24]). The precipitation was computed, as defined in Faias et al. [13], for the period between October of the year before the growth period and September of the growth period year (Table 1). Lastly, two final sets of models were separately fitted with the dataset for each understory management alternative, RUL or NUR, according to the following expression:

$$rw_{ijt} = (\mu_{0j} + \beta_0) + \beta_1 tc_{ijt} + \beta_2 Pr_t + \beta_3 CI_{ij} + \beta_4 Tr_{jt} + \beta_5 (tc_{ijt} \times Tr_{jt}) + \varepsilon_{ijt} \tag{2}$$

where rw is the cork ring width (mm); tc is the cork ring age (years); Pr is the annual precipitation (mm); Tr represents the variables of each understory management alternative described in Table 1;  $\beta_0$ ,

$\beta_1, \beta_2, \beta_3, \beta_4, \beta_5$ , are the fixed effects parameters;  $\mu_{0j}$  is the random effect;  $i$  is the tree index;  $j$  is the plot index;  $t$  is the cork growth year index; and  $\varepsilon_{ijt}$  is the error term.

Considering the RUL management, two alternative variables were tested (Table 1): LSeeding, which takes value 1 in the following year after lupine seeding in Autumn; and PLupine, which identifies the visual presence of lupine, by taking value 1 in the two years following its seeding. For the NUR management, three variables were considered (Table 1): Shrubs, which identifies the presence of shrubs species in understory observed two years after clearing; TShrubs, which identifies the time without understory removal; and HShrubs, which gives the understory mean height (m) estimated with the previously developed model as a function of time.

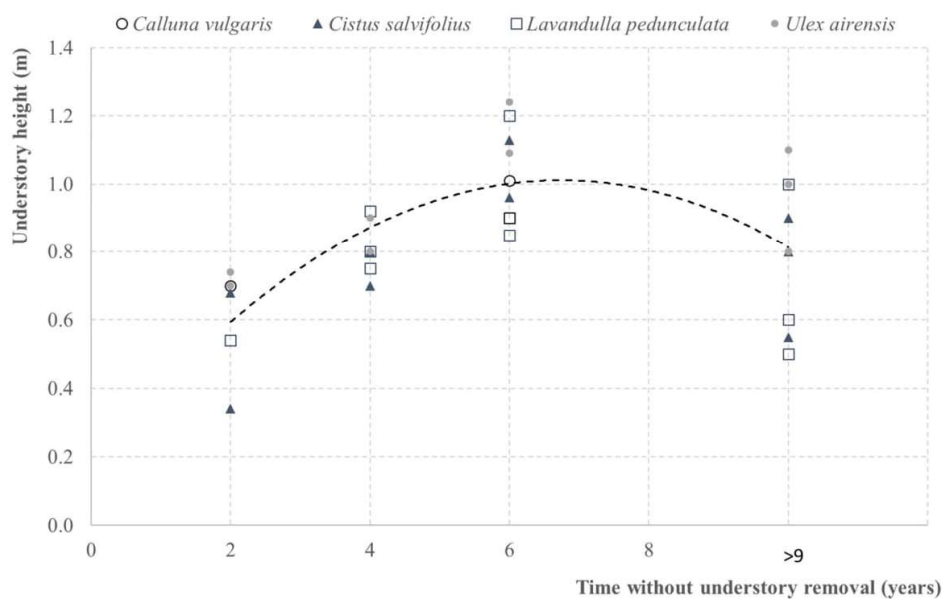
All models were fitted using the procedure PROC MIXED from software SAS 9.4 (SAS, Cary, NC, USA) [25]. The RANDOM statement, from this procedure, was applied to specify the random effects associated with nested structure (trees inside plots). The random effect parameter was tested in all the fixed parameters and the selection criteria for its inclusion in the model was the lowest Akaike information criterion (AIC) value. Variance components used the covariance structure. Significance of the parameter estimates was evaluated considering  $\alpha = 0.05$ .

### 3. Results

#### 3.1. Understory Model

The main shrub species within the trial showed an increasing pattern of total shrub height (HShrubs) in the following years after understory removal (Figure 2), which potentially reached a maximum total height at about 7 years, before starting to decline afterwards. The following equation was fitted for the mean total height ( $R^2 = 0.93$ ), as a function of time without understory removal:

$$HShrubs = 0.1663 + 0.2508 \times TShrubs - 0.0186 \times TShrubs^2 \quad (3)$$



**Figure 2.** Total height evolution for the main understory shrub species present in the stands trial. The trend line shows the evolution of the total mean height value.

### 3.2. Annual Cork Growth Models

Testing each of the distance-dependent competition indices as unique explanatory variable for the cork ring width model, the only index presenting a coefficient significantly different from zero (Table 2) was the one expressed as the number of competitors, with tree diameter higher than the subject tree diameter, within a 20-m radius (CI2). This index estimated parameter showed a negative effect, demonstrating that an increasing number of larger trees within a 20-m radius is associated with a reduction of the cork ring width. Later, the CI2 index was included while fitting the full models for cork ring width (Equation (2)). Table 3 shows the main results for the two alternative models (original and final) for the RUL model, showing the results of four alternative models. The LSeeding variable, as well as its interaction with cork age, was not statistically significant (RUL1A). However, the PLupine variable was statistically significant, presenting a negative coefficient, as well as, its interaction with the cork age with a positive coefficient (RUL2A). In both RUL models, the CI2 index was not significant and was removed from the final model (RUL1B, RUL2B).

Considering the NUR model, Table 4 shows three alternative models (original and final), where the coefficients for both variables, Shrubs and TShrubs (Table 1), and their interaction with cork age were statistically significant, with similar AIC values (NUR1A, NUR2A). The coefficient for HShrubs (NUR3A) was positive and the coefficient of its interaction with cork age was negative. For these models, the CI2 index was not significant and therefore was removed from the final models. Simultaneously, the coefficient for the cork ring age was not statistically significant, and the final model was fitted excluding this variable (NUR1B, NUR2B, NUR3B).

To understand either the dynamics of PLupine or HShrubs interactions with cork ring age on the cork ring width, the first partial derivative was computed for each understory management variable ( $t_c > \beta_4 / \beta_5$ ). The value obtained for the PLupine interaction suggests a negative effect on the ring width, up to 5.4 years of cork growth ( $\beta_4 / \beta_5 < 0$ ); and then it is converted into a positive effect ( $\beta_4 / \beta_5 > 0$ ). For the HShrubs interaction there was a positive effect on cork ring width up to 6.6 years of cork growth ( $\beta_4 / \beta_5 > 0$ ), representing the point where the shrubs potentially reached their maximum height, and then this effect was no longer observed ( $\beta_4 / \beta_5 < 0$ ).

The significance of the plot's random effects was tested in all the fixed parameters through the refitting of both models. Results showed that the random effect parameter convergence, significance and a lower AIC value was obtained when it was added to the intercept parameter of each model.

**Table 3.** Parameter estimates for the two alternative cork ring width (rw) models (with and without the CI variable) regarding the RUL management variables listed in Table 1 ( $t = 1008$ ), where:  $t_c$  is the cork ring age (years);  $P_r$  is the annual precipitation (mm);  $CI_2$  is the number of competitors, within 20 m, with  $d_{uj} > d_{ui}$ ;  $L_{Seeding}$  takes value 1 in the year after lupine application (Autumn);  $PL_{lupine}$  takes value 1 in the two years following its seeding.

Parameters	RUL1A Model (AIC = 2705)				RUL1B Model (AIC = 2699)			
	Estimate	p-value	Lower	Upper	Estimate	p-value	Lower	Upper
$\beta_0$	3.2431	<0.0001	2.9917	3.4945	3.2367	<0.0001	3.0084	3.4649
$\beta_{1\ t_c}$	-0.2313	<0.0001	-0.2588	-0.2039	-0.2315	<0.0001	-0.2588	-0.2041
$\beta_{2\ P_r}$	0.0016	<0.0001	0.0013	0.0018	0.0016	<0.0001	0.0013	0.0018
$\beta_{3\ CI_2}$	-0.0027	0.905	-0.0462	0.0408				
$\beta_{4\ L_{Seeding}}$	-0.0816	0.522	-0.3315	0.1683	-0.0815	0.522	-0.3313	0.1684
$\beta_{5\ t_c \mid L_{Seeding}}$	-0.0125	0.616	-0.0615	0.0365	-0.0126	0.615	-0.0615	0.0364
$\mu_{0(\text{intercept})}$ variance	0.3382		0.2510	0.4804	0.3358		0.2497	0.4758
Residual variance	0.6822		0.6231	0.7503	0.6820		0.6229	0.7499

Parameters	RUL2A Model (AIC = 2700)				RUL2B model (AIC = 2695)			
	Estimate	p-value	Lower	Upper	Estimate	p-value	Lower	Upper
$\beta_0$	3.4619	<0.0001	3.1843	3.7396	3.4464	<0.0001	3.1916	3.7012
$\beta_{1\ t_c}$	-0.2724	<0.0001	-0.3068	-0.2381	-0.2727	<0.0001	-0.3070	-0.2383
$\beta_{2\ P_r}$	0.0015	<0.0001	0.0013	0.0017	0.0015	<0.0001	0.0013	0.0017
$\beta_{3\ CI_2}$	-0.0062	0.780	-0.0497	0.0373				
$\beta_{4\ PL_{lupine}}$	-0.3994	0.001	-0.6433	-0.1554	-0.3980	0.001	-0.6417	-0.1543
$\beta_{5\ t_c \mid PL_{lupine}}$	0.0738	0.001	0.0290	0.1187	0.0736	0.001	0.0288	0.1184
$\mu_{0(\text{intercept})}$ variance	0.3386		0.2515	0.4804	0.3369		0.2506	0.4770
Residual variance	0.6786		0.6198	0.7462	0.6782		0.6195	0.7458

**Table 4.** Parameters estimates for the three alternative cork ring width (rw) models (with and without the CI variable) regarding the NUR management variables listed in Table 1 ( $n = 1006$ ), where:  $tc$  is the cork ring age (years);  $Pr$  is the annual precipitation (mm);  $CI2$  is the number of competitors, within 20 m, with  $d_{uj} > d_{ui}$ ; Shrubs is the presence of shrubs in understory observed two years after clearing;  $TShrubs$  is the time without understory removal;  $HShrubs$  estimates understory mean height (m) as a function of time.

NUR1A Model (AIC = 2588)						NUR1B Model (AIC = 2584)					
Parameters	Estimate	p-value	Lower	Upper	Upper	Estimate	p-value	Lower	Upper	Upper	
$\beta_0$	2.0443	<0.0001	1.7534	2.3353	2.3353	2.0903	<0.0001	1.8129	2.3676	2.3676	
$\beta_{1\ tc}$	-0.1006	<0.0001	-0.1445	-0.0567	-0.0567	-0.0970	<0.0001	-0.1403	-0.0537	-0.0537	
$\beta_{2\ Pr}$	0.0016	<0.0001	0.0014	0.0019	0.0019	0.0016	<0.0001	0.0014	0.0018	0.0018	
$\beta_{3\ CI2}$	0.0241	0.307	-0.0222	0.0704	0.0704						
$\beta_{4\ Shrubs}$	0.8414	<0.0001	0.5772	1.1056	1.1056	0.8478	<0.0001	0.5840	1.1116	1.1116	
$\beta_{5\ tc \times Shrubs}$	-0.1074	<0.0001	-0.1583	-0.0564	-0.0564	-0.1104	<0.0001	-0.1610	-0.0598	-0.0598	
$\mu_{0(intercept)}$ variance	0.3983		0.2994	0.5559	0.5559	0.4031		0.3036	0.5611	0.5611	
Residual variance	0.5928		0.5413	0.6521	0.6521	0.5921		0.5406	0.6512	0.6512	
NUR2A Model (AIC = 2584)						NUR2B Model (AIC = 2579)					
Parameters	Estimate	p-value	Lower	Upper	Upper	Estimate	p-value	Lower	Upper	Upper	
$\beta_0$	2.0235	<0.0001	1.7140	2.3331	2.3331	2.0440	<0.0001	1.7394	2.3486	2.3486	
$\beta_{1\ tc}$	-0.0878	0.001	-0.1394	-0.0362	-0.0362	-0.0827	0.001	-0.1326	-0.0329	-0.0329	
$\beta_{2\ Pr}$	0.0015	<0.0001	0.0013	0.0017	0.0017	0.0015	<0.0001	0.0013	0.0017	0.0017	
$\beta_{3\ CI2}$	0.0179	0.459	-0.0294	0.0652	0.0652						
$\beta_{4\ TShrubs}$	0.2214	<0.0001	0.1489	0.2940	0.2940	0.2262	<0.0001	0.1547	0.2976	0.2976	
$\beta_{5\ tc \times TShrubs}$	-0.0290	<0.0001	-0.0420	-0.0160	-0.0160	-0.0301	<0.0001	-0.0428	-0.0174	-0.0174	
$\mu_{0(intercept)}$ variance	0.3992		0.3004	0.5564	0.5564	0.3996		0.3011	0.5562	0.5562	
Residual variance	0.5857		0.5348	0.6443	0.6443	0.5854		0.5345	0.6439	0.6439	
NUR3A Model (AIC = 2553)						NUR3B Model (AIC = 2546)					
Params	Estimate	p-value	Lower	Upper	Upper	Estimate	p-value	Lower	Upper	Upper	
$\beta_0$	1.0555	<0.0001	0.5867	1.5242	1.5242	1.4576	<0.0001	1.2531	1.6620	1.6620	
$\beta_{1\ tc}$	0.0789	0.086	-0.0112	0.1690	0.1690						
$\beta_{2\ Pr}$	0.0015	<0.0001	0.0012	0.0017	0.0017	0.0015	<0.0001	0.0013	0.0017	0.0017	
$\beta_{3\ CI2}$	0.0080	0.744	-0.0398	0.0557	0.0557						
$\beta_{4\ HShrubs}$	2.3692	<0.0001	1.7604	2.9779	2.9779	1.8573	<0.0001	1.6398	2.0747	2.0747	
$\beta_{5\ tc \times HShrubs}$	-0.3548	<0.0001	-0.4750	-0.2346	-0.2346	-0.2518	<0.0001	-0.2799	-0.2237	-0.2237	
$\mu_{0(intercept)}$ variance	0.4032		0.3038	0.5612	0.5612	0.4012		0.3026	0.5576	0.5576	
Residual variance	0.5707		0.5211	0.6278	0.6278	0.5721		0.5224	0.6292	0.6292	

## 4. Discussion

### 4.1. Intraspecific Competition Driver: Tree Level Distance-Dependent Indices

A previous study by Paulo et al. [11] revealed a significant effect of distance-dependent tree competition indices on tree crown characteristics, when looking for pure cork oak stands from 98 to 238 trees per hectare. For the present study, the number of competitors within a 20-m radius with tree diameter larger than the subject tree diameter presented a negative effect on annual cork growth, when fitted as single explanatory variable. However, when this tree competition index was tested jointly with the cork age, the annual precipitation, and the understory management related variables, it did not reveal any further significant effect on annual cork growth for this specific stand density range. Hence, there should be further research on the intraspecific competition effect on the tree and cork growth for different stand densities and structures.

### 4.2. Interspecific Competition Driver: Lupine Application Characteristics

The periodic application of a leguminous species (lupine) beneath cork oak trees as in the RUL plots from the present trial represent a common understory management practice of the *montado* system, but in this particular case without cattle pasture. Faias et al.'s [13] results indicated that periodic lupine application did not show any effect on annual cork growth, as well as, tree radial growth, considering one cork debarking rotation cycle. The same conclusion could be obtained from the present study if only considering the effect of the lupine application in the autumn on the cork ring of the following year. However, when considering the lupine visual presence on the field—the two years following its application—a negative effect on the annual cork growth was revealed until cork ring ages around 5 years. At this point, it changes to a positive effect on cork ring width. More research on the effect of other applied forage species on the annual cork growth is required, for instance, with natural and sown rainfed grasslands [8], which have been associated with ecosystem biodiversity increase, pasture productivity, and resilience [26].

### 4.3. Interspecific Competition Driver: Understory Growth Characteristics

The measured total shrub height on these specific spontaneous species in the understory showed a pattern over period of a cork debarking rotation cycle, in line with the reported pattern noted by Santana et al. [27], which had been described as having a sharp increase with time after clearing followed by a leveling off. It could also be seen that *Cistus* and *Lavandula* species potentially reach a maximum cover, and then start declining, as noted in Díaz Barradas et al. [28]. However, the *Ulex* species pattern was distinct from the increasing pattern showed in several studies, where it was considered a period longer than the one observed in this study (e.g., [29]). The present results revealed a positive effect of understory height on the cork ring width until 6 years of cork growth after debarking. From this cork ring age, the understory revealed a negative effect on annual cork growth. These results are in line with conservative understory management strategies that minimize soil intervention to reduce the negative impact on tree root development [30] and on tree regeneration patterns and viability [31]. It is also in line with the findings of Mendes et al. [4], which suggest that making a shrub cut every 5–6 years supports the normal natural regeneration of the understory shrubs, with a minor effect on local species richness of soil biota. In contrast, Caritat et al. [10] showed no significant effect of the presence of shrubs on radial growth on 10 cork oak trees growing with or without shrubs. Martin et al. [32] also indicated no significant effect when comparing understory and soil management practices on holm oak growth in sites with different soil and understory characteristics. These results should also not be seen as contradictory to the experimental study by Caldeira et al. [6], which suggests that oak trees are more vulnerable to hydraulic failure in a stand with shrub invasion, due to two main differences. First, the latter not only addresses extreme drought events, but also an extreme stand invasive shrubs condition, dominated by *Cistus ladanifer* L., which is not similar to any spontaneous shrub species in the present trial. Second, the NUR plots from the present study represent a common

management alternative for the cork forest systems, whereas the other represents an extreme case of the absence of management.

## 5. Conclusions

Linear models developed in this study were used to contribute to the knowledge about the effect of intra- and interspecific drivers, such as distance-dependent competition indices or understory management operations, on annual cork growth. Their application should not be extrapolated for understory conditions and compositions distinct from the ones described—Podzolic soils with stand densities up to 132 trees per hectare. The analyses undertaken do not show any impact of intraspecific competition on cork growth, expressed through a set of competition indices. In fact, competition indices are not significant when added to a cork growth model that already includes cork age, precipitation of the previous growing year, and understory management.

Under these trial conditions, regarding interspecific competition, this study suggests that after debarking, the understory can be maintained during some years without affecting cork growth (6 years in this trial). Not taking into consideration fire risk, which would be higher for a cork forest system, this conclusion may lead to a decreasing number of clearings within a cork debarking rotation cycle that may be favorable to local biodiversity. On the other hand, lupine application immediately after debarking seems to have a negative impact on cork growth, but may be considered after some years (5 years in this trial).

Answering the last question research question originally proposed for this study, there is a clear interaction between the understory management and cork age, with a different impact of the first depending on whether its application takes place at the beginning of the cork debarking period or in another year within the period.

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<b><i>Title</i></b>	<b>II.3. Intra-annual tree diameter increment and seasonal leaves nutrient variation in cork oak species under three understory management alternatives in Podzol soils</b>
<b><i>Authors</i></b>	Sónia P. Faias, Paulo N., Firmino, Joana A. Paulo, Margarida Tomé, Gerardo Moreno
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# Intra-annual tree diameter increment and seasonal leaves nutrient variation in cork oak species under three understory management alternatives in Podzol soils

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## ABSTRACT

Cork oak is an important species in the Mediterranean agroforestry systems. However, there are few studies providing knowledge outcomes about the impact of different understory management practices on the tree and cork growth. Monthly diameter increments, monitored with band dendrometers, and the seasonal variation of the specific leaf area (SLA) and N, P and K content of current-year leaves, were collected during two consecutive years from an uneven-aged cork oak pure stand that included debarked trees at two different years. This dataset allowed studying how trees respond to three distinct understory management alternatives (UMA): spontaneous understory vegetation maintenance (NUR, as control); understory removal with biomass incorporation into the soil (RUI); and understory removal with simultaneous NP fertilization (RUF). Particularly, overlooking the interaction of UMA with the tree diameter increment and the leaves nutrients content.

A parametric approach was performed to identify seasonal patterns for the leaves variables, and differences among UMA and asynchronous cork debarking cycles (YD). Differences were found between UMA and for the combined effect with YD, where the P content was higher on RUF in the two years after performing understory operations, whereas for the N content was higher in the second year. A linear mixed model was performed for the diameter increment, which allows simultaneously considering understory management, tree debarking management and temporal correlations. In the intra-annual diameter increment results suggests an effect in the trees debarked earlier in the following year after fertilization. Thus, a difference on RUF was revealed in both approaches.

**Keywords:** *Quercus suber* L., dendrometers, spontaneous shrubs, fertilization, tree diameter increment

## INTRODUCTION

Evergreen sclerophyllous oaks, such as cork oak and holm oak, are common species in the Mediterranean forests and traditional known in the Iberian Peninsula as "montados" and "dehesas". In those systems, antropogenic interventions are common due to management affecting soil functions and the mineralisation rate which determines soil nutrient availability (e.g. Moreno & Obrador 2007, Gómez-Rey *et al.* 2013). Generically, the water, the nutrients and the light are the elected resources in plants competition (Vila & Sardans 1999). In "montados", the first two resources take a more relevant role, due to climate or soils features or to competition, intra or inter species (e.g., Faias *et al.* 2019).

Oliveira *et al.* (1996) compare four young cork oak trees with three mature ones, growing in a typical "montado" in southwest Portugal and found that the seasonal variability of N, P, K, Ca and Mg in leaves were in agreement with reported values in other evergreen oak species. Silvopastoral treatments in cork oak stands in the catalonian region analysed in Robert (1997) seem to be favourable to the N and the P foliar contents for this species but had no effect on radial growth. Robert *et al.* (1996) discusses that the increase in the P content in the leaves from plots submitted to vegetation control may be a consequence of the shrubs removal which reduces competition for this nutrient, or may be due to soil organic matter enrichment from the shrubs residuals left in the stand. Courtois & Masson (1999) aiming to set up a relationship between cork quality and its mineral content (or with the leaves mineral content), demonstrate that cork quality may be related to the cork K content but seems independent of the leaf inorganic content. Vaz *et al.* (2011) studied the *Quercus* species and concluded that changes in SLA may be an indicator of leaf acclimation to light conditions, specifying that *Quercus suber* leaves showed higher ability to adjust the allocation of total leaf nitrogen than *Quercus ilex*.

Generically, tree diameter measurement is used as an indicator of growth and yield but it may also provide information about the presence of competition (e.g. Tomé *et al.* 1994) or how management may affect the tree growth (e.g. Faias *et al.* 2018). Previous studies on oak species focus on stem annual growth (e.g. Tomé *et al.* 2006), some with dendrochronological techniques (e.g. Leal *et al.* 2015) and others focus on monthly growth (e.g. Martín *et al.* 2014). Martín *et al.* (2014) addressed the relationship between climatic variables and holm oak intra-annual stem increment and pointed out firstly water availability as the main driver and secondly that the growth response to climate is restrained by tree size and competition. Martín *et al.* (2015) also for the holm oak species, found no significant effect on tree growth when comparing understory and soil management practices.

A trial established in a mature cork oak stand covering two different cork debarking cycles aimed to compare the response of trees growing under distinct understory management

alternatives (UMA). Faias *et al.* (2018) using data from this trial indicate no effect between the maintenance of spontaneous shrubs or understory removal with lupine seeding on cork tree wood increment, along a cork rotation of 9 years. The shrub maintenance in the understory at a certain level can improve biodiversity in Mediterranean forests (Torrás *et al.* 2009) by potentially accumulating soil organic C with time, however the C/N ratio may depend on the *Cistus* species (Gómez-Rey *et al.* 2013). Natividade (1950) stated that common spontaneous shrubs species present in “montado” when incorporated into the soil may reduce soil pH, due to its high C/N ratio. For the present study within the referred trial, selected trees were monthly monitored for the diameter increment along two consecutive years and current-years leaves were seasonally sampled to better understand the influence of climate on growth during the different year seasons. This study aims to provide information on the short term effect of three distinct understory management alternatives on tree growth and leaf mineral nutrition growing in Podzolic soils.

## MATERIAL AND METHODS

### Trial description

The experimental trial, located in Portugal near the Montargil village (39°3.242'N, 8°10.588'W), was implemented in 2016, in an uneven-aged pure cork oak stand which includes trees already debarked along two asynchronous cork debarking cycles: 2003 to 2012 and 2006 to 2015 (Figure 1). Soils are classified as Podzols, according to the IUSS Working Group (2006). The understory layer composed by spontaneous vegetation dominated by *Cistus salvifolius* L., *Lavandulla pedunculata* L. and *Ulex airensis* L. sparsely distributed. Other species are also found with lower expression: *Calluna vulgaris* (L.) Hull, *Cistus crispus* L., *Daphne gnidium* L., *Genista triacanthos* Brot.

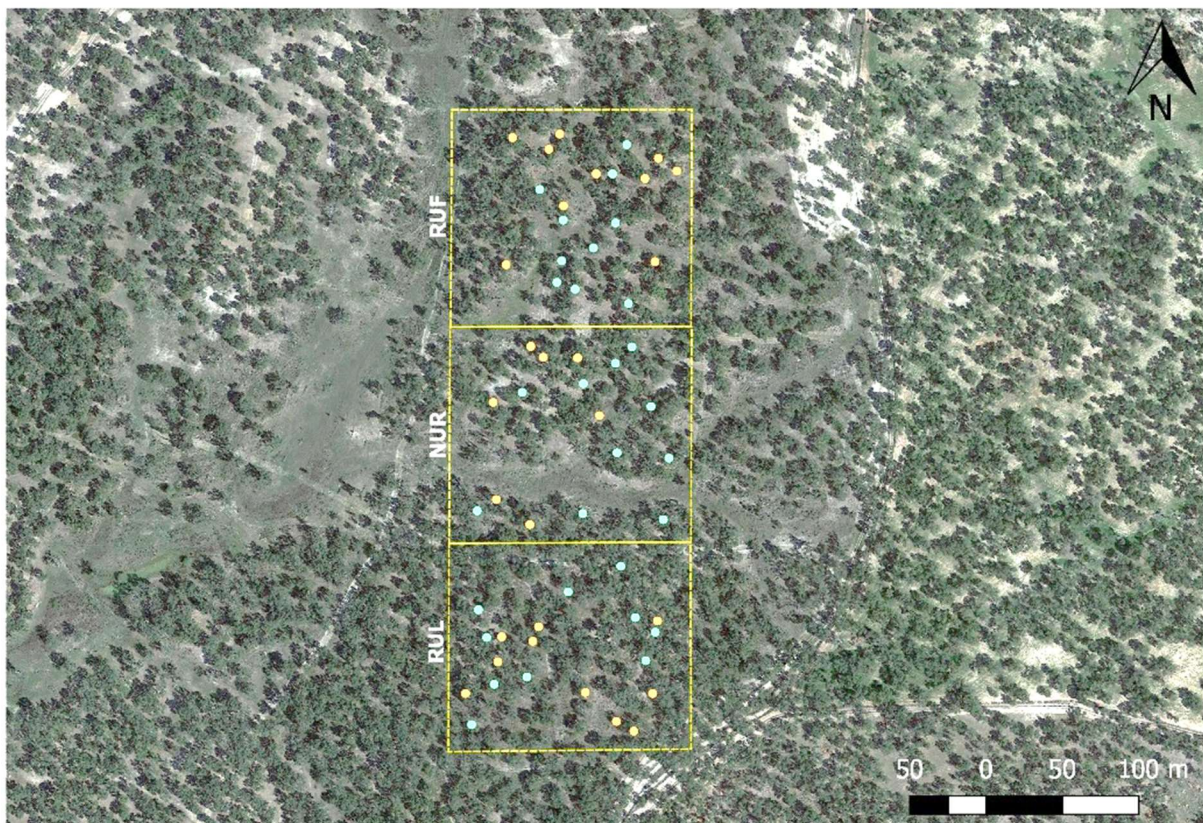


Figure 1. Plots location with tree distribution differentiated by cork debarking cycle—blue circles are trees debarked in 2003 and 2012, orange circles are trees debarked in 2006 and 2015, where RUL represents the understory removal followed by periodic lupine seeding and NUR represents the maintenance of spontaneous understory vegetation.

The trial focused on the comparison of three distinct understory management alternatives (UMA), performed on plots with 2 hectares each, and including a 20 m border to ensure no impact of non-managed neighbor areas on the trees. The following understory operations were performed in November 2016: RUI, removal of the understory followed by incorporation of organic matter into the soil using a crusher equipment; NUR, maintenance of spontaneous

shrubs species; RUF, removal of the understory followed by incorporation of organic matter into the soil using a crusher equipment and fertilization with 20-kg.ha<sup>-1</sup> N and 50-kg.ha<sup>-1</sup> P. The fertilizer amount was determined after soil analysis as recommend by Goes & Tenreiro (2001) for cork oak stands. Top soil moisture, nitrogen and carbon components were obtained inside and outside crown cover projection of those selected trees (Table 1).

### Data collection

At the tree level, diameter at breast height without cork (du) was measured and crown width was estimated using Paulo *et al.* (2016) model (Table 1). In each UMA (plot), 10 vigorous trees were selected by cork debarking cycle – trees debarked in 2012 or in 2015 – according to their tree diameter close to the stand quadratic mean diameter (dug). In those trees were placed, at breast height over cork, a dendrometer band DB20 (EMS Brno, Czech Republic), to monthly monitored the diameter increment over cork before and after performing understory operations. A first set of dendrometers were installed in June 2016 (30 trees) as baseline and the second set (27 trees) when the understory operations were performed. The understory composition and biomass were evaluated (Table 1) at the tree level before understory removal, within each monitorized tree crown projection area.

Table 1. Stand characterization by plot before applying UMA with standard error in parenthesis. Understory biomass and soil variables were sampled at the 30 trees with dendrometers installed in June 2016.

Plot	N	dug	CC	Wu	Rs(i)	Rs(o)	Hs(i)	Hs(o)
RUI	129	29.49	60	0.026 (0.005)	10.1 (0.4)	10.5 (0.9)	7.8 (0.5)	8.2 (0.6)
NUR	110	28.53	48	0.034 (0.006)	9.7 (0.7)	9.1 (0.8)	5.8 (0.4)	9.8 (1.6)
RUF	106	28.57	46	0.010 (0.003)	8.5 (0.6)	7.1 (0.5)	7.1 (0.4)	8.4 (0.5)

[N] number of trees per hectare; [dug] quadratic mean diameter at breast height under cork (cm); [CC] crown cover percentage; [Wu] understory biomass (kg/m<sup>2</sup>) with 4 years growth; [Rs] mean soil C/N ratio; [Hs] mean top soil moisture (%); (i) inside crown cover projection area; (o) outside crown cover projection area

In the first set of monitorized trees – 5 trees by cork debarking cycle and by UMA – current-year leaves were seasonally sampled, with a telescopic scissor, from the crown top branches at the four main cardinal directions (N, S, W, E). The leaves sampling was taken before performing UMA operations, in June 2016 and September 2016, and afterwards seasonal repeated in 2017 and 2018: when young leaves thrive (spring), before the first rain (summer), and in the winter. After separating the leaves-limbo, fresh limbo-area was measured and its' dry weight was obtained, to compute specific leaf area (SLA) by dividing the leaves area (cm<sup>2</sup>)

to the leaves dry weight (g). Leaves nutrients contents, N, P and K were analysed however, P and K contents were not obtained before performing UMA operations.

### Data analysis

Two distinct methodologies were defined considering the distinct type of tree response variables: seasonal leaves contents variability and monthly diameter increment. The comparison of tree specific leaf area and nutrient contents was done with a 3-factor ANOVA (factors: season, debarking cycle, UMA), performed with the PROC ANOVA procedure of the SAS 9.4 (SAS 2011).

Regarding the nested structure of the monthly diameter increment data - trees inside plots - and the temporal correlation from repeated tree observations at different months of each year, a mixed modelling approach was considered (e.g. Pinheiro & Bates, 2000). Focusing the study research question, local conditions were not addressed (climate and soil), though the known positive correlation of precipitation with cork annual increment (e.g. Oliveira *et al.* 2016, Faias *et al.* 2019), because all the trees were exposed to the same environment. The presence of temporal correlations was fitted regarding the cork debarking cycles (YD), understory management (UMA) and their interaction, considering the following linear mixed model structure:

$$y_{ijlm} = \mu + \beta_{i(j)} + \gamma_l + \tau_m + x_i + (x|\gamma|\tau)_{ijlm} + \varepsilon_{ijlm}$$

where  $y_{ijlm}$  is the diameter increment of tree  $i$  at plot  $j$  at measurement  $l$  (mm);  $\mu$  is the general mean;  $\beta_{i(j)}$  is a tree random effect within each plot;  $\gamma_m$  is a month fixed-effect;  $\tau_n$  is a year fixed-effect;  $x$  is related to the debarking and understory management variables (single or combined) and  $\varepsilon_{ijklm}$  is residual error.

All variables were tested for significance at 5% confidence. All models were fitted using the procedure PROC MIXED from software SAS 9.4 (SAS 2011). The RANDOM statement was applied to specify the random effects associated with nested structure (trees inside plots). Variance components used the covariance structure.

## RESULTS AND DISCUSSION

### Leaves analysis

Specific leaf area (SLA) expressing the leaf morphology modification as an adaptive response to resource conditions showed higher values (Figure 2) when the current-year leaves were fully expanded at the baseline year (2016). This range decreased in the following two years regardless the understory management alternatives (UMA). However, the ANOVA results for the leaves seasonal sampling (Table 2) show that SLA was significantly different between UMA. The leaves samples taken at the baseline year (June and October 2016) displayed a distinctive leaf N percentage between UMA (Figure 2). Comparisons among UMA (Table 2) showed significant differences for the leaves N and P contents. The N content pattern in RUI was higher in the first year after performing understory operations while in the second year the N pattern was higher in RUF (Figure 2). Considering the two years after performing understory operations, RUF presents a distinctive higher pattern of the P content. On the other hand, the lower pattern of both N and P foliar content in NUR is in line with Robert (1997) suggestion that shrub clearing may be favorable to this species nutrition, either by reduction the competition for the nutrients in the soil or due to the biomass incorporation into the soil. K content shows an opposite pattern from the P content being higher during summer. ANOVA results show that K content was significantly different regarding UMA interaction with Season, which may be related to a peak in July 2018 (Figure 2), where RUI has a higher value and RUF the lower value.

Table 2. Results from ANOVA ( $Pr > F$ ) for the leaves seasonal sampling specific leaf area (SLA) and nutrients contents (N, P, K), where YD relates to the trees debarked in 2012 or 2015; Season is sample time within the year (spring, summer, winter).

<b>Effect</b>	<b>SLA (cm<sup>2</sup>/g)</b>	<b>N (%)</b>	<b>P (mg/g)</b>	<b>K (mg/g)</b>
UMA	0.0006	<0.0001	<0.0001	0.2046
YD	<0.0001	<0.0001	0.0921	0.103
Season	<0.0001	<0.0001	<0.0001	<0.0001
UMA YD	0.8148	0.0154	0.0174	0.0002
UMA Season	0.9987	0.0069	<0.0001	0.0005
YD Season	0.0324	0.7409	0.9983	0.4855
UMA YD Season	0.9707	0.5434	0.9689	0.7972

### Tree diameter increment modelling

Mean tree diameter increment varied along the year increasing during the spring and autumn, although trees debarked in 2012 present lower values (Figure 3), due to the known negative correlation of cork annual growth with time. Focusing in the effect on tree growth of the three distinct UMA, the linear mixed model results presented in Figure 4 are relate to the interaction

between UMA, cork debarking cycle (YD) and temporal correlations – year (YM) and month (MM) measurements. A few number of tree were significant concerning the random effects indicating that those trees have features not explained by the tested independent variables. The parameters estimates range (Figure 4) are generally significant in the spring and autumn months, regardless UMA and YD. Comparing both years after performing UMA operations, the spring peak in 2017 was earlier and shorter than in 2018, which is positively correlated to distinct precipitation during that seasons, as shown by the grey bars in Figure 3.

The following year after UMA operations performed in November 2016, the RUF plot displays in April 2017 an earlier effect in trees from both cork debarking cycles, while in May 2017 the effect is distinctive for the trees debarked in 2012 (Figure 4). This may be in line with Natividade (1950) recommendation to fertilize in the middle of a cork debarking cycle and not at the beginning. Regarding the trees debarked in 2015 a distinctive positive trend is shown in spring 2017 and 2018 in the NUR plots comparing with the plots under vegetation control (RUI, RUF), both with shrubs removal with incorporation into the soil (Figure 4).

## **CONCLUSION**

The study results in the leaves N and P contents, as well as, in the intra-annual diameter increment suggests an effect in the trees debarked earlier (in 2012) the following year after fertilization. Therefore, it was decided to perform an additional fertilization in November 2018 in order to validate this potential effect the following year.

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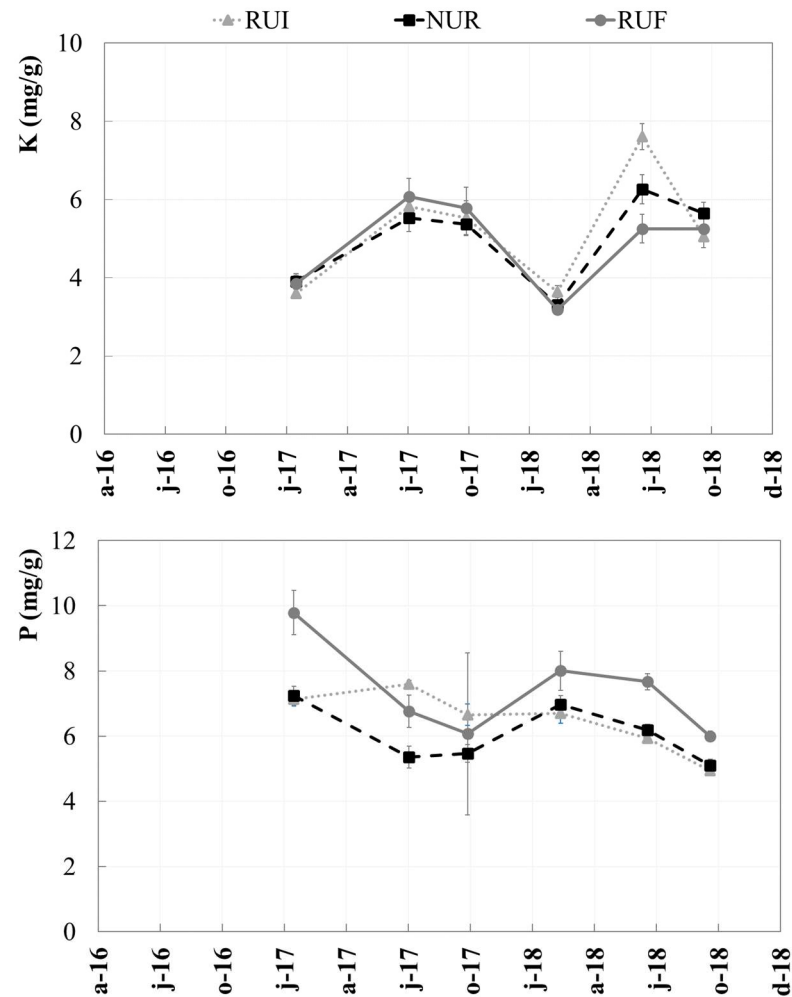
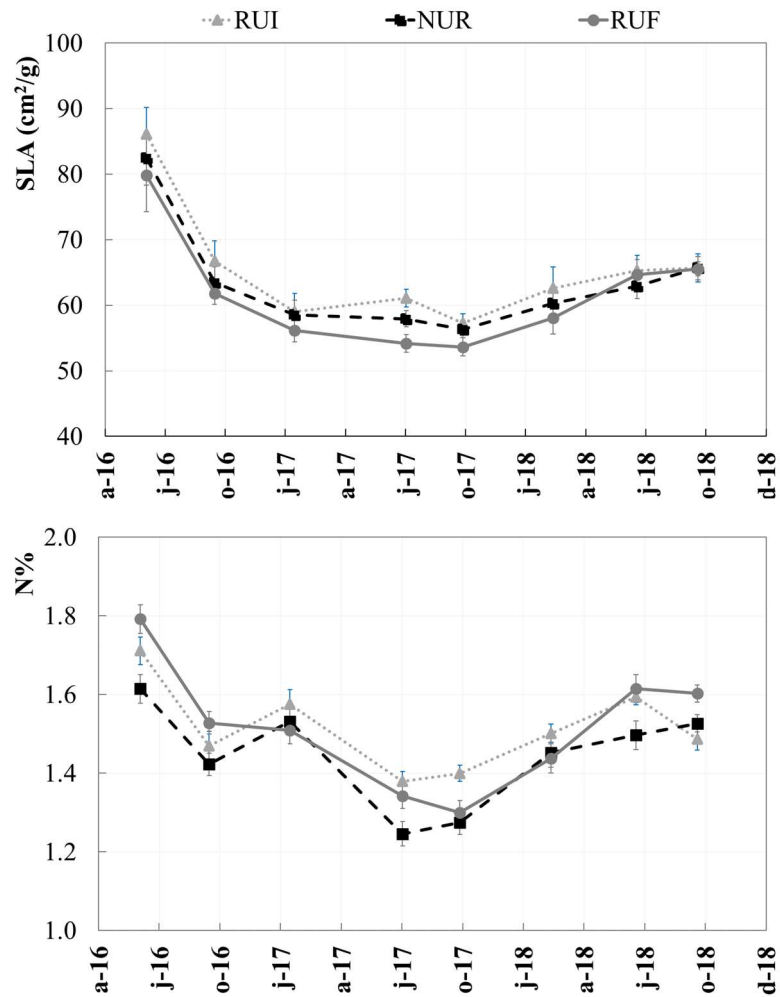
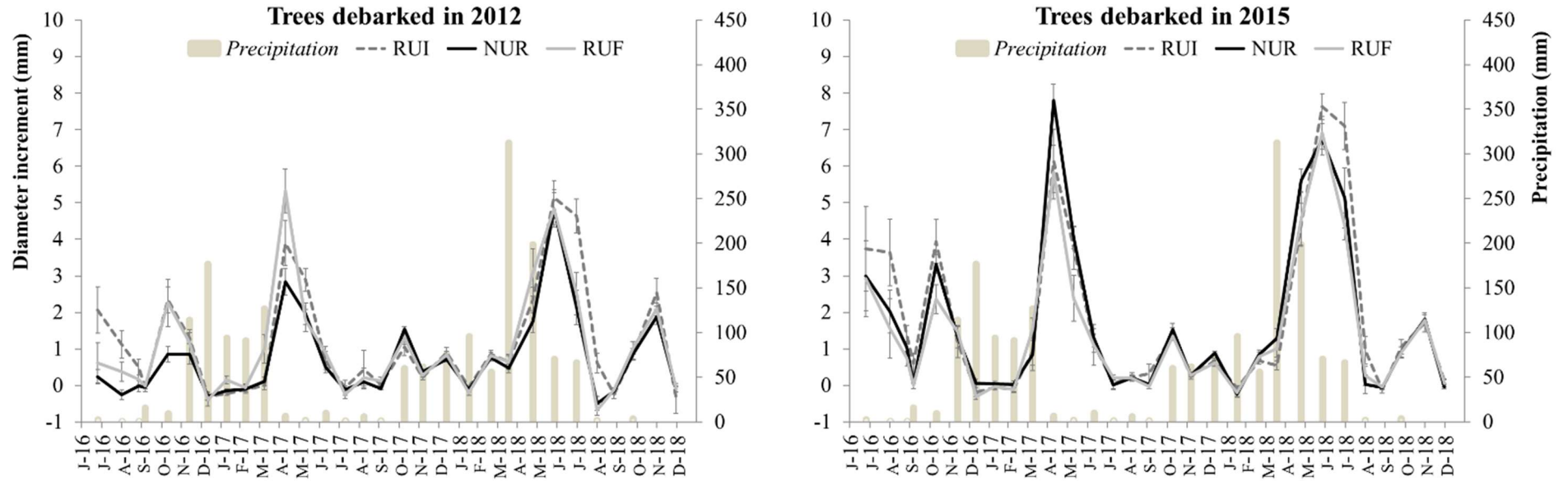
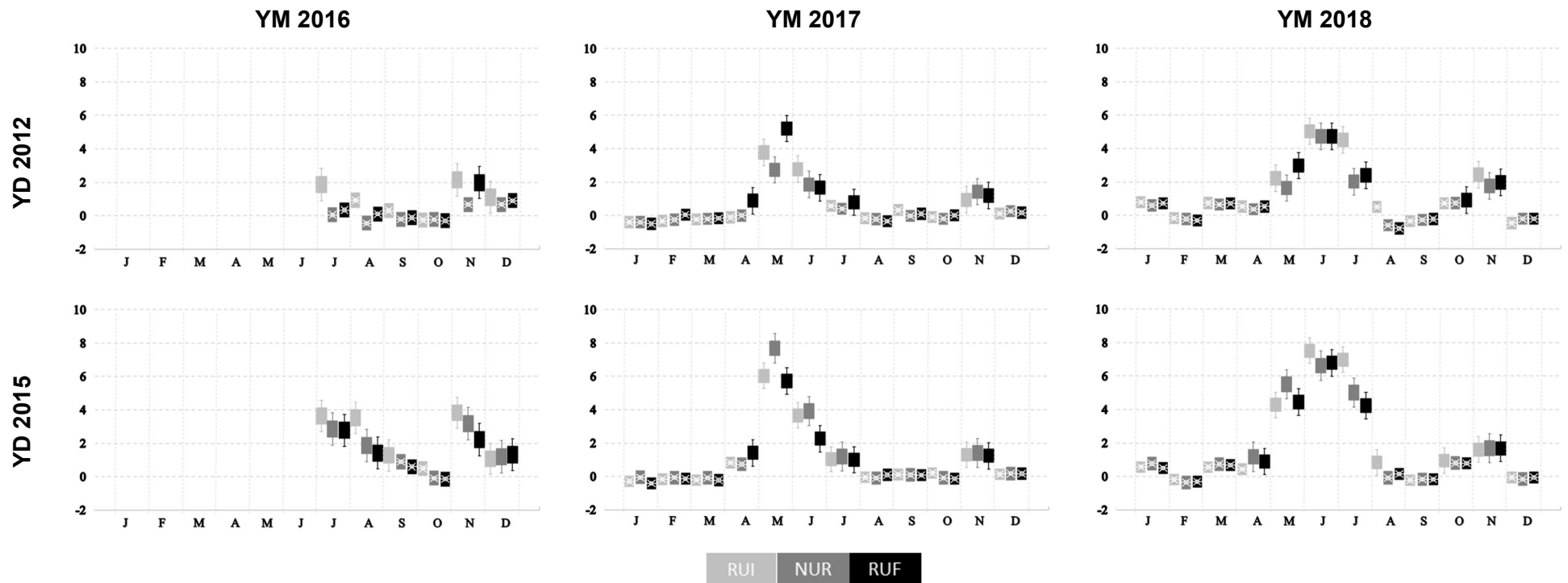


Figure 2 - Comparison of leaves SLA and nutrients contents in the three UMA for two consecutive years. Only for the baseline year before performing the understory operations (2016) is available data concerning SLA e N percentage.



1 Figure 3. Monthly precipitation and mean tree diameter increment for the trees of each debarking year, before and after performing understory  
 2 operations, for each UMA, where: RUI – understory removal with MO incorporation; NUR – no understory removal; RUF – understory removal  
 3 with MO incorporation and NP fertilization.  
 4



1 Figure 4. Parameters interval for the interaction between UMA, YD and temporal correlations (YM and MM) by month, for each UMA and cork  
 2 debarking cycle. The squares with blank dots and without standard error interval represent the non-significant parameters.  
 3

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**III. What is the impact of local tree density on tree growth in cork oak stands?**

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**Title**                    **III.1. Estimation of stand crown cover using a generalized crown diameter model: application for the analysis of Portuguese cork oak stands stocking evolution.**

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**Authors**                Joana A. Paulo, Sónia P. Faias, Célia Ventura-Giroux, Margarida Tomé

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## Estimation of stand crown cover using a generalized crown diameter model: application for the analysis of Portuguese cork oak stands stocking evolution

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Célia Ventura-Giroux,  
Margarida Tomé

A generalized non-linear tree crown diameter model was developed with the aim of allowing the computation of tree crown diameter over a large range of tree dimensions, and allowing its inclusion in forest growth and yield models. The model was formulated to provide biological meaning to the predicted values. Due to the nested structure of the data analyzed (trees within stands), both mixed- and fixed-effect models were developed. Since tree crown diameter is not frequently measured in forest inventories, the validation of the mixed model was carried out by considering the population specific response. The results demonstrate that when the measurements required for the mixed model calibration are not available, the use of the fixed effect model results in less biased and more accurate estimates. The fixed model was applied to the data from the two last Portuguese National Forest Inventories (NFI) to analyze the change in stand crown cover and assess the stocking evolution of cork oak stands in Portugal between 1996 and 2006. Results showed an increase in the frequency of stands with crown cover lower than 20%, as well as a decrease in the frequency of stands with crown cover between 20 and 40%. Average crown cover values were significantly different in the two NFI, with a decrease from 28.0 to 26.5% over the considered period.

**Keywords:** *Quercus suber*, Stand Crown Cover, Tree Crown Diameter, Nonlinear Mixed Effects Model, Nonlinear Fixed Effects Model, Portuguese National Forest Inventory

### Introduction

Stand crown cover is an important variable for the assessment of forest productivity and sustainability. Its computation requires the measurement or estimation of the tree crown diameter, which is time-consuming and cost expensive, and therefore is not frequently measured in forest inventories. This has led to the development of generalized crown diameter models to this purpose (Gill et al. 2000, Condes & Sterba 2005, Thorpe et al. 2010).

In the last decade, crown diameter models have been developed for cork oak (*Quercus suber* L.) by Paulo et al. (2002), Sánchez-González et al. (2007) and Paulo &

Tomé (2009). In particular, Paulo et al. (2002) developed a linear relation between diameter at breast height (dbh) and tree crown diameter (cw) with a limited data set collected on two typical low densities stands (varying from 67 to 97 tree ha<sup>-1</sup>). From a biological standpoint, linear relationships can only be applied to young stands, when both variables are in the linear phase of the growth curve. In older stands, the relationship between diameter and crown width growth is no longer linear. Therefore, the usage of linear models as done by Paulo et al. (2002) is considered not suitable for the application to a large geographical scale. A crown diameter mo-

del was developed by Sánchez-González et al. (2007) using a large data set from the second Spanish National Forest Inventory (NFI), where all trees with diameter at breast height above 7.5 cm were measured. Despite considering five alternative model functions (linear, parable, power, monomolecular and Hossfeld II), none of these was formulated in order to reflect biological characteristics, such as the existence of an upper asymptote in the relationship between diameter and crown width. The final selected model was a concave parabolic function which included the quadratic mean diameter under cork as independent variable and a value of zero for model interception. Due to its formulation, this model predicts, for some combinations of diameter at breast height and quadratic mean diameter, a decrease of tree crown diameter for larger diameters. Thus, this model also can not be considered suitable from a biological standpoint.

Despite several supporting measures for combating forest dieback across European Union countries (Requardt et al. 2009), cork oak tree mortality is currently increasing and is one of the main concerns for the future sustainability and productivity in Mediterranean oak woodlands. Its cause is likely due to the interaction of several biotic and/or abiotic factors (Sousa et al. 2007). According to the Portuguese NFI, a

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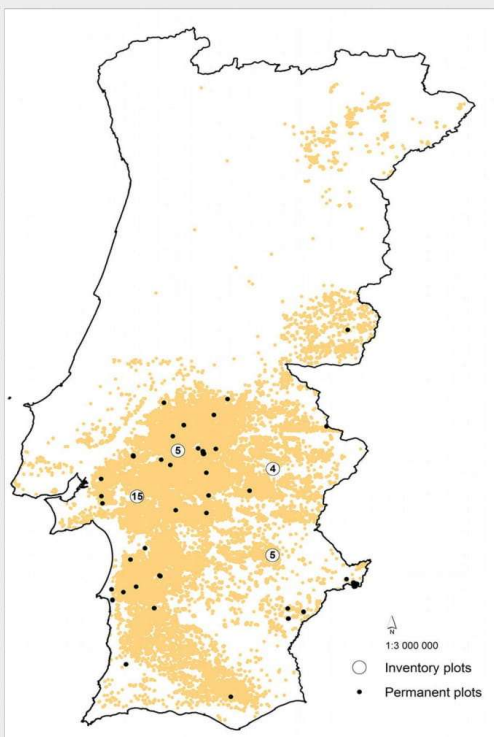
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Fig. 1 - Location of the sampling plots used in this study.



decrease in the stocking of stands has been recorded – from an average stand density of 85 to 65 trees ha<sup>-1</sup> –, as well as in stand basal area under cork – from 5.72 to 4.82 m<sup>2</sup> ha<sup>-1</sup> (DGF 2001, AFN 2010), with consequent losses in cork production and carbon sequestration (Paulo & Tomé 2010b, Coelho et al. 2012) that impact the Portuguese forests and economy. However, information is lacking on another variable that is important for the analysis of stand stocking, *i.e.*, stand crown cover.

Cork oak stands are generally managed as agroforestry or silvopastoral areas, with crown cover traditionally used for defining stand stocking limits according to the management objectives, *i.e.*, cork, pasture and/or animal production (Natividade 1950,

Montero & Cañellas 2003).

The main objective of this research is the development of a generalized non-linear model for the tree crown diameter prediction that can be used for a large range of tree diameter values and that is biologically representative, in order to allow its inclusion in growth and yield models such as the SUBER model (Paulo & Tomé 2010a, 2010b, 2014, Paulo 2011, Paulo et al. 2011), NFI data sets and other plot types where the lower threshold of diameter at breast height (dbh) over cork is 2.5 cm. All candidate models were formulated to ensure biologically meaningful predictions, as suggested by Burkhart & Tomé (2012). The developed model will be applied to the data from the last two Portuguese NFI (DGF 2001, AFN

2010), allowing the assessment of the evolution of stands crown cover in Portuguese cork oak stands between 1996 and 2006.

## Material and methods

### Data collection

Tree crown diameter (cw) was computed at tree level as the average of crown radius measurements taken on the four main cardinal points. The data set used to fit the tree crown diameter model consisted of 12 768 observations, measured on 320 permanent plots spread over the distribution range of cork oak in Portugal. Permanent plots had a circular shape with an area of 2827 m<sup>2</sup>. A set of independent observations was also used to validate the selected model. This additional data set consists of 1373 observations taken at 29 forest inventory plots (circular plots of 2827 m<sup>2</sup>). All plots were located in cork oak pure stands. Fig. 1 shows the distribution of the plots used in this analysis.

For both the above data sets the following stand parameters were calculated: number of trees per hectare (N), basal area (Gu), dominant diameter (dudom), dominant height (hdom) and quadratic mean diameter (dug). All stand variables related to tree diameter refer to diameter under cork (du in cm). This variable was computed by subtracting cork thickness (ct in mm) measured with a caliper on trees with mature cork (du = d - 2ct/10), or using the model presented by Paulo & Tomé (2014) for the estimation of dbh under cork in trees presenting virgin cork at breast height (undebarked trees). Only trees with dbh over cork > 7.5 cm were considered in the computation of the above stand variables. This definition allows the application of the proposed model in future national forest inventory data analysis. Nonetheless, the developed model can be applied to all trees over 2.5 cm of dbh over cork, as this threshold was used for tree measurements in the plots for both the fitting and the validation data sets. Due to the low average density of cork oak stands, dominant trees were defined as the 25 thickest trees per hectare (Paulo et al. 2015). The range of values characterizing the fitting and validation data sets is presented in Tab. 1.

A total of five distance-independent competition indexes were computed (Burkhart & Tomé 2012), namely: the ratio between the tree diameter under cork (du) and the dominant diameter (du\_dudom), between du and the quadratic mean diameter (du\_dug), and between du and the maximum diameter (du\_dumax). Additionally, two competition indexes (indicated as G>du, and G≥du,) were computed as the sum of the basal area of all trees with a diameter larger than the subject tree, and the sum of the basal area of all trees with a diameter greater than or equal to that of the subject tree, respectively.

Tab. 1 - Summary statistics of the data sets used for fitting and validate the models developed in this study. (du): diameter at breast height under cork; (cw): crown diameter; (hdom): dominant height; (dudom): dominant diameter; (dug): quadratic mean diameter; (N): number of trees per hectare; (Gu): basal area under cork.

Data set	Value	cw (m)	du (cm)	dug (cm)	hdom (m)	N (ha)	Gu (m <sup>2</sup> )
Fitting (n=12768)	Minimum	0.4	0.6	3.9	2.1	4	0.02
	Mean	4.7	20.7	18.5	9.1	291	8.03
	Maximum	19.8	128.9	57.3	18.2	929	30.12
Validation (n=1373)	Minimum	0.2	0.6	10.8	7.2	35	3.34
	Mean	4.9	21.9	18.8	8.5	375	10.91
	Maximum	21.5	112.7	48.5	11.9	792	39.11

**National Forest Inventories data**

The NFI carried out in 1995-1996, designated as IFN4 (DGF 2001), includes 371 measured plots, while the 2005-2006 NFI, designated as IFN5 (AFN 2010), includes 970 plots. Tree diameter at breast height was measured in both inventories, tree total height was measured for dominant trees in IFN5 and tree crown diameter was measured in sample trees in IFN4. Their values are published in official reports (DGF 2001, AFN 2010).

**Crown diameter model fitting**

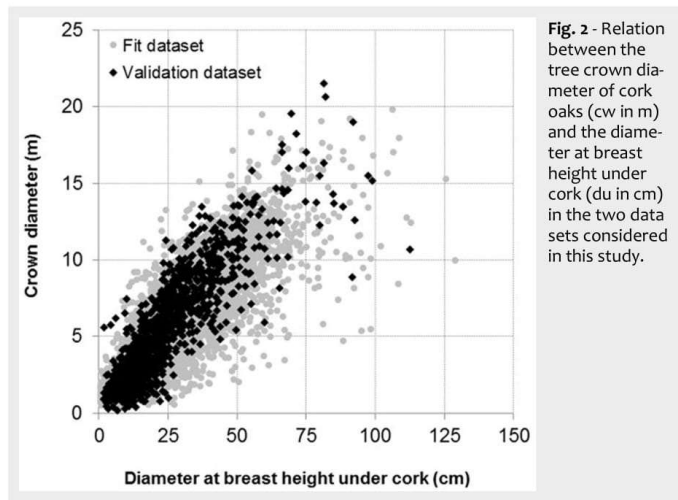
Candidate models for the relationship between tree height and diameter were obtained from the list proposed by Paulo et al. (2011). Among the 33 models originally proposed by Huang et al. (2000), Paulo et al. (2011) selected those increasing monotonically and showing an upper asymptote. The existence of an inflection point (Lei & Parresol 2001) was not considered compulsory, since the relation between tree diameter and tree crown variables did not show any inflection point. This is supported by data measurements observed for both the fitting and the validation data sets (Fig. 2), as well as by previous reports for cork oak (Sánchez-González et al. 2007) and other species (Condes & Sterba 2005).

Some of the candidate functions had to be modified from their original form in order to ensure consistent values at the point  $(du, cw) = (0, cw_0)$ , where  $cw_0$  is a positive value corresponding to the tree crown diameter when the individual tree reaches 1.30 m of total height. Since  $cw_0$  has to be estimated, such candidate models included an additional parameter as compared with their original formulation by Huang et al. (2000). No limits were considered for the number of parameters to be included in the model.

Overall, ten candidate models were selected for further analyses (see Tab. S1 in Appendix 1). Fitting of the selected candidate functions was carried out using the data from each plot and the nonlinear least squares (NLS) method implemented in the SAS® MODEL procedure (SAS Institute 2011a). To ensure meaningful estimates, only plots with more than 30 observations were considered. The mean square error of prediction ( $MSE_i$ ) for plot  $i$  was calculated for each candidate model as follows (eqn. 1):

$$MSE_i = \frac{\sum_{j=1}^{n_i} (\hat{\epsilon}_{ij})^2}{n_i - 1}$$

where  $\hat{\epsilon}_{ij}$  is the residual from the  $j$ -th tree in the  $i$ -th plot and  $n_i$  is the number of trees in the  $i$ -th plot. The sum of  $MSE$  obtained for each plot ( $\sum MSE$ ) was computed for each function, and used as a criterion to select the best-fitting candidate model (Paulo et al. 2011). Additional criteria were the adjusted R-square ( $adj-R^2$ ) and mean square error ( $MSE$ ) obtained by fitting each equa-



**Fig. 2 -** Relation between the tree crown diameter of cork oaks ( $cw$  in m) and the diameter at breast height under cork ( $du$  in cm) in the two data sets considered in this study.

tion to the complete fitting data set.

Values predicted by the selected model for each plot were plotted against the observed stand variables for all the parameters considered, as well as against the tree competition indexes values calculated for each corresponding plot and tree. In addition, regression analysis was carried out by ordinary least squares, in order to identify which parameters of the model were mostly related to the stand variables and/or tree distance-independent competition indexes. In order to avoid multicollinearity problems due to overparametrization of the model, only variables largely correlated with the estimated coefficients were included (Paulo et al. 2011). After the model parameters have been expressed as a function of these variables, the model was finally refitted using the complete fitting data set, and the significance of coefficients assessed by asymptotic t-tests.

Heteroscedasticity was frequently detected by plotting the studentized residuals versus the predicted values for each tree variable. To overcome this problem, two alternative weight functions were tested. The weight functions were defined as (eqn. 2, eqn. 3):

$$w_{ij} = \frac{1}{cw_{ij}^2}$$

$$w_{ij} = \frac{1}{e^{cw_{ij}}}$$

where  $w_{ij}$  is the weight given to the observation,  $cw_{ij}$  is the predicted value of crown diameter and  $i, j$  are the plot and tree indexes, respectively. The selection of the weight function was made based on the Akaike's information criterion (AIC) and MSE values obtained. The model obtained at this stage was designated as the fixed effects model.

The fixed effects model was finally refitted using a mixed model approach (Pin-

heiro & Bates 2000). Due to the nested structure of the data (trees inside plots), random effects associated to the plot were tested on each of the fixed model parameters using the SAS® macro NLINMIX (SAS Institute 2011b), and resulted in three alternative mixed effects models, whose formulation differed in the parameter including the plot random effect. The selection of the best-fitting mixed-effect model was carried out based on the Akaike's information criterion (AIC) and MSE values.

**Evaluation of model performances**

The evaluation of the predictive performance of the models (model validation) was carried out using the independent validation data set on the following models: (i) the fixed-effect and (ii) the mixed-effect models developed in this study; (iii) the fixed-effect model proposed by Paulo et al. (2002); and (iv) the mixed-effect model developed by Sánchez-González et al. (2007). The model proposed by Paulo & Tomé (2009) was not considered since its application is restricted to young trees.

The mixed effect model validation may be carried out considering the model population or subject specific response. The latter requires the measurements of the response variable (crown diameter) in a subsample of trees in the plot, a process called calibration procedure (Fang & Bailey 2001, Meng & Huang 2009). Since the models developed in this study were applied at data collected on forest inventories (where no measurements of tree crown diameter were made), the validation was carried out considering the population specific response. In this case, the mean responses were obtained with the fitted nonlinear mixed effects models by setting to zero the random effects. This allowed to test the usefulness of the inclusion of random parameters in the model in the case the calibration procedure was not applicable.

**Tab. 2** - Fitting statistics obtained for candidate models 1, 4 and 8. Only the models for which convergence was achieved in all plots are shown.

Model	SMSE	Adj-R <sup>2</sup>	MSE
1	57.99	0.800	1.81
4	57.82	0.806	1.76
8	58.27	0.806	1.76

Model efficiency was calculated as the proportion of variation explained by the model (*Ef* – eqn. 4):

$$Ef = 1 - \frac{\sum_{i=1}^n r_i^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where  $r_i$  is the residual for observation  $i$ ;  $y_i$  is the tree crown diameter for observation  $i$ ;  $\bar{y}$  is the mean value of the tree crown diameter from all the observations and  $n$  is the number of observations in the validation data set.

To evaluate the model bias, the mean value of residuals (*Mr*) was calculated as follows (eqn. 5):

$$Mr = \frac{\sum_{i=1}^n r_i}{n}$$

and the mean of absolute residuals (*Mar*) was computed to evaluate the model precision (eqn. 6):

$$Mar = \frac{\sum_{i=1}^n |r_i|}{n}$$

The 5<sup>th</sup> and 95<sup>th</sup> percentiles (*p5* and *p95*) of the distribution of residuals were also computed. Models obtained from the application to the validation data set were also compared by plotting their predicted values in the same diagram in order to help assessing their predictive performances.

**Analysis of stand stocking values in Portuguese cork oak stands**

To analyze pure cork oak stands stocking

from IFN4 to IFN5, tree crown diameter was estimated for each tree in the inventory plots using the model selected based on the criteria mentioned above. The predicted tree crown diameters allowed to assess the stand crown cover, expressed as a percentage. For each of the IFN4 and IFN5 data sets, these values were grouped into classes with a 10% range. Due to the low frequency of stands with more than 50% of stand crown cover, all stands above this threshold were included in a single class. Using the IFN4 values as a reference, percent variation of each crown cover class was determined for the period 1996-2006 (IFN4 and IFN5).

The average stand crown cover of pure cork oak stands in Portugal was computed for the years 1996 and 2006. Crown cover mean values of the IFN4 and IFN5 plots were compared using a two-samples *t*-test. Equal variances of the two samples compared was verified by an *F*-test.

**Results**

**Crown diameter model fitting**

The full list of candidate models tested in this study is reported in Tab. S1 (Appendix 1). Models 1, 4 and 8 had the best goodness-of-fit statistics and achieved convergence for all plots (Tab. 2). Models 4 and 8 performed slightly better than model 1, and were therefore considered for the further analyses.

The strongest relationships for model parameters were found between dominant height (*hdom*) in model 4 (parameters *b* and *c*) and *du\_dug* competition index (*i.e.*, the ratio between tree diameter and stand

quadratic mean diameter under cork) in model 8 (parameter *b*). In both models the parameter *a*, associated to the asymptote value, had the weakest relationship to any of the considered variables. As dominant height was not available in forest inventory data, model 8 (including the parameter *b* expressed as function of *du\_dug*) was selected for the next stage. The fixed effects model was therefore defined as (eqn. 7):

$$cW = 28.502 \cdot e^{\left( \frac{-66.436 + 4.201 \frac{du}{dug}}{19.817 + du} \right)}$$

Since the selected model includes three parameters, a total of three alternative mixed effects models were tested, each model including the random effect ( $u_i$ ) in one of the parameters *a*, *b* or *c*. The inclusion of a random effect to parameter *c* caused the model not to converge, as well as the inclusion of more than one random effect in the model. After comparison of the AIC values for the three alternative mixed effect models, the mixed model including a random parameter in the parameter *b* ( $u_b$ ) was selected. Hence, the random effect model was formulated as follows (eqn. 8):

$$cW = 25.123 \cdot e^{\left( \frac{-58.346 + 3.490 \frac{du}{dug} + u_b}{17.919 + du} \right)}$$

Tab. 3 reports the parameter estimates and variance components for both fixed- and mixed-effect crown-diameter models.

**Assessing predictive performances**

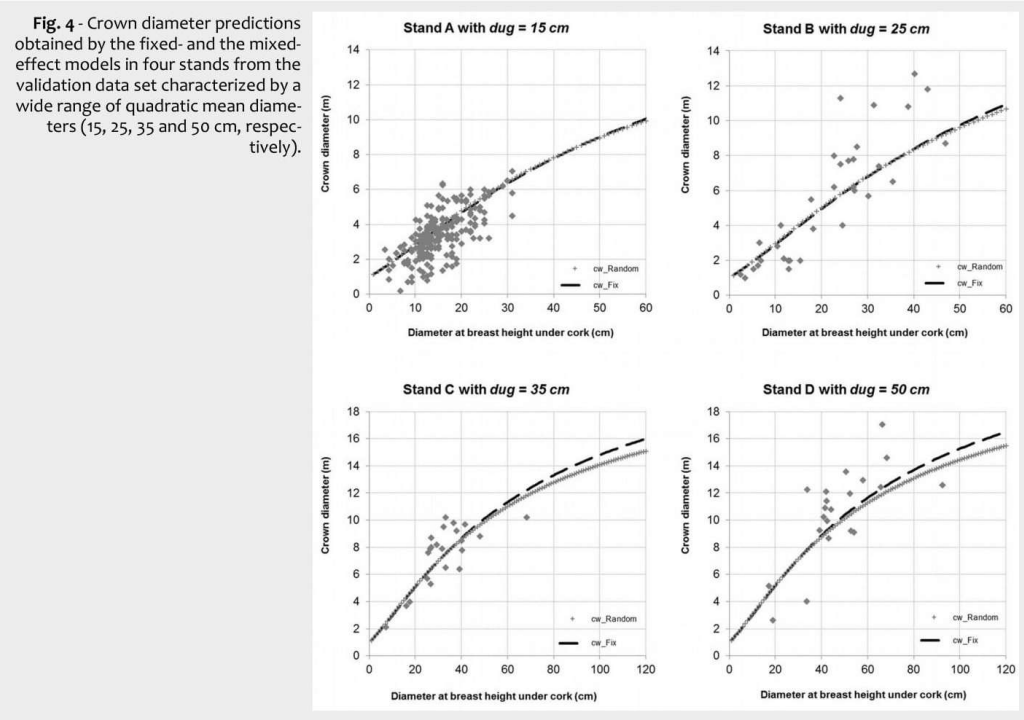
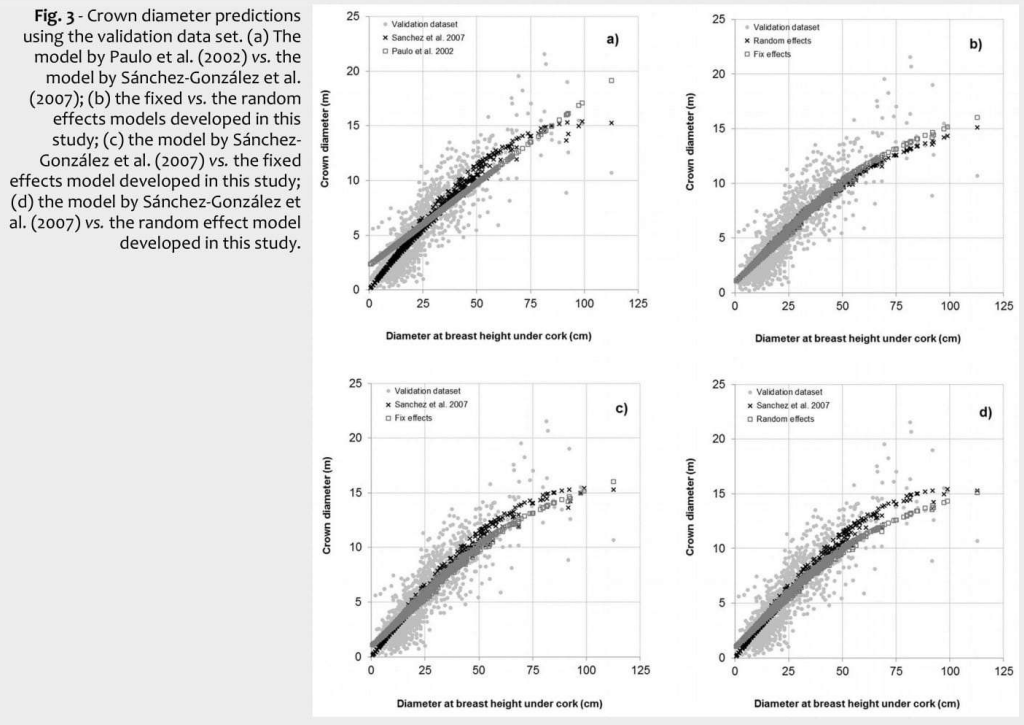
Validation statistics were used for the comparison of the predictive performances of the fixed and random models developed here, as well as of the models proposed by Paulo et al. (2002) and Sánchez-González et al. (2007). The results of the validation step are presented in Tab. 4. The fixed effects model developed in this study presented very similar results to those obtained using the model by Sánchez-González et al. (2007). Contrastingly, the model by

**Tab. 3** - Parameter estimates and variance components for the selected models.

Stats	Param	Fixed Effects Model			Mixed Effects Model				
		Estimate	Pr> t	Lower	Upper	Estimate	Pr> t	Lower	Upper
Fixed Parameter	<i>a</i>	28.5024	<0.0001	27.2894	29.7155	25.1226	<0.0001	24.0906	26.1546
	<i>b<sub>0</sub></i>	66.4364	<0.0001	63.0029	69.8699	58.3459	<0.0001	54.9818	61.71
	<i>b<sub>1</sub></i>	4.2013	<0.0001	3.7377	4.6649	3.4903	<0.0001	2.7093	4.2713
	<i>c</i>	19.8168	<0.0001	18.9521	20.6816	17.9188	<0.0001	16.8642	18.9733
Variance of random effects	-	-	-	-	28.0575	-	23.428	34.2169	
Residual variance	-	0.06374	-	0.06221	0.06534	0.04992	-	0.0487	0.05119

**Tab. 4** - Validation statistics for the fixed and random models compared in this study.

Model	Mr	Mar	p5	p95	EF
Fixed effects	-0.0101	1.1324	-2.1860	2.8087	0.794
Random effects $u_b$	-0.0410	1.1621	-2.2390	2.8416	0.785
Paulo et al. (2002)	-0.5927	1.5187	-2.8931	2.8028	0.700
Sánchez-González et al. (2007)	0.0307	1.0939	-2.1879	2.5433	0.806



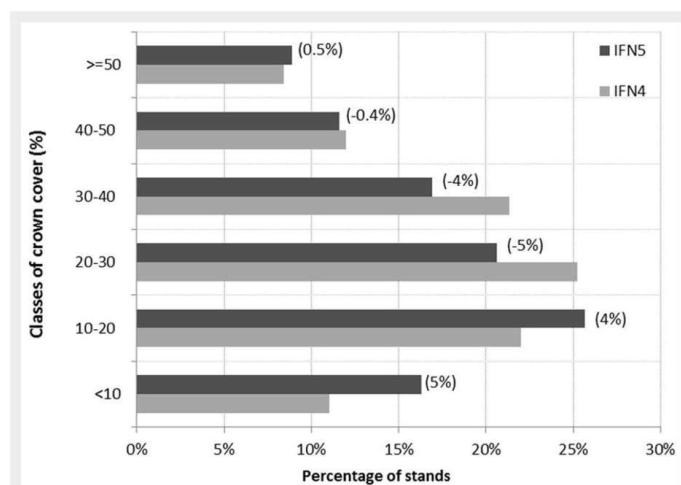


Fig. 5 - Frequency of classes of stand crown cover predicted by the fixed effect model using data from two different forest inventories (IFN4 - DGF 2001; IFN5 - AFN 2010). The differences (in percentage) of predicted values for IFN5 as compared with IFN4 are reported in brackets.

Paulo et al. (2002) showed the worst performances due to its linear formulation. Therefore, the fixed-effect model was selected for the analysis of cork oak stands stocking evolution.

The results of the validation step carried out for the models considered in this analysis are displayed in Fig. 3, where pairwise comparisons of their predicted values are shown: (a) the Paulo et al. (2002) model versus the Sánchez-González et al. (2007) model (Fig. 3a); (b) the fixed- versus the random-effects model developed in this study (Fig. 3b); (c) the Sánchez-González et al. (2007) versus the fixed effects model (Fig. 3c); and (d) the Sánchez-González et al. (2007) versus the random effect model proposed in this analysis (Fig. 3d).

The results of the application of the fixed- and random-effect models on four stands from the validation data set are shown in Fig. 4. These stands were selected in order to better analyze the model performances over a wide range of quadratic mean diameters (15, 25, 35 and 50 cm, respectively).

#### Evolution of stand stocking values in Portuguese cork oak

Average crown cover values of pure cork oak stands in Portugal were estimated to be 28.0% and 26.5% based on IFN4 and IFN5 data sets, respectively, resulting in a decrease of the average value by 1.5% in the period 1996-2006. Such difference was statistically significant after the application of the t-test ( $p < 0.05$ ). In addition, stands were grouped in 10% range classes of crown cover percentage, and for each class the difference in frequency between the IFN4 and the IFN5 was calculated (Fig. 5). The

differences between IFN4 and IFN5 ranged from 0.4-0.5% for high crown cover classes (> 40%) up to 4-5% for lower crown cover classes (10-40%).

#### Discussion

##### Crown diameter modeling

Although an asymptotic trend is expected in the relationship between diameter at breast height and tree crown diameter, several authors observed a linear relation between the two mentioned variables (Hasenauer et al. 1997, Condes & Sterba 2005, Sánchez-González et al. 2007, Paulo & Tomé 2009). This was also the case in this study, where a large range of values of tree diameter at breast height and crown diameter were analyzed (dbh up to 128.9 cm and cw up to 21.5 m). The underlying reason seems related to the size of trees included in the available data sets, that were far from their potential maximum growth. For example, Goes (1984) found monumental cork oak trees with dbh of 200 cm and more than 30 m crown radius, while Sánchez-González et al. (2007) reported a largest tree with dbh of 124.80 cm and a crown diameter of 17.45 m. This supports the hypothesis that the linear relationship between dbh and tree crown diameter observed in this study is due to the lack of old-growth, large trees in the available data sets.

Linear relationships are not considered suitable for the development of crown diameter models as they do not provide biological meaning for parameter values or predicted values (Burkhart & Tomé 2012). This is particularly important when models

are applied to a large range of tree and stand values. In this study, model selection has been carried out by restricting the choice to models with formulations that can provide adequate behavior to this purpose.

Another important issue concerning tree variable modeling is related with the nested structure of the data (trees within plots). Taking this structure into account, a mixed model approach was used including random parameters at plot level. This approach is commonly used in different sectors of forest research, e.g., modeling tree variable relation (Adame et al. 2008, Calama & Montero 2004, Paulo et al. 2011, Paulo & Tomé 2010a). Although the use of mixed models is suitable for the analysis of the data sets considered in this study, the computation of subject-specific responses is possible only when the predicted variable is measured in some individuals of the sample (trees inside plots). When these data are not available (as in our case), the calibration process is not carried out, the random effects are assumed to be zero, and a population average response can only be obtained. In nonlinear models, such as those applied for modeling tree crown diameter, population response estimates are not equal to estimates obtained with fixed effect models. This was demonstrated by Meng et al. (2009), who showed that when the calibration process is not accomplished, the fixed effect models result in lower prediction errors than the population response estimates. Similar results were obtained by De-Miguel et al. (2013). However, in order to enable the computation of the best predictions, results should include also the mixed-effect model parameters and the variance estimates when model calibration is possible (De-Miguel et al. 2013).

In this study, a distance-dependent competition index (the ratio between the tree diameter and the quadratic mean diameter) was included in the formulation of the model. Such index is related to the hierarchical position of each tree within the stand (Burkhart & Tomé 2012). Similarly, Paulo & Tomé (2009) and Sánchez-González et al. (2007) also found the quadratic mean diameter to be the most significant stand variable in their models.

Model comparisons carried out in this study revealed that the predictive performances of the developed fixed-effect model were similar to those obtained using the model by Sánchez-González et al. (2007). However, the absence of an asymptote value and the interception of the model made at when  $y=0$ , do not ensure a biological meaning to model predictions. The estimated value for the asymptote was 28.5 m for the fixed-effects model and 25.1 m for the random-effects model. The former value seems more suitable for the cork oak species, as compared with values obtained on monumental trees in Portugal (Goes 1984), while the latter has to be considered

too low. Furthermore, the model interception (corresponding to the tree crown value when total height reaches 1.3 m) was 1.00 m for the fixed effects model and 0.97 m for the random effects model. Both values are considered suitable for the species analyzed.

#### Evolution of stand stocking values for Portuguese cork oak stands

Crown cover percentage is traditionally one of the most important variables for the management of cork oak stands both in typical silvopastoral areas and in forest stands. Values recommended for management of these stands (Natividade 1950, Montero & Cañellas 2003, Serrada et al. 2008) are remarkably higher than the average value of 26.6% that currently characterizes Portuguese stands of cork oak, according to AFN (2010). Based on the estimates obtained using the proposed model, an increase in frequency of lower crown cover classes (< 20%) and a decrease in frequency of higher crown cover classes (20% to 40%) was observed for cork oak stands in Portugal between 1996 and 2006. Since the area covered by cork oak stands in Portugal has not changed in the same period based on the available data (DGF 2001, AFN 2010, ICNF 2013), two main causes may be hypothesized to explain the aforementioned reduction in crown cover percentage, namely, an increase of the area of new cork oak plantations and a decrease of the stocking in adult stands.

The low stocking of adult stands may lead to a decrease in the potential value of cork production, an increase of landscape fragmentation (Costa et al. 2014), and a decrease in tree regeneration of stands (Caldeira et al. 2014). In the long term, if the current trend will last, a large area of cork oak stands might be compromised in terms of sustainability of cork production. These results call for the definition of supporting measures for the protection of stands and for the increase of stand density by natural or artificial tree regeneration, both in pure forest and silvopastoral areas.

#### Conclusion

Forest inventories provide important data sets for stands characterization. However, tree crown diameter is frequently not measured in forest inventories, since it is time-consuming and cost expensive. Generalized crown diameter models allow to predict and evaluate crown cover, a relevant stand variable for cork oak stands management.

In this study, two generalized crown diameter models were developed, including a competition index that takes into account the effect of the position of trees in the stand structure on their crown diameter. Model evaluation, model characteristics and parameter estimation values highlighted that the fixed-effect model should be used when measurements of crown diameter are not available for the calibration

procedure, while the mixed-effect model should be chosen when model calibration is feasible.

The fixed effects model was applied to data from the two last Portuguese forest inventory data in order to assess changes of crown cover values in the period 1996-2006. Results showed a decrease in crown cover values of Portuguese cork oak stands, increasing the frequency of stands with less than 20% crown cover and decreasing the frequency of stands with 20% to 40% crown cover percentage. Average crown cover also decreased from 28.0% to 26.5% in the same period. These results highlight the constraints that may affect the sustainability of cork production in some stands in Portugal.

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### Supplementary Material

#### Appendix 1

**Tab. S1** – List of the candidate models analyzed in this study.

**Link:** [Paulo\\_1624@suppl001.pdf](mailto:Paulo_1624@suppl001.pdf)

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**Title**                    **III.2. Inter-tree competition pattern in undebarked cork oak plantations: outcomes for management**

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## Inter-tree competition analysis in undebarked cork oak plantations as a support tool for management in Portugal

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### Abstract

Scheduling the first thinning in young cork oak stands is an important decision in management that is usually subjectively defined by each manager. An analysis of competition in cork oak plantations is extremely relevant as a support for this important decision. This study aimed to understand the relationship between stand characteristics and tree growth efficiency, and subsequently help identify the presence or absence of an inter-tree competition pattern in cork oak stands that were never debarked. The inter-tree competition was assessed by looking to several stand characteristics: (1) comparison with the self-thinning line; (2) stand density measures, such as stand spacing coefficient and relative spacing; (3) stand structure measures evaluated through the skewness and variability; and (4) tree relative growth rate pattern over tree size. Data used for this analysis were gathered from permanent plots that were established in even-aged stands located across the cork oak distribution area in Portugal. The study shows that the most common stand densities on young cork oak plantations might not lead to serious inter-tree competition before the first cork extraction. This information is relevant to support the potential timing and severity of the first thinning in order to retain more trees until the second cork extraction when cork quality can be taken into account in the selection of the trees to be removed.

**Keywords** *Quercus suber* L. · Relative growth rate · Gini coefficient · Self-thinning · Relative spacing · Spacing coefficient · Skewness · Thinning

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## Introduction

Since cork production has an important role in the economic return of foresters, it is extremely relevant to ensure the future of the cork oak species area. Cork oak stands characterized by a low number of trees per hectare are traditionally managed as silvopastoral systems. The Portuguese official statistics identified an increase of cork oak plantation area during the last 30 years, which were established primarily in arable land (ICNF 2013). These young cork oak plantations may have initial stand densities higher than 800 trees-ha<sup>-1</sup> (IFAP 2018) that are significantly high when compared with the mature stands characterized by values around 66 trees-ha<sup>-1</sup> (AFN 2010). The impact of planting a higher number of trees per hectare has raised several questions by forest managers regarding the optimal stocking and thinning schedules on young cork oak plantations. However, the lack of research supporting decisions on this issue is still evident. Based on data from Portuguese national forest inventories (NFI), Fonseca et al. (2017) concludes that the existing cork oak stands in Portugal did not reached the species' maximum potential stocking. This study also discusses optimal densities based on the stand density index (SDI) and subsequently proposes the values of 45% for silvopastoral systems and 60% for cork oak systems. Natividade (1950) suggests the use of the spacing coefficient that is the ratio between the average tree distance and mean tree crown width, considering the value of 1.25 as the threshold below which inter-tree competition leads to a decrease in cork production.

Several authors in the forestry literature have addressed inter-tree competition. The methodologies proposed to evaluate and characterize tree competition are used both in forest modelling and in forest management planning (Burkhardt and Tomé 2012). Perry (1985) described concepts to evaluate the impact of competition on stand structure evolution and individual tree's growth efficiency, using plots from a thinning trial in *Pseudotsuga menziesii*. The evolution of the competition pattern in *Eucalyptus globulus* stands was evaluated comparing different conditions of site productivity and spacing (Tomé et al. 1994; Soares and Tomé 1996). In those eucalyptus young stands, the individual tree's relative growth rate in diameter decreases exponentially with tree size before the onset of competition and levels out when inter-tree competition affects the small trees' growth (Soares and Tomé 1996). Additionally, it is important to find if the dominant trees maintain their growth rate or if competition affects even the dominant trees (Binkley 2004). Brand and Magnussen (1988) defined one-sided competition, when smaller neighbors do not affect larger trees, and two-sided competition, when all the trees share resources. Larger trees usually capture more light than smaller ones, thus competition for light is usually assumed to be asymmetric (Binkley et al. 2006), while competition for water and nutrients is considered two-sided or sometimes as symmetric. In cork oak traditional stands, two-sided competition patterns are expected because light is usually not limited due to stands being sparse, hence water is the scarcest resource (Sarris et al. 2007). Cabon et al. (2018) study on *Quercus ilex* L. demonstrates that thinning increased growth at the stem level and discusses an optimal thinning intensity that maximizes tree growth and stand density as a function of water limitation. Premer et al. (2017) study focusing on forest restoration of a mixed forest was based on competition indices that reflect the competitive neighborhood and the thinning release.

The knowledge regarding the competition type and intensity present in a stand is extremely valuable to support the decision on silvicultural treatments' application with special relevance for thinning. The current lack of knowledge regarding the presence of competition in young cork oak plantations may limit the forest management design,

namely the thinning regime definition. The present study focuses on the analysis of inter-tree competition using information collected in cork oak even-aged stands never debarked that were regenerated by broadcast sowing or established by plantation, according to the forest management approach recommended by the forestry services across the 80s and 90s in Portugal. This forest management approach was designed with a high initial number of trees per hectare at planting in order to reduce the impact of heavy mortality that usually takes place in cork oak plantations. It is also suggested that the first thinning to reduce the number of trees should be performed a few years before the first cork extraction (Montero and Cañellas 1999; Pulido et al. 2003). When thinning takes place, the trees to be removed are selected by visual observation (poor stem forms or signs of weakness) and/or, particularly in plantations, in a systematic way in order to achieve the required number of trees per hectare. No information regarding their potential as future cork producers is available at this time since this can only be evaluated at the second cork extraction (first cork with properties similar to the future mature cork). Therefore, the systematic selection criteria of thinning may result in the removal of trees that would be good cork quality producers. The primary aim of this study is to contribute to the understanding of tree competition patterns in cork oak plantations before the first debarking operation. This information can be used to maintain the maximum number of trees per hectare that ensures tree competition at a light level until the second cork extraction, thereby allowing the assessment of cork properties and remove trees that produce low-quality cork.

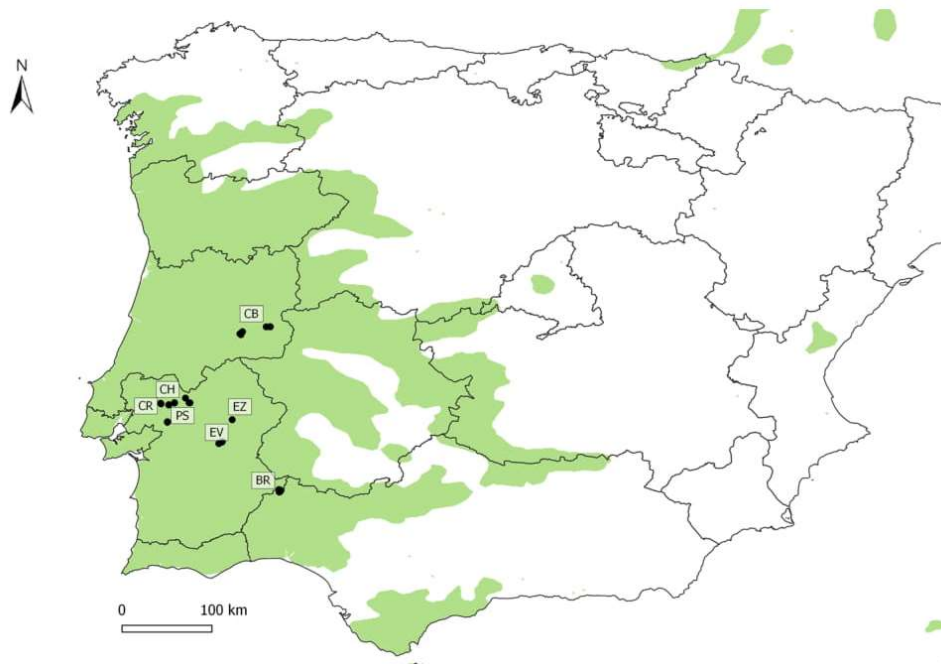
## Materials and methods

### Data collection

The dataset used in this study includes tree level information collected from a set of permanent plots monitored by the Forchange (Forest Ecosystem Management under Global Change) research group (at the Forestry research centre from Instituto Superior de Agronomia). The plots established in pure cork oak even-aged stands and located across the cork oak species major distribution area in Portugal (Fig. 1), cover different stand ages and stocking and were never debarked. A set of these plots were established to develop a model to predict site index for cork oak stands in Portugal, based on climate and soil variables (Paulo et al. 2015a). Some plots have been measured only two times and others more than three times, usually with an interval of 3 to 4 years. For each site, the forest manager has indicated when the stands were thinned and for some its severity level to reduce the stand density (Table 1). Trees were measured for diameter at breast height ( $d$ ) and total tree height ( $h$ ). Crown radius was not measured in all inventories, therefore crown width was estimated at the tree level using Paulo et al. (2015b) model. Stand characteristics were computed for each inventory year (Table 1). Dominant height ( $h_{dom}$ ) was calculated using the 25 trees per hectare with the largest diameter (as it is used in the Portuguese NFI due to the fact that most cork oak stands have less than 100 trees per ha) and site index estimated using the Sánchez-González et al. (2005) dominant height growth model.

### Characterization of the competitive status

The characterization of the competitive status was carried out at the plot level and along the repeated measurements. The analysis was based on several methodologies: (1) location



**Fig. 1** Natural distribution area of cork oak species (in green) for the Iberian Peninsula ([www.euforgen.org](http://www.euforgen.org)) and location in Portugal of the dataset region sites (see Table 1) and plots (black dots). (Color figure online)

of the plot in relation to the self-thinning line; (2) analysis of the spacing coefficient and of the relative spacing as measures of inter-tree competition; (3) analysis of the diameter distribution skewness and variability; (4) study of the relationship of individual tree relative growth rate (RGR) over tree size.

A stand reaches the maximum size-density or self-thinning, when resources no longer support additional growth and the suppressed plants eventually die. The concept of self-thinning law, introduced by Reineke (1933), assumes a linear relationship between tree size and stand density in logarithmic scales. In young stands, before intra-competition begins, Zeide (1987) refers a curvature instead of a straight line, which also may occur in older stands due to a decline in self-tolerance. The maximum size-density was graphically assessed, displaying all the plots jointly with the cork oak self-thinning line published by Fonseca et al. (2017).

Relative spacing (RS) measures competition through the relationship between average tree distance and dominant height ( $h_{dom}$ ). The RS incorporates the effects of site quality, stand age, and the forest species (Wilson 1946). It is usually computed based on a regularly spaced stand, thereby it is a useful measure to study the evolution of stand density ( $N$ ):

$$RS = \frac{100}{h_{dom}\sqrt{N}} \quad (1)$$

On the other hand, the spacing coefficient (SC) measures inter-tree competition by the ratio between the average tree distance and the mean crown width ( $\overline{cw}$ ):

$$SC = \frac{100}{\overline{cw}\sqrt{N}} \quad (2)$$

**Table 1** Plot characteristics identified by county acronym and site, which is separated by stand age (t, in years) and/or stand density (N, number of trees per hectare)

Region	Site	Plots	TH	t	N	dg	hdom	S	CC	
CH*	1	6		28	761	14.1	–	15	60	
		6	Yes	29	406	17.7	8.4	15	25	
		6		34	398	19.2	8.7	15	39	
CB	1	1		18	943	6.6	5.0	15	17	
		1		21	510	8.6	5.8	15	24	
		1		18	433	2.9	–2.9	12	5	
		1		21	400	3.1	3.5	12	6	
	2	1		7	494	2.2	2.5	17	5	
		1		10	500	6.5	3.5	17	19	
		1		7	360	0.3	1.7	16	1	
	3	1		10	355	3.6	2.9	16	9	
		3		3	19	443	9.6	4.9	14	25
		3	Yes	22	390	13.4	5.2	14	34	
EZ	1	1		9	680	4.4	2.6	16	31	
		1		13	610	6.3	3.8	16	30	
		1		16	580	8.3	4.8	16	32	
		1		19	545	10.2	5.3	16	39	
	2*	6		33	1383	12.6	7.6	14	73	
		7		39	765	15.1	8.9	14	79	
		7	Yes	42	400	18.5	9.3	14	47	
		7		45	397	19.5	9.1	14	69	
		7		50	399	20.4			75	
		7		57	390	22.0	9.5	12	84	
EV	1	1		9	877	5.4	3.8	17	24	
		1	Yes	12	562	9.4	4.6	17	31	
	2	5		14	298	8.1	4.7	16	17	
		5		17	287	11.5	5.9	16	25	
PS	F1	1		12	615	9.7	5.7	18	40	
		1	Yes	15	335	12.9	7.2	18	33	
		1		18	315	15.0	7.3	18	37	
	G1	1		12	400	2.9	4.0	16	5	
		1		17	395	6.9	5.8	16	13	
	G2	1		12	550	3.5	4.5	17	10	
		1	Yes	17	330	10.4	6.7	17	21	
BR*	1	2		36	67	21.8	6.4	12	7	
		2		42	67	25.5	7.7	12	17	
	2	4		33	179	18.4	6.7	13	13	
		4		39	178	21.9	8.0	13	34	
	3	2		39	200	19.0	8.2	14	20	
		2		45	165	23.2	10.0	14	41	

Table 1 (continued)

Region	Site	Plots	TH	t	N	dg	hdom	S	CC
CR	M1	2		7	223	2.4	3.0	18	4
		2		11	223	12.2	6.2	18	18
T = 16.0 °C		2		14	220	19.0	8.4	18	37
		2		17	220	21.5	9.3	18	51
P = 642 mm	M2	2		6	340	1.0	2.4	18	4
		2		10	330	7.7	5.0	18	14
	V1	2		13	295	11.8	5.9	18	23
		2		16	293	13.6	6.5	18	28
		2		9	138	2.3	2.5	16	2
		2		13	115	6.5	3.8	16	4
	V2	2		16	105	12.8	5.5	16	9
		2		19	103	16.1	6.7	16	13
		2		9	380	3.8	3.6	17	7
		2		13	355	8.2	5.7	17	16
	P1	2		16	353	13.2	7.9	17	34
		2		19	325	15.3	8.3	17	38
		2		15	318	9.9	5.8	17	19
	P2	2	Yes	21	233	19.5	8.0	17	40
		2		25	230	22.0	9.0	17	49
		2	Yes	21	240	23.9	8.8	17	57
	R1	2		25	240	26.3	10.1	17	66
		4		13	426	6.1	4.8	17	13
		4		16	403	10.7	6.2	17	28
		4	Yes	20	330	14.3	7.4	17	44
	R2	4		23	315	15.8	8.0	17	52
		2		13	150	7.5	15.2	17	8
		2		16	150	13.1	6.4	17	17
		2	Yes	20	143	17.3	8.0	17	26
		2		23	143	19.5	8.3	17	30

TH identifies the stand age where the thinning operation occurs, dg is the quadratic mean diameter over cork (cm), hdom is dominant height (m), S is the site index for the species standard stand age (80 years), CC is the crown cover percentage

\*Older stands identifier

Since crown width is a critical factor for spacing coefficient assessment, a quantitative check of the reliability of Paulo et al. (2015b) model, was performed for the plots with crown radius measured (see supplementary material).

Natividade (1950) suggests that cork production is affected when the SC takes values smaller than 1.25, corresponding to a percent crown cover close to 58% that still allows light inside the stand. However, the SC implies the measurement/estimation of crown radii, thus it is important to find a correspondence between the SC threshold and the RS that is

much easier to compute. To analyse the RS and SC relationship were used all the plots from the dataset.

In the analysis of the diameter distribution, the skewness takes particular importance. A population growing under high densities have a skewed distribution, by establishing a hierarchy between dominant individuals and suppressed ones over time (Harper 1977). To assess size variability, several authors indicate the use of several measures of the size distribution, such as measures of inequality, as the Gini coefficient (GC) (e.g. Tomé et al. 1994; Pretzsch and Schütze 2016). The GC, connected to the Lorenz curve, is usually applied in Economics to illustrate the income distribution within the population of a country. In forestry, it is used as an index to analyse stand variability in which higher values indicate that the distribution in a stand is very heterogeneous. To compute the GC, trees were first arranged in ascending order, using the *ineq* package of the R software (Zeileis 2014). Stand structure and variability can be influenced by thinning, thus to compute the skewness for the tree diameter at breast height by using software R, only the plots without thinning were considered.

The tree relative growth rate (RGR) is a measure of growth efficiency, reflecting the tree genetic potential, environment conditions and the competition effect. RGR over tree size allows assessing the beginning of asymmetric competition in young even-aged stands (e.g. Perry 1985; Soares and Tomé 1996). The RGR is the increase in size per unit of size and per unit of time. RGR was computed using tree diameter at breast height ( $d$ ) for the plots measured at least in three consecutive stand ages ( $t$ ) with different time intervals ( $i$ ):

$$RGR = \frac{\ln(d_{t+i}) - \ln(d_t)}{(t+i) - (t)} \quad (3)$$

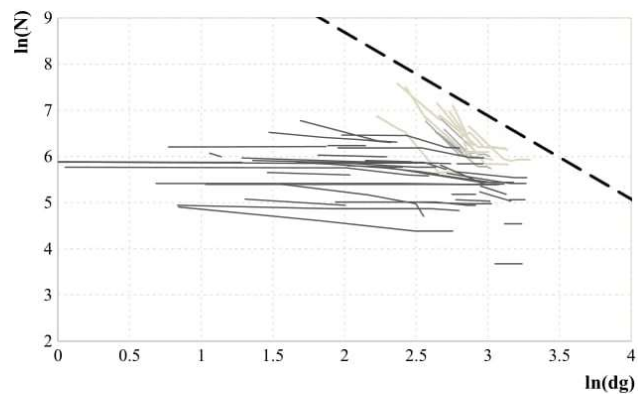
When competition is not present, smaller trees have greater growth efficiency than larger trees, which have higher maintenance costs, and the plot of RGR over tree size shows a decreasing pattern. Small and large trees with similar RGR values indicate that competition is on its early stage and the plot of RGR over tree size is nearly a horizontal line. Asymmetric competition is present when larger trees have greater growth efficiency, with signs of smaller trees suppression, and the plot of RGR as a function of tree size shows an increasing pattern.

## Results

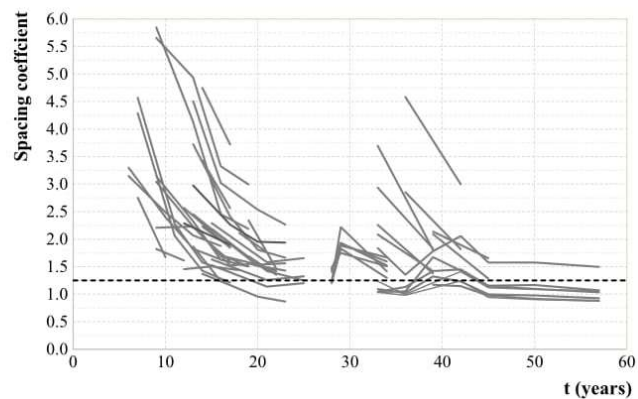
### Self thinning

The evolution of stands according to the self-thinning line indicates that for any increase in individual tree size, there is a decrease in stocking density as shown for cork oak in Fonseca et al. (2017). The distribution pattern for the majority of the plots sites characterized in Table 1 are still distant from the published self-thinning line (Fig. 2). This agrees with the expected deviation from the line in young stands as referred by Zeide (1987) and showed by Le Goff et al. (2011) in beech young stands. However, the older sites with high stocking, represented in Fig. 2 in light grey (CH and EZ2), are closer to this line displaying a decreasing linear pattern that is a characteristic of self-thinning.

**Fig. 2** Plot of the self-thinning line (dashed line) from Fonseca et al. (2017) together plot measurements. The grey lines are separately representing the subset of plots: light grey present CH and EZ2 sites with higher stand age and higher stocking (see Table 1), and dark grey present all other sites



**Fig. 3** Representation of the spacing coefficient evolution (SC) over stand age (t), for the sites described in Table 1. The dashed black line identifies the Natividade (1950) SC reference value



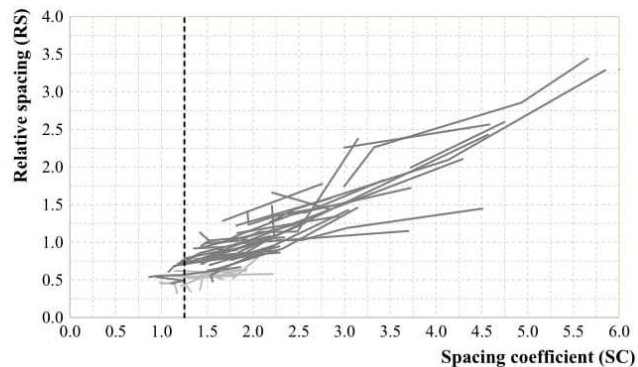
### Stand density measures

In general, the spacing coefficient (SC) computed for each plot site exhibited a decreasing trend with stand age (Fig. 3). The sites from older stands on the right of Fig. 3 (BR, CH, and EZ2), although having lower SC values, show a similar pattern to the other sites decreasing to values smaller than the value of 1.25. Additionally, the sites (CH, EZ2), where thinning occurred later than usual (usually before 20 years), indicate a peak as a response to thinning (Fig. 3). The relative spacing (RS) computed for each plot showed an increasing trend with SC (Fig. 4). Considering the SC reference value of 1.25, a parallel range of RS values between 0.6 and 0.8 can be observed for the plots from older sites (EZ2, CH).

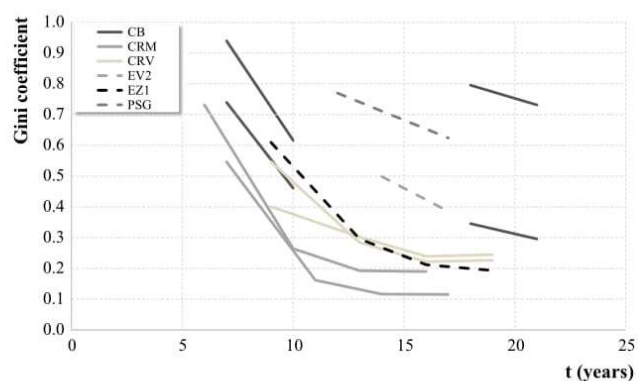
### Size distribution measures

The unthinned plots in Fig. 5 (see also Table 1) present an initially high Gini coefficient (GC), followed by a sharp decrease and leveling off with time. This trend denotes an initially stronger inequality of size between the trees, followed by a period of slight variability. The diameter distribution is initially positively skewed (right shallow), with several small trees and a few dominant individuals, and becomes descending with dominant height to skewness' values around zero, thereby indicating a tendency for a symmetric

**Fig. 4** Representation of the relative spacing evolution (RS) over spacing coefficient (SC). The dashed black line identifies the Natividade (1950) SC reference value; light grey present CH and EZ2 sites (see Table 1), and dark grey present all other sites



**Fig. 5** Representation of the Gini coefficient (GC) for the diameter distribution over stand age (t) for the unthinned sites (see Table 1)

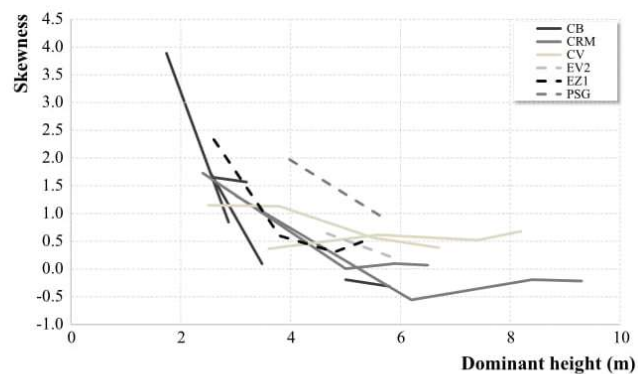


distribution (Fig. 6). Two plots from sites CB and CRM presented a different behavior (Fig. 6)—descending to negative values—that would correspond to a significant number of dominant and codominant trees and a small number of suppressed individuals.

### Tree relative growth rate over size pattern

The evolution of the relative growth rate (RGR) pattern in diameter over tree size of the study sites (see Table 1) are shown in Figs. 7, 8 and 9, in which each graph presents the RGR computed with the plot's consecutive measurements. Figures 7 and 8 display different initial spacing and stand ages lower than 25 years. Figure 7 presents the unthinned plots and Figs. 8 and 9 presents the thinned plots, in which the dashed lines represent the RGR response to thinning. The younger stands, with or without thinning, display similar RGR patterns over stand size and time (Figs. 7 and 8). In the initial stages, RGR is higher for smaller trees decreasing as a function of tree size. The RGR lines, when the stand is nearly 20 years, differs little among tree size with values around 0.05 and not related to thinning occurrence. The same successive RGR pattern is present regardless of the initial spacing. Figure 9 presents the plots from the site EZ2 characterized by high stocking, where the thinning occurred later than usual and considering three levels of thinning severity. The first two RGR lines before thinning at 42 years show a decreasing pattern with stand size, but with lower values than 0.05 as already referred for the younger stands. The lines immediately after thinning display a similar pattern for the medium and high severities where

**Fig. 6** Representation of the skewness over dominant height (hdom) for the unthinned sites (see Table 1)



trees respond to the release. After thinning, the two last RGR lines differ slightly among tree size, regardless of the thinning severity levels.

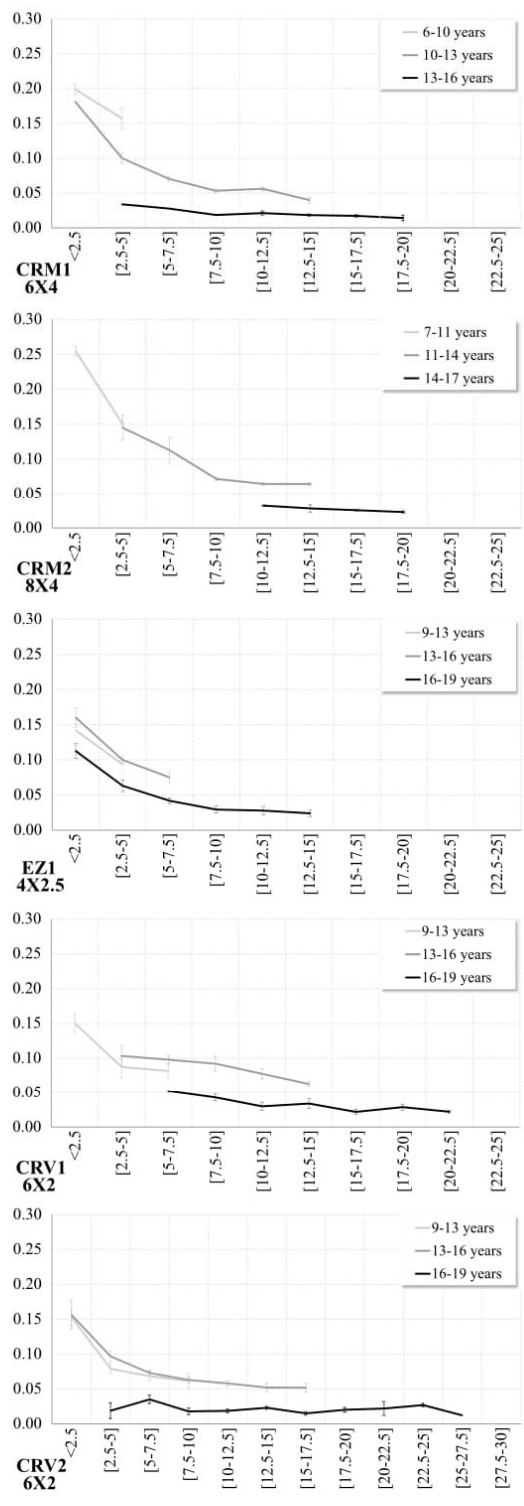
## Discussion

The present results are based on the analysis of a dataset covering the majority extension of the cork oak specie distribution area in Portugal. The dataset includes site indices ranging from 12 to 18 (Table 1) with distinct stand and edapho-climatic characteristics. Paulo et al. (2015b) presents the distribution of these site indices in Portugal and Palma et al. (2014) presents the potential distribution map for cork oak based on edapho-climatic boundaries. Additionally, these results may contribute for the improvement of growth and production models. For the cork oak species, available growth and yield models, such as ALCORNOQUE (Sánchez-González et al. 2007) and SUBER (Tomé 2004; Paulo 2011), the latter can be accessed at SIMFLOR platform (Faías et al. 2012), currently include only a few measures regarding inter-tree competition. However, none of these two models takes into account size-density trajectories, which could help to establish the individual mortality rules required to predict stand mortality, particularly in extreme conditions.

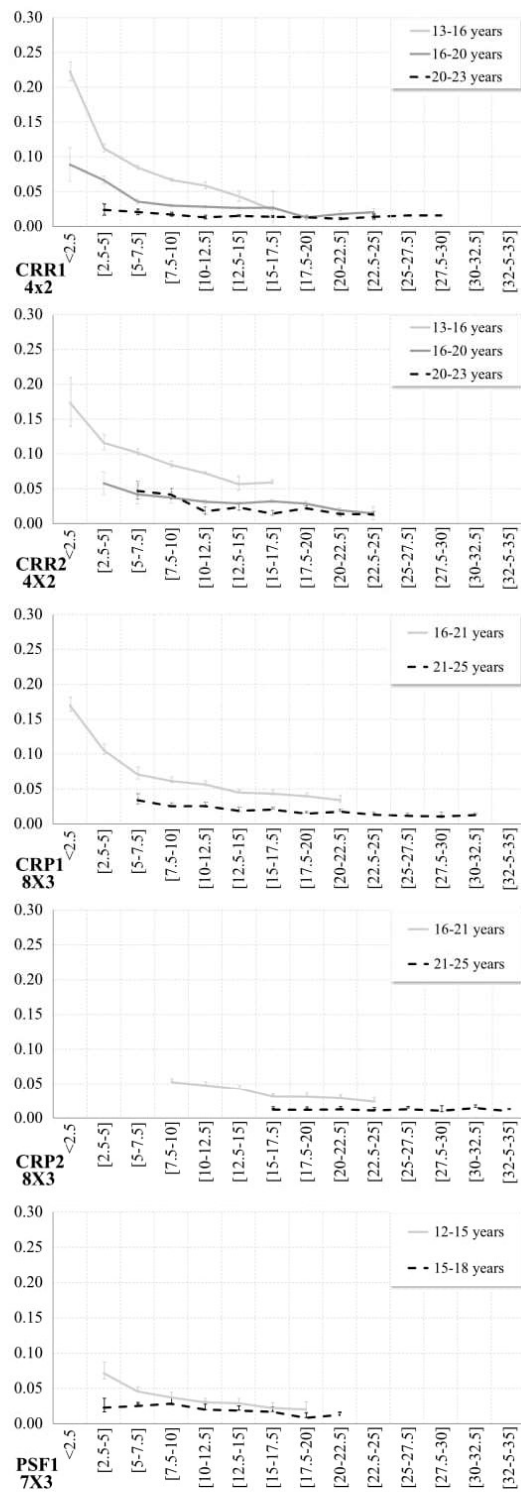
## Stand size-structure and variability

Using data from the last two published Portuguese forest inventories (DGF 2001; AFN 2010) and including research plots ranging between 10 and 265 trees per hectare, Fonseca et al. (2017) developed a self-thinning line for cork oak stands. Considering this line to discuss the proximity to self-thinning of the study stands, the majority with stand ages lower than 25 years are still far from their maximum potential stocking value and from the decrease slope tendency of the line. Plots from stands older than 25 years and with higher tree densities exhibit a distinct behavior and are closer to the Fonseca et al. (2017) curve. The evolution of the linear relationship between tree size and stand density in logarithmic scales for these older stands is typical from self-thinning stands (Le Goff et al. 2011), thereby suggesting that a thinning operation should be carried out soon. According to the Portuguese NFI measuring rules, trees bifurcated below 1.30-m are counted as individual trees. This feature is significantly common in cork oak trees since an individual tree can present up to five branches (Paulo and Tomé 2010).

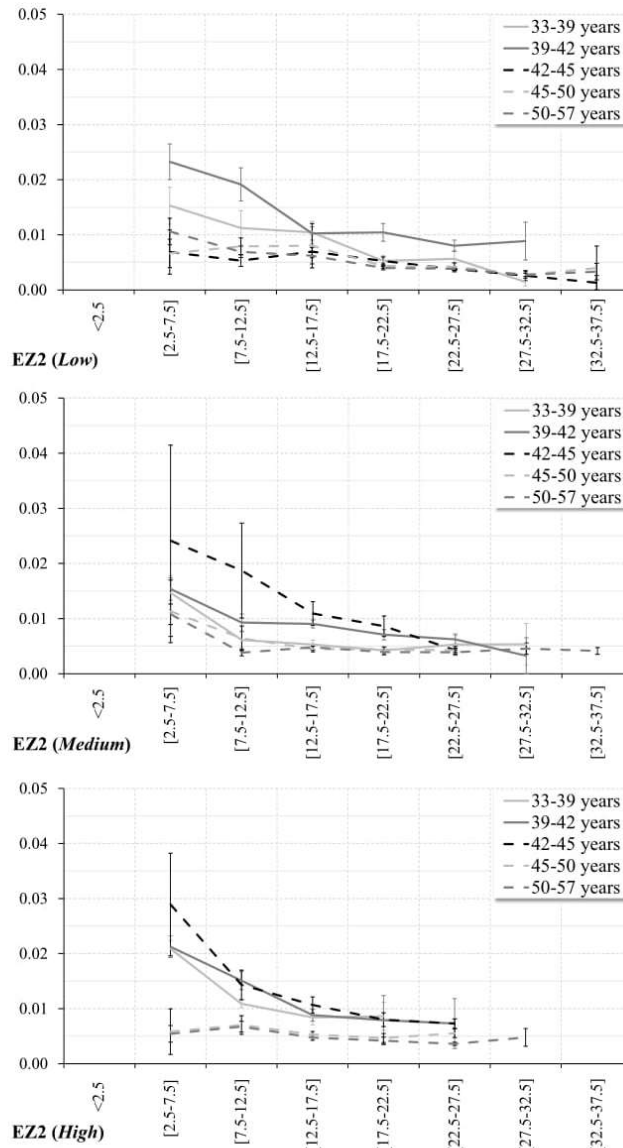
**Fig. 7** a CRM1, b CRM2, c EZ1, d CRV1, e CRV2. Relative growth rate (RGR) evolution over diameter classes for the unthinned plots selected from the study sites (see Table 1)



**Fig. 8** a CRR1, b CRR2, c CRP1, d CRP2, e PSF1. Relative growth rate (RGR) evolution over diameter classes for the thinned plots selected from the study sites with stand ages lower than 25 years (see Table 1). The dashed line represents RGR pattern after thinning



**Fig. 9** **a** EZ2. Relative growth rate (RGR) evolution over diameter classes for the thinned plots from the EZ2 site with low thinning intensity (see Table 1). The dashed line represents RGR pattern after thinning. **b** EZ2. Relative growth rate (RGR) evolution over diameter classes for the thinned plots from the EZ2 site with medium thinning intensity (see Table 1). The dashed line represents RGR pattern after thinning. **c** EZ2. Relative growth rate (RGR) evolution over diameter classes for the thinned plots from the EZ2 site with high thinning intensity (see Table 1). The dashed line represents RGR pattern after thinning



In the present study, when bifurcation occurs below 1.0-m, the first order branches are assumed as distinct individuals. However, the percentage of this occurrence is small due to the early formation pruning procedure. Regarding this definition of the number of trees per hectare, the published self-thinning line (Fonseca et al. 2017) might overestimate the stand density and consequently older stands from the present study may be closer to the line.

The linear relationship present between relative spacing (RS) and spacing coefficient (SC) may be a useful measure for forest management since computing RS does not imply the measurement of individual tree crowns. Natividade's (1950) threshold of 1.25 for the SC corresponds to RS values between 0.6 and 0.8 when the study stands (EZ2, CH) reach

an asymptotic tendency. These values characterize lower densities when compared to *Pinus pinaster*, traditionally managed in Portugal for RS values of approximately 0.20–0.28 (Fonseca and Duarte 2017). Perry (1985) relates the presence of competition in unthinned plots of *Pseudotsuga menziesii* to RS values around 0.75 and 0.87, when smaller trees are suppressed. The species ecology characteristics (shade or pioneer), tree crown shape (round or narrow) and management goals (wood and/or non-wood) might explain the distinct values observed for RS thresholds.

The diameter distribution over dominant height for the study-unthinned sites presented a skewness-descending pattern where the proximity of values around zero indicates a tendency for symmetric distribution. Similarly, Perry (1985) describes in *Pseudotsuga menziesii* stands an initial positive skewness that is established by fast early growth of sprinters that become negatively skewed as tree size increases and slower growers catch up. Furthermore, these unthinned sites showed a steeper decreasing pattern of the Gini coefficient over stand age, indicating a tendency to reduce size variability that is in line with similar results found by Pothier (2017) when focusing on tree species with five degrees of shade tolerance. The initial high size variability may be a consequence of the cork oak trees' adaptation to site conditions similar to the one observed by Tomé et al. (1994) suggesting that variability in young *Eucalyptus globulus* plots could be a response from seedlings transplanting. The spacing trials of eucalyptus in Soares and Tomé (1996) displayed a clear stand variability related to stand density, although at the same spacing stand growth tend to be similar. In other study on a eucalyptus hybrid clone established with different vegetation management practices was found greater variability between the trees in the weedy control at the canopy closure (Little et al. 2003). While considering the stand development for the present study cork oak sites, no distinctive pattern was found regarding their initial stocking range.

### Tree growth efficiency

In line with similar patterns found by some authors (e.g. Perry 1985; Tomé et al. 1994; Soares and Tomé 1996; Binkley 2004; Pothier 2017), the young stands of the present study in its early stage showed that smaller trees have higher growth efficiency than larger trees with higher maintenance costs. No differences in growth efficiency were observed between the young stands regarding their site index or initial stand density. In these young stands, at a comparable stand age, thinning did not produce a release since the relative growth rate in diameter over the same tree size was maintained. Therefore, the competition was not severe before thinning. On the other hand, the thinning procedure on the older stands with higher stocking revealed a tree response in the medium and heavy thinning severities and evidenced the presence of competition before this procedure. Those stands had high canopy cover before thinning (see Table 1) and the release according to Binkley (2004) changed the interaction in dominance. This indicates a hierarchy among trees in accessing the available resources (Pretzsch and Biber 2010). Shade-tolerant species use light lower intensity, which determines their competitive ability, Le Goff et al. (2011) shows that tree survival may be more affected in shade intolerant species stands, like oak, when compared to more tolerant species such as, ash or beech. The cork oak older stands under analysis, present a stand age interval lower than other inter-tree competition studies on oaks or evergreen species (e.g. Pothier 2017). Thus, these cork oak stands can be considered as an illustrative limit condition for the thinning occurrence, which under typical management conditions is performed on stands with less than 20 years before the trees reach a minimum size for the first debarking.

## Conclusion

The dataset used for representing the current cork oak plantations in Portugal allowed an analysis of the inter-tree competition level before the first cork debarking. This study contributes to forest manager's awareness regarding their stands competitive status, to help determining the thinning procedure for their stands.

Concerning those initial stand densities, the majority of the young stands are far from reaching their maximum size-density and far from reaching the crown cover limit from which cork production can be affected. The decreasing relative growth rate pattern over tree size showed that competition did not affect small trees' growth efficiency before an age of 20 years. However, older stands with higher density showed signs of inter-tree competition. Although it was not found a clear pattern indicating a growth efficiency loss, these older stands presented a response to a later thinning procedure when the thinning severity was more intense.

The results of this study suggest that the first thinning operation should be carried out when the stand is closer to a symmetric distribution, allowing 'slower growers' individuals to catch up. Assessing information about the stand growth pattern can support the decision of delaying thinning until the second cork extraction to obtain cork quality features and/or making a previous lighter severity thinning in order to maintain enough trees until the second cork debarking.

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## Compliance with ethical standards

**Conflicts of interest** The authors declare that they have no conflict of interest.

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## Tree diameter growth for cork oak stands in the Iberian Peninsula

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### ABSTRACT

Tree growth models have been an ongoing research to help predicting forest evolution and providing tools for forest management. A more accurate model for the cork oak tree diameter increment was developed considering stand variability, stand characteristics and intraspecific competition.

The Iberian region is known for its main contribution to the world's cork production. The present study compiled a unique Iberian dataset from shared information of cork oak trees measured in Portugal and Spain sites, spread along this species distribution in the Iberian Peninsula. The dataset includes different stand growth stages and cork debarking rotation cycles from 8 to 12 years. This wide dataset enhanced the awareness to implement a diameter growth model that can predict throughout different stands and their environment features.

Two approaches to predict diameter growth were compared: 1) an aged independent difference equation method – ADE; 2) a potential growth function multiplied by a modifier function expressing intraspecific competition – IPOTxM. Stand variability associated to climate and soil site conditions, was tested to include in both approaches, namely precipitation, evapotranspiration, temperature and soil group types. Both approaches were fitted applying an iterative procedure to update stand annual variables from the first to the second inventory. Competition indices with a negative correlation with diameter increment were included in both final models. Regarding site characteristics, only precipitation was positively correlated with diameter increment in the potential growth equation. Comparing with the IPOTxM approach, the developed ADE model revealed a better predictability for the diameter increment. However for the wood diameter increment prediction with the Spanish dataset, the IPOTxM is less biased and more precise.

**Keywords:** *Quercus suber*, competition indices, potential growth, modifier, age-independent difference equation

## INTRODUCTION

Individual tree growth models, when incorporated into decision-support systems, help to improve forest management by predicting stand development with the possibility to simulate a large range of thinning type and severity. In the case of cork oak species, growth and yield models, such as the SUBER (Tomé 2004, Paulo 2011) and the ALCORNOQUE (Sánchez-González *et al.* 2007) models, may also be a useful tool to determine the age at which trees may be debarked for the first time or the optimum cork extraction rotation.

Tree diameter growth may be influenced by tree genetic, environment, such as soil and climate, stand characteristics, tree size and inter-tree competition. Competition may be defined as an interaction between individuals about sharing a resource with limited supply, that influences tree growth patterns (Begon *et al.* 1986) and the stand structure (Perry 1985). The functions used to quantify competition range from simple formulations, expressing the tree hierarchical position within the stand, to complex indices expressing distance, size and number of local neighbours. Foresters designate the later as distance-dependent competition indices and the first as distance-independent indices (Munro 1974). Burkhart & Tomé (2012) made the state-of-the-art on how to consider local competition in tree growth modelling and point out that studies comparing the performance of the two indices types did not found a large improvement, or no improvement, when using distance-dependent competition measures.

Tree growth has been successfully modelled by first estimating the potential growth for a tree of a particular size without competition and then multiplying by a modifier function scaled between zero and one in order to take into account reduction in growth due to inter-tree competition (e.g. Arney 1985, Soares & Tomé 2003, Murphy & Shelton 1996). The potential growth can be defined as the species potential growth or as the potential growth for a specific site. In the first case, the potential growth depends just on tree size and the modifier(s) include the effects of site, stand characteristics and inter-tree competition. In the second case, the potential growth is given by the tree size, stand conditions and environment. The modifier characterizes the impact of inter-tree competition where a value of one indicates no impact on the potential growth, and a value of zero indicates that the tree is so suppressed that no growth occurs. Growth functions expressed as difference equations have also been often used by modellers to estimate tree and stand growth (e.g. Bailey & Clutter 1974, Sánchez-González *et al.* 2005, Almeida *et al.* 2010). Tomé *et al.* (2006) have proposed the use of age-independent difference equations for eucalyptus and cork oak species in Portugal.

Trees measurements are usually with an interval length that may cover several years and differ between plots, fact that becomes a challenge in tree diameter growth modelling as first noted by Cao (2000). Growth equations commonly predict annual diameter growth using stand

attributes from the beginning of a growth period but they are fitted using an average annual growth rate as the dependent variable and the values of tree and stand variables at the beginning of the measurement period. Cao (2000) pointed out that this assumption is too simple because stand and tree variables change annually. Subsequently, he proposed an iterative method to account for yearly values of tree and stand variables by fitting tree survival and growth when data are available for periods larger than one year. Crecente-Campo *et al.* (2010) and Nunes *et al.* (2011) compared the proficiency of two models, one fitted using a variable growth rate through an iterative approach and the second based on a constant growth rate approach and concluded that the variable growth rate approach performed slightly better than the constant growth rate approach.

Cork oak is a very important species in the Iberian region which is responsible for 80% of the world's cork production (APCOR, 2018). Hence, it is crucial for forest managers to have tools to simulate stand growth under different management alternatives that they can use to support management decisions. For the cork oak species, two tree diameter growth models are available: 1) a growth model for dominant trees using the age-independent difference equations approach (Tomé *et al.* 2006) and 2) a model of the potential times modifier type (Sánchez-González *et al.* 2006), but in which inter-tree competition is not taken into account. The main objective of this study was to develop a more accurate distance independent diameter growth model for cork oak stands in the Iberian Peninsula, considering the variability associated with different climatic and soil conditions and inter-tree competition. Two approaches to predict tree diameter increment – age-independent difference equation and potential diameter growth multiplied by a modifier – were compared and fitted with an iterative method that allow different growth rates within the measurement periods.

## **MATERIAL**

The study was based on an Iberian dataset that joined the data from permanent plots located in several sites across Portugal (PT) and Spain (ES). The dataset gathered unpublished data and data used to developed country models (Sánchez-González *et al.* 2006, Montero 1987, Paulo & Tomé 2017). The plots are located in 28 sites from different ecological regions (Table 1) spread along the cork oak distribution area in the Iberian Peninsula (Figure 1). The sites include areas of pure, even-aged and uneven-aged stands, where trees are being explored for cork production. Tree diameter at breast height under cork (*du*) was obtained from the perimeter taken after debarking, the most interesting variable in cork oak, and from now on designated as diameter. The annual wood diameter increment (*idu*) was initially computed as the difference between the tree diameters measured in consecutive debarking years divided

by the time interval of the cork rotation period (Figure 2). Due to the low density of the Portuguese stands, the dominant trees were classified as the 25 largest in du trees per hectare; however, Spanish stands used other definition, the 100 largest in du trees per hectare, due the higher stand density of these stands.

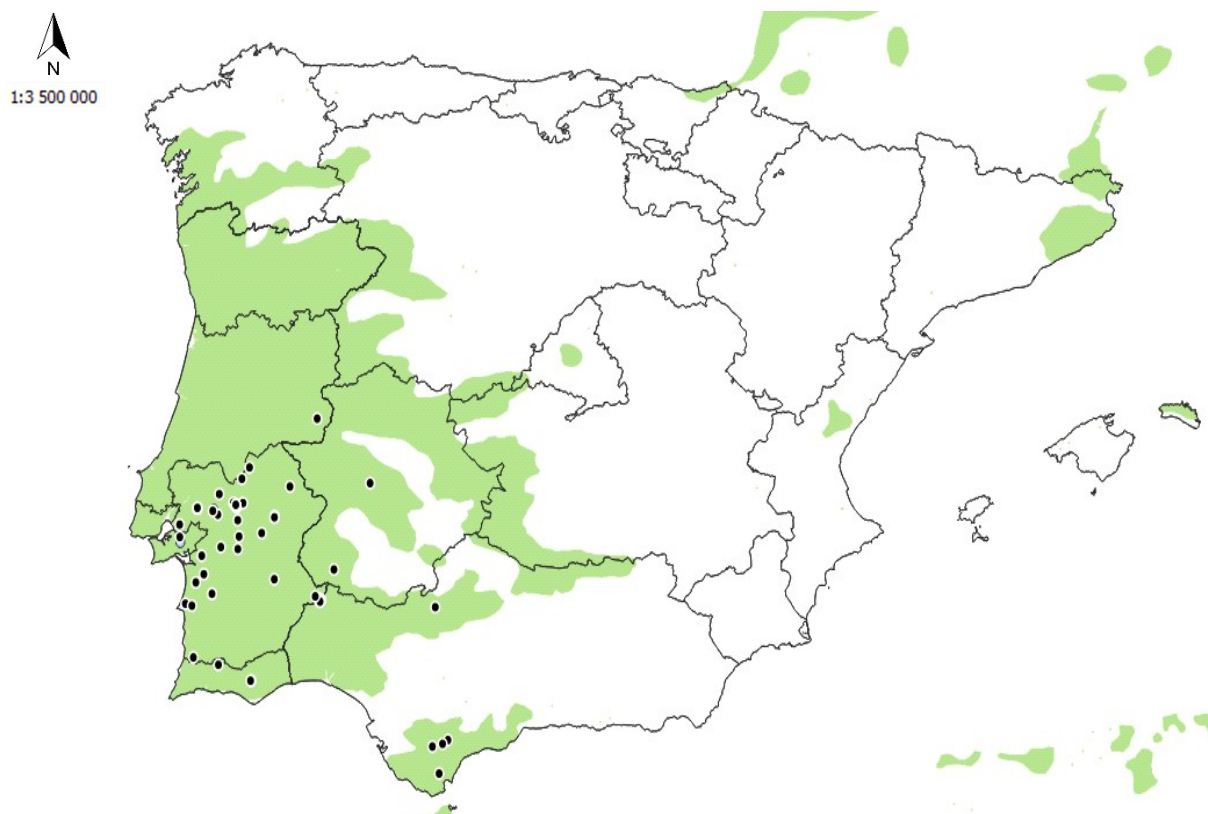


Figure 1. Natural distribution area of cork oak for the Iberian Peninsula (EUFORGEN 2009, [www.euforgen.org](http://www.euforgen.org)) and localization of the sites from the dataset with NUTII region delimitation.

Accessing the digital cartography available at the Portuguese Agency for the Environment website (<http://sniamb.apambiente.pt/webatlas/>) soil type and soil parameters were gathered for the Portuguese regions. The soil information for the Spanish regions was gathered from the soil database used in Fernández-Getino & Duarte (2016). The climate variables for Spain were obtained from the meteorological station nearest from each plot, available at GEOPORTAL ([www.mapama.gob.es/](http://www.mapama.gob.es/)), and for Portugal from the meteorological station nearest to each plot, obtained from the network of the Portuguese Meteorological Service ([www.ipma.pt/](http://www.ipma.pt/)). Table 1 shows, for each site: T, mean annual temperature (°C); P, mean annual precipitation (mm); ETP, mean real evapotranspiration (mm); the most frequent FAO soil group according to the IUSS Working Group (2006); and soil parameters: pH and top organic carbon content (OC), calculated using the function in Fernández-Getino & Duarte

(2016) ( $OC = 3.65811 - 0.38396 \times pH$ ). Fernández-Getino & Duarte (2016) published an Iberian map with the distribution of the main soil groups. The Podzol soil type is only available for the Portuguese dataset which distribution overlays the blank area of Fernández-Getino & Duarte (2016) map.

Stand characteristics were computed at the start of each cork rotation period (Table 2), namely: *dumin*, *dumax*, *dudom* and *dug*, respectively the minimum, maximum, dominant and quadratic mean diameters (cm); *N*, number of trees per hectare; *Gu*, basal area per hectare under cork ( $m^2$ ). The dataset includes a total of 6560 trees corresponding to 204 plots, where 9 plots had trees from two different cork debarking cycles. Therefore, all the trees were debarked at least twice, with debarking rotation periods from 8 to 12 years. This Iberian dataset was split in order to obtain a validation dataset not used in the models fitting, where the plots with two debarking cycles were not split in order to maintain data independence. The complete dataset was stratified by NUT II region, soil type and cork rotation (*tc*), and 10% of the plots in each strata with more than one plot were randomly selected for validation. The following procedure was applied: a random number was obtained for each plot, and the plot was selected for validation if the random number was higher than 0.10. The fitting dataset included 189 plots and the validation dataset 24 plots (Table 3). Site index (*S*) for the Portuguese plots was estimated with the M2 model developed by Paulo *et al.* (2015). For the Spanish plots from Cadiz (Andaluzia) *S* was estimated using the dominant height growth model developed by Sánchez-González *et al.* (2005). For the other Spanish sites was estimated with the model M2 in Paulo (2011).

Table 1. Distribution of plots by site, soil type and climate. Identifier of the NUTII region for each site within brackets.

Site	Plots	tc	P	T	ETP	Soil type	pH	OC
(J) Alcacér do Sal	1	9	572	16.3	500	Podzol	5.0	1.7
(J) Avis	1	9	617	16.1	600	Podzol	5.0	1.7
(J) Abrantes	1	9	677	15.5	600	Podzol	5.0	1.7
(J) Benavente	1	9	646	16.7	600	Podzol	5.0	1.7
(J) Coruche	15	8,9,10	642	15.9	600	Podzol	5.0	1.7
(J) Grandola	1	9	609	15.6	600	Podzol	5.0	1.7
	1	10			500	Regosol	6.0	1.4
(J) Estremoz	4	10	590	15.4	500	Luvisol	7.0	1.0
(J) Évora	1	9	625	15.7	450	Luvisol	6.0	1.4
	1	10	669	15.5	600		7.0	1.0
(J) Mora	35	9	617	16.1	600	Podzol	5.0	1.7
	1	11				Luvisol	6.0	1.4
(J) Moura	9	9	689	16.2	450	Regosol	6.0	1.4
(J) Montemor-o-novo	2	9,12	669	15.5	500	Luvisol	6.0	1.4
(J) Odemira	1	10	587	15.1	600	Luvisol	6.0	1.4
(J) Ponte-de-sôr	1	9	617	16.1	600	Podzol	5.0	1.7
	1	11	677	15.5		Podzol	5.0	1.7
(J) Portalegre	1	9	889	15.1	500	Cambisol	5.3	2.7
(J) Portel	1	9	544	15.5	500	Luvisol	6.0	1.4
(J) Santiago-do-Cacém	1	12	493	15.7	500	Regosol	6.0	1.4
(J) Sines	1	11	493	15.7	600	Podzol	5.0	1.7
(G) S.Brás-de-Alportel	1	9	523	17.2	600	Regosol	6.0	1.4
(C) Idanha-a-nova	1	9	632	15.4	500	Luvisol	6.0	1.4
(L) Palmela	2	9	735	16.1	600	Podzol	5.0	1.7
(X) Badajoz	15	9	666	15.9	1100	Regosol	5.1	1.4
(X) Caceres	15	9	654	15.2	1100	Regosol	5.1	1.4
(A) Cadiz – BRR	15	9	1065	15.4	1200	Cambisol	5.3	2.7
(A) Cadiz – MAJ	16	9,11	900	15	1100	Cambisol	5.3	2.7
(A) Cadiz – ROB	30	9,10,12	900	15	1100	Cambisol	5.3	2.7
(A) Cadiz – SAU	13	9,10,12	900	15	1100	Cambisol	5.3	2.7
(A) Sevilha	15	9	918	13.5	900	Regosol	6.4	1.0

tc, cork rotation (years); P, mean annual precipitation (mm); T, mean temperature (°C); ETP, real evapotranspiration (mm), OC<sub>1</sub> organic matter content (%)

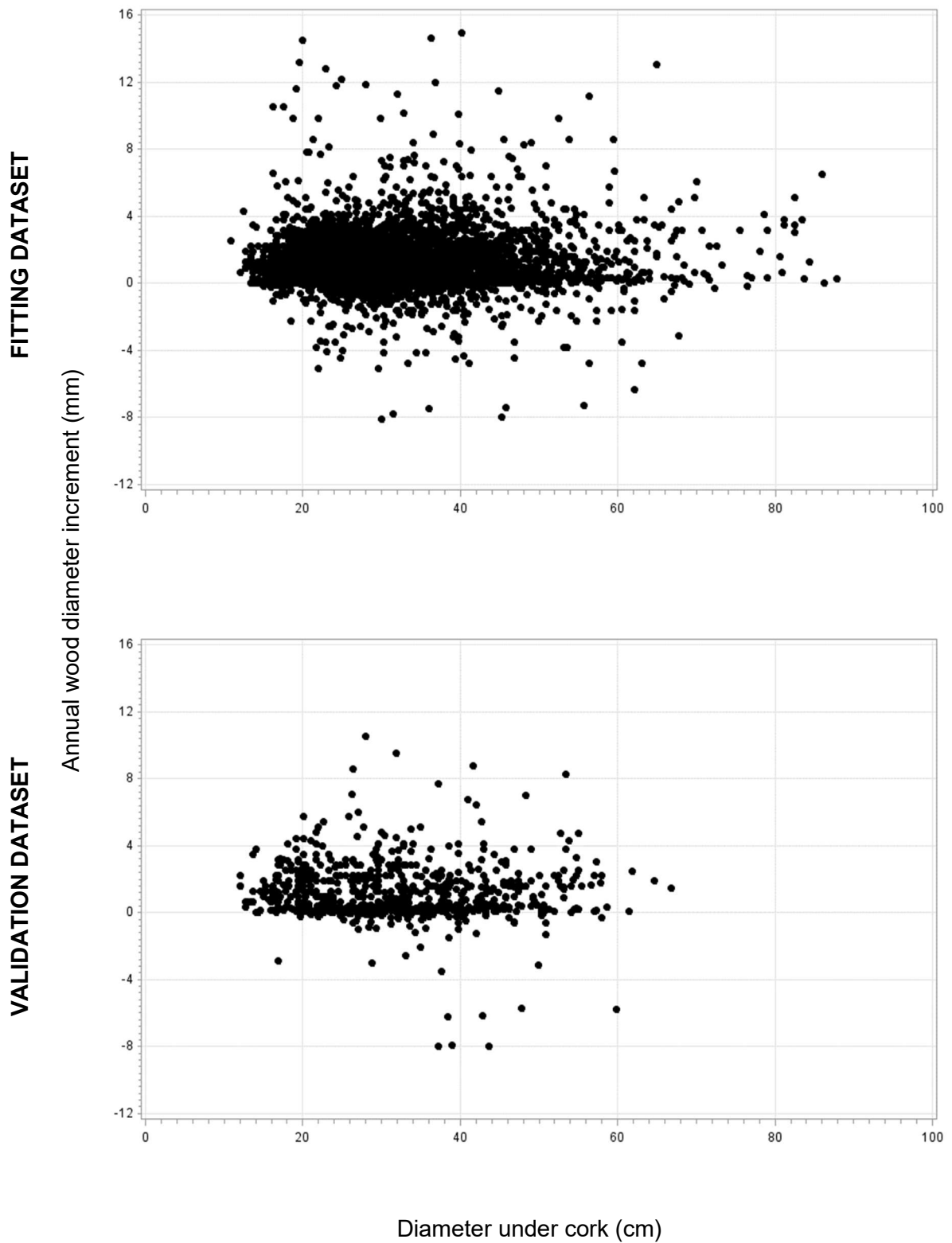


Figure 2. Annual wood diameter increment (mm) distribution over diameter under cork (cm).

1 Table 2. Descriptive statistics for the stand variables at the starting year of each measurement period (cork rotation).

Region NUT II	tc	Plots	Fitting dataset						Validation dataset						
			idu		dudom		N		idu		dudom		N		
			min	max	min	max	min	max	min	max	min	max	min	max	
Alentejo (J)	8	9	-5.1	4.6	22.8	39.9	46	135	–						
	9	62	-8.1	14.5	20.4	96.8	21	251	5	-2.1	7.1	24.4	52.0	74	222
	10	6	-2.9	6.8	45.8	75.2	60	198	3	-8.0	9.6	41.4	50.7	117	187
	11	2	-3.8	7.0	45.6	52.8	131	170	1	-0.3	8.3	48.8		120	
	12	1	-3.1	15.0	70.4		187		1			42.5		170	
Algarve (G)	9	1	-0.6	3.8	41.8		104		–						
Centro (C)	9	1	1.9	7.5	57.1		74		–						
Setubal (L)	9	1	0.2	5.7	68.2		113	1	-7.9	10.5	53.4		70		
Andaluzia (A)	9	71	-1.5	4.5	28.4	76.1	32	336	8	-1.0	2.5	26.3	53.3	42	208
	10	5	-0.6	0.9	30.6	45.9	192	422	1	-0.2	1.9	39.7		200	
	11	1	0.0	0.3	39.3		135		1	-0.2	0.5	29.9		326	
	12	1	-0.2	0.6	44.5		224		1	0.0	0.4	34.2		304	
Extremadura (X)	9	28	-15.3	14.6	28.8	54.6	64	366	2	-8.0	5.7	34.5	47.6	96	472

dudom is dominant diameter at breast height (cm), N is the number of trees per hectare and Gu is the basal area per hectare (m<sup>2</sup>).

2



## METHODS

Two different approaches were tested for the diameter increment modelling: 1) an age-independent difference equation (ADE) and 2) a potential growth function multiplied by an inter-tree competition factor or modifier (IPOTxM).

### Age-independent difference equation

When modelling tree growth it is important to use functions that have a shape compatible with the principles of biological growth (Burkhardt & Tomé 2012): i) the curve limited by the value zero at a specific beginning ( $t=0$  or  $t=t_0$ ); ii) the existence of an asymptote; iii) the relative growth rate should show a maximum in an initial phase and decreases thereafter; iv) the existence of an inflection point. Several functions follow these properties but they can be grouped in three family curves: Lundqvist-Korf, Richards and Hossfeld. Zeide (1993) using the differential form of the growth functions, found that all equations analysed could be decomposed either by a subtraction or by a division – subtraction of logarithms – of the two components: growth expansion and growth decline. Two basic forms were found differing in the decline component: in the first form (LTD) the decline is proportional to the logarithm of age, while in the second form (TD) it is either a power function or an exponential function of age. The first leads to the Lundqvist-Korf and Hossfeld functions while the second to the Richards function. By these findings, Zeide (1993) shows that the functional form of the growth must be species-specific. In the case of cork oak, previous authors (Almeida *et al.* 2010, Tomé *et al.* 2006, Sánchez-González *et al.* 2005) found the Richards growth function to be the most appropriate for cork oak, reason why this function was adopted for the present study. The Richards function includes three parameters:  $A$ , an asymptote;  $k$ , related with the growth rate; and  $m$ , a shape parameter.

The majority of cork oak stands are uneven-aged or most of the times with unknown stand age ( $t$ ), thus the age-independent formulation of a growth function as a difference equation (ADE), that does not include age (Tomé *et al.* 2006), was selected to model tree diameter increment with the Iberian dataset. In this function, the differences between stands and between trees within a stand is achieved by expressing at least one of the parameters as a function of site, stand and inter-tree competition variables (Tomé *et al.* 2006).

The ADE diameter growth model fitted using the entire dataset with the following formulation of the Richards function:

$$du_{it2} = A \left\{ 1 - e^{-k\Delta t} \left[ 1 - \left( \frac{du_{it1}}{A} \right)^{(1-m)} \right] \right\}^{\left( \frac{1}{1-m} \right)} \quad (\text{Equation-1})$$

where  $du_{(t1)}$  and  $du_{(t2)}$  are the diameter (cm) of the  $i$  tree;  $\Delta t=t_2-t_1$  is the time interval between consecutive  $t$  values.

### Potential growth x modifier (IPOTxM)

The potential growth was modelled by fitting a model for the diameter growth of the dominant trees using the Richards function formulated as an age-independent difference equation (Equation 1) with the parameters expressed as a function of site and stand variables. The inter-tree competition is part of the modifier ( $mdf$ ) that, multiplied by the potential growth ( $ipot$ ), allows for the prediction of tree diameter increment of a particular tree. The potential wood diameter growth (mm) is computed with the diameter taken from the dominant trees ( $idom$ ). The modifier was selected from a set of combinations based on the logistic or exponential functions (Soares & Tomé 2001) bounded between 0 and 1.

$$ipot = \frac{du_{idom_{t2}} - du_{idom_{t1}}}{\Delta t} \quad (\text{Equation-2})$$

$$mdf = \frac{1}{1+e^{-x}} \quad (\text{Equation-3})$$

$$du_{i_{t2}} = du_{i_{t1}} + ipot \times mdf \quad (\text{Equation-4})$$

The potential growth function was developed with the data set restricted to the dominant trees while the IPOTxM model (Equation-4) used the trees with diameter lower than the stand dominant diameter.

### Model development

A similar methodology was used to develop the ADE and IPOT models using the Richards formulation from Equation-1, where the asymptote parameter was fixed to the value 200 cm as in Tomé *et al.* (2006). In fact, the dataset does not include trees close to the asymptotic value for diameter leading to asymptote estimates that are not realistic and that may differ largely between models. This threshold (200-cm) was considered as the maximum acceptable diameter according to published data on monumental trees (Goes, 1984).

As a first step, the models were fitted with the  $k$  and  $m$  parameters not depending from site, stand or competition variables. A set of variables that could explain the differences in tree growth among sites, stands and trees within the stand, were selected namely: site index, soil and climate variables, stand characteristics and inter-tree competition variables. The four available soil types within the study were included as dummy variables. Several distance-

independent competition indices (Table 3) were tested in the ADE equation and in the modifier equation of the IPOTxM approach.

All the defined site and stand variables were tested in the  $k$  and  $m$  parameters from Equation-1, first as a single variable to evaluate the biological behaviour of the parameter sign associated to each variable, and then as some linear combinations of variables. The ADE and IPOTxM models with better performance were then fitted using the iterative procedure proposed by Cao & Strub (2008). The method starts by fitting the growth model assuming a constant growth rate along the growth period. Tree growth is predicted with this preliminary growth model and the stand and tree variables computed for each year, allowing to fit a new model with growth rate values that are different during the measurement interval. The procedure is repeated until the convergence of parameters estimates is achieved. Dummy variables were necessary to identify each different cork period length from 8 to 12 years, between inventories. The models were fitted with the PROC MODEL procedure of the SAS software 9.4 (SAS Institute Inc.).

Table 3. Distance-independent competition indices tested within the models.

Name	Formulation
<i>Relative tree dimension</i>	$icm = \frac{du_i}{X_m}$
<i>Proportional to the subject tree</i>	$APB = \frac{10000}{N} \times \frac{gu_i}{Gu}$
<i>Larger than the subject tree</i>	$BAL = \frac{1}{R_s} \times \left(1 - \frac{Gu_{>di}}{Gu}\right)$

$du_i$  is the tree diameter at breast height under cork;  $gu_i$  is the tree basal area under cork ( $m^2$ );  $X_m$  is a variable expressing the quadratic mean diameter at breast height under cork (dug) or maximum diameter at breast height under cork ( $du_{max}$ ), or the dominant diameter at breast height under cork ( $du_{dom}$ );  $N$ , number of trees per hectare;  $Gu$ , basal area per hectare under cork ( $m^2$ ).

### Model evaluation

Model evaluation included: i) the evaluation of the regression assumptions; ii) non-existence of serious collinearity among the independent variables; iii) significance and sign of the parameters associated with site, stand and inter-tree competition variables; iv) model efficiency and mean squared error.

The regression assumptions of normality and homocedasticity of errors were evaluated for each model. The non-normality of model errors, assessed with QQ plots, was overcome by

applying the Huber function for robust estimation (Myers 1990). The non-existence of serious collinearity between independent variables was assessed by the variance inflation factors. The modelling efficiency (EF), computed as an equivalent to the coefficient of determination for linear regression ( $R^2$ ), and the mean squared error (MSE) were compared among models to support the model ranking, and the significance of the parameters evaluated as well as their biological behaviour.

In order to compare both approaches, ADE and IPOTxM, the predictive performance of the selected models was carried out using the validation dataset (Table 2). The root mean squared error (RMSE) was assessed, as well as the mean value of the residuals (Mres) and the mean of the respective absolute value (Mares), used to evaluate the bias and the precision of the models, respectively (Soares *et al.* 1995). The residuals for the diameter growth over diameter classes were also analysed by country. In the case of the IPOTxM model, the evaluation was made using the observed potential growth and using the potential growth estimated with the selected IPOT model. This evaluation was important in order to separate the error due to the potential growth estimation and to the modifier.

## RESULTS AND DISCUSSION

### Selection of the model for the age-independent difference equation (ADE)

The site index (S) is commonly used in modelling to express the site conditions, but it requires that the age is known in even-aged stands. Otherwise site quality may be assessed by including into the models climate and soil variables as in Paulo *et al.* (2015) model to predict site index for cork oak. When testing the S variable, either in the k or m parameters, the estimates for the parameter associated with S were positively correlated with diameter increment.

Other independent variables expressing site characteristics were tested on the parameters k or m for the ADE model (Table 4). Soil type dummy variables for Luvisol and Podzol were significant in both parameters. Precipitation and temperature were also significant in both parameters but their signal did not agree with biological expectations. In what concerns stand variables variables expressing the general environment of competition (Tomé & Burkhart 1989), N and Gu, were significant but the sign of the parameter associated with Gu is difficult to interpret as it expresses an increase in growth that might be explained by the size of the trees and not by the competition environment. Stand variables related with tree size/age (dug, dumax and dudom) are highly significant and express an increase in growth. The distance-dependent competition indices expressed as the tree relative dimension are more significant

than APB or BAL, the last not significant. All the significant indices exhibit a correct sign, expressing a negative correlation with inter-tree competition (Table 4).

Table 6 shows the selected models that include a single regressor or a linear combination of regressor variables for the ADE models that were fitted with the iterative procedure. The relative tree dimension with the dominant diameter and stand density have a negative correlation with diameter increment. The Luvisol soil type in parameter  $m$  indicates a positive correlation, while the Podzol shows a negative correlation with diameter increment. Although with slight difference in MSE values, the ADE3 was the selected model.

#### Selection of the potential growth times the modifier equation (IPOTxM)

Regarding the IPOT model, the same independent variables related to site and stand used in the ADE model were tested (Table 5). Stand density, mean temperature and pH were not significant on either of the parameters. Although ETP was significant, the parameter sign is not the expected. Soil type variables were significant in both parameters with the exception of the Luvisol soil type. Precipitation, stand dominant diameter (dudom) and stand basal area (Gu) showed a positive effect in IPOT models, the last difficult to explain.

Table 7 shows three selected models fitted with the iterative procedure that include a single regressor or a linear combination of regressor variables for the IPOT and for the modifier formulation. All alternatives present similar modelling efficiency. Using the validation dataset helped to select the combination of those models that lead to a lower RMSE. The selection was for the IPOT2xMDF3 model (Table 8).

#### Final models evaluation

Two of the most commonly used methods to develop tree growth models, difference equations approach (ADE) and potential times modifier method (IPOTxM), were used. Table 9 shows the statistics computed with the validation dataset to characterize the predictive ability of the selected models from Table 6 and Table 7. The ADE method is less biased and more precise than the IPOTxM approach. In the later, the results when using the real or the estimated potential growth are not very different.

Regarding the performance of both models by country, the ADE is more precise for Spain (Table 9). Figure 3 shows the mean of the residuals and the mean of the absolute value of the residuals for the diameter growth by diameter classes, where the ADE model was generally less biased and more precise regardless the tree size

## **CONCLUSION**

The objective of this research was to fill a gap in cork oak growth modelling by taking into account the most important drivers of tree growth: site and stand characteristics and inter-tree competition. This study showed that these drivers, not all considered in existent models, do play a role in cork oak diameter growth.

The model developed in this work focus on trees that were already debarked, therefore with a perimeter over bark larger than 70 cm that corresponds to values of diameter under bark between 15 and 17 cm (depending on cork thickness). Figures 4 show the estimated annual diameter increment plotted over each one of the variables selected to take the effect of each of these drivers into account. Some conclusions can be drawn from these graphics:

- Generally, diameter increment decreases with tree diameter. Therefore the maximum of diameter increment occurs before cork debarking.
- Inter-tree competition has a slight effect on diameter increment.
- Stand density evaluated by the number of trees per ha has also some impact on tree growth but less clear than the effect of inter-tree competition.
- The effect of site quality is not clear.

The present model is an important added-value for the cork oak forest simulators as it will allow the test of alternative management approaches considering different thinning regimes. This decision is particularly relevant for cork oak as one of the most important management decision is the type of system: forest for cork production versus a silvopastoral system combining cork production with sheep or cattle grazing.

## **ACKNOWLEDGEMENTS**

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Table 4. Estimates for the parameters  $k$  and  $m$  of the age-independent model fitted with Equation-1, when just one independent variable is used (A=200 cm). (Table continue in next page)

Variable	Parameter $k$					Parameter $m$					
	MSE	R <sup>2</sup>	$k_0$	$k_{\text{region}}$	$m$	MSE	R <sup>2</sup>	$k$	$m_0$	$m_{\text{region}}$	
Site variables (climate and soil)	S	3.7545	0.9683	0.001839 ( <i>&lt;0.0001</i> )	0.000047 ( <i>0.0026</i> )	0.862962 ( <i>&lt;0.0001</i> )	3.7559	0.9682	0.002421 ( <i>&lt;0.0001</i> )	1.085686 ( <i>&lt;0.0001</i> )	-0.01806 ( <i>0.0108</i> )
	Annual P	3.7575	0.9682	0.002903 ( <i>&lt;0.0001</i> )	-6.45E-07 ( <i>0.0242</i> )	0.856263 ( <i>&lt;0.0001</i> )	3.7570	0.9682	0.002438 ( <i>&lt;0.0001</i> )	0.638364 ( <i>&lt;0.0001</i> )	0.000305 ( <i>0.0188</i> )
	Mean T	3.7556	0.9682	-0.00047 ( <i>0.6218</i> )	0.000181 ( <i>0.0042</i> )	0.809303 ( <i>&lt;0.0001</i> )	3.7553	0.9683	0.002319 ( <i>&lt;0.0001</i> )	2.091495 ( <i>&lt;0.0001</i> )	-0.08294 ( <i>0.0049</i> )
	ETP	3.7593	0.9682	0.002602 ( <i>&lt;0.0001</i> )	-2.67E-07 ( <i>0.1072</i> )	0.828766 ( <i>&lt;0.0001</i> )	3.7601	0.9682	0.002379 ( <i>&lt;0.0001</i> )	0.757496 ( <i>&lt;0.0001</i> )	0.000089 ( <i>0.2229</i> )
	OC	3.7610	0.9682	0.00243 ( <i>&lt;0.0001</i> )	-0.00002 ( <i>0.725</i> )	0.841691 ( <i>&lt;0.0001</i> )	3.7607	0.9682	0.002396 ( <i>&lt;0.0001</i> )	0.80336 ( <i>&lt;0.0001</i> )	0.023999 ( <i>0.4451</i> )
	pH	3.7588	0.9682	0.001407 ( <i>0.0087</i> )	0.000172 ( <i>0.0598</i> )	0.810855 ( <i>&lt;0.0001</i> )	3.7597	0.9682	0.002343 ( <i>&lt;0.0001</i> )	1.139044 ( <i>&lt;0.0001</i> )	-0.05963 ( <i>0.1456</i> )
	Cambisol	3.7610	0.9682	0.002398 ( <i>&lt;0.0001</i> )	-8.60E-07 ( <i>0.9925</i> )	0.847141 ( <i>&lt;0.0001</i> )	3.7609	0.9682	0.002393 ( <i>&lt;0.0001</i> )	0.841036 ( <i>&lt;0.0001</i> )	0.016849 ( <i>0.6789</i> )
	Luvisol	3.7438	0.9683	0.002014 ( <i>&lt;0.0001</i> )	0.00101 ( <i>&lt;0.0001</i> )	0.687322 ( <i>&lt;0.0001</i> )	3.7452	0.9683	0.002125 ( <i>&lt;0.0001</i> )	0.739499 ( <i>&lt;0.0001</i> )	-0.45528 ( <i>&lt;0.0001</i> )
	Podzol	3.7562	0.9682	0.002447 ( <i>&lt;0.0001</i> )	-0.00026 ( <i>0.0079</i> )	0.839415 ( <i>&lt;0.0001</i> )	3.7560	0.9682	0.002401 ( <i>&lt;0.0001</i> )	0.820031 ( <i>&lt;0.0001</i> )	0.120095 ( <i>0.0078</i> )
	Regosol	3.7609	0.9682	0.002389 ( <i>&lt;0.0001</i> )	0.000041 ( <i>0.6416</i> )	0.850353 ( <i>&lt;0.0001</i> )	3.7599	0.9682	0.00243 ( <i>&lt;0.0001</i> )	0.882424 ( <i>&lt;0.0001</i> )	-0.04931 ( <i>0.1871</i> )

P, mean annual precipitation (mm); T, mean temperature (°C); ETP, real evapotranspiration (mm), OC is organic carbon content (%).

		<i>Parameter k</i>					<i>Parameter m</i>				
Variable	MSE	R <sup>2</sup>	k <sub>0</sub>	k <sub>stand</sub>	m	MSE	R <sup>2</sup>	k	m <sub>0</sub>	m <sub>stand</sub>	
<i>Stand variables</i>	N/100	3.7551	0.9683	0.002314 ( <i>&lt;0.0001</i> )	-0.00013 ( <i>0.0011</i> )	0.713063 ( <i>&lt;0.0001</i> )	3.7556	0.9682	0.002155 ( <i>&lt;0.0001</i> )	0.639115 ( <i>&lt;0.0001</i> )	0.0581 ( <i>0.0026</i> )
	Gu	3.7546	0.9683	0.002093 ( <i>&lt;0.0001</i> )	0.000021 ( <i>0.0017</i> )	0.826251 ( <i>&lt;0.0001</i> )	3.7578	0.9682	0.002382 ( <i>&lt;0.0001</i> )	0.924646 ( <i>&lt;0.0001</i> )	-0.00682 ( <i>0.0201</i> )
	dug	3.7201	0.9685	0.000457 ( <i>0.0046</i> )	0.00003 ( <i>&lt;0.0001</i> )	0.335318 ( <i>0.0008</i> )	3.7262	0.9685	0.001591 ( <i>&lt;0.0001</i> )	1.004418 ( <i>&lt;0.0001</i> )	-0.01778 ( <i>&lt;0.0001</i> )
	dudom	3.7006	0.9687	0.00013 ( <i>0.3520</i> )	0.00003 ( <i>&lt;0.0001</i> )	0.285566 ( <i>0.0021</i> )	3.7068	0.9687	0.001516 ( <i>&lt;0.0001</i> )	1.121045 ( <i>&lt;0.0001</i> )	-0.01786 ( <i>&lt;0.0001</i> )
<i>Competition indices (icm)</i>	du/dug	3.7350	0.9684	0.006354 ( <i>&lt;0.0001</i> )	-0.00196 ( <i>&lt;0.0001</i> )	1.520198 ( <i>&lt;0.0001</i> )	3.7207	0.9685	0.005706 ( <i>&lt;0.0001</i> )	0.792457 ( <i>&lt;0.0001</i> )	1.133978 ( <i>&lt;0.0001</i> )
	du/dumax	3.7467	0.9683	0.005289 ( <i>&lt;0.0001</i> )	-0.00233 ( <i>0.0016</i> )	1.400132 ( <i>&lt;0.0001</i> )	3.7432	0.9684	0.004052 ( <i>&lt;0.0001</i> )	0.940299 ( <i>&lt;0.0001</i> )	0.899148 ( <i>&lt;0.0001</i> )
	du/dudom	3.7245	0.9685	0.008172 ( <i>&lt;0.0001</i> )	-0.00361 ( <i>&lt;0.0001</i> )	1.78226 ( <i>&lt;0.0001</i> )	3.6984	0.9687	0.010478 ( <i>0.0023</i> )	0.889932 ( <i>&lt;0.0001</i> )	2.777442 ( <i>0.0013</i> )
	APB	3.7566	0.9682	0.002199 ( <i>&lt;0.0001</i> )	3.47E-09 ( <i>0.0067</i> )	0.774442 ( <i>&lt;0.0001</i> )	3.7554	0.9683	0.002242 ( <i>&lt;0.0001</i> )	0.792984 ( <i>&lt;0.0001</i> )	-1.44E-06 ( <i>0.0001</i> )
	BAL	3.7610	0.9682	0.002387 ( <i>&lt;0.0001</i> )	1.47E-06 ( <i>0.8537</i> )	0.844553 ( <i>&lt;0.0001</i> )	3.7610	0.9682	0.002388 ( <i>&lt;0.0001</i> )	0.843871 ( <i>&lt;0.0001</i> )	-0.00016 ( <i>0.9602</i> )

du is quadratic mean diameter at breast height under cork (cm), dumax is maximum diameter at breast height under cork (cm), dudom is dominant diameter at breast height under cork (cm), N is the number of trees per hectare, Gu is the basal area per hectare under cork (m<sup>2</sup>), APB and BAL see Table 3.

Table 5. Estimates for the parameters  $k$  and  $m$  of the potential growth model fitted with Equation-1, when just one independent variable is used

		<i>Parameter k</i>					<i>Parameter m</i>				
	<b>Variable</b>	<b>MSE</b>	<b>R<sup>2</sup></b>	<b>k<sub>0</sub></b>	<b>k<sub>region</sub></b>	<b>m</b>	<b>MSE</b>	<b>R<sup>2</sup></b>	<b>k</b>	<b>m<sub>0</sub></b>	<b>m<sub>region</sub></b>
<i>Site variables (climate and soil)</i>	S	4.899	0.9599	0.00309 ( <i>&lt;0.0001</i> )	-0.00006 (0.0003)	0.830334 ( <i>&lt;0.0001</i> )	4.8983	0.9599	0.002396 ( <i>&lt;0.0001</i> )	0.543591 (0.0023)	0.027568 (0.0003)
	Annual P	4.8463	0.9604	0.000547 (0.0449)	2.10E-06 ( <i>&lt;0.0001</i> )	0.780091 ( <i>&lt;0.0001</i> )	4.8354	0.9604	0.002241 ( <i>&lt;0.0001</i> )	1.740937 ( <i>&lt;0.0001</i> )	-0.00117 ( <i>&lt;0.0001</i> )
	Mean T	4.9009	0.9599	0.002813 (0.0345)	-0.00002 0.8203	0.935898 ( <i>&lt;0.0001</i> )	4.9014	0.9599	0.002552 ( <i>&lt;0.0001</i> )	0.808153 (0.1579)	0.009046 (0.809)
	ETP	4.8448	0.9604	0.000489 (0.0268)	1.50E-06 ( <i>&lt;0.0001</i> )	0.65246 ( <i>&lt;0.0001</i> )	4.8156	0.9606	0.002023 ( <i>&lt;0.0001</i> )	1.981416 ( <i>&lt;0.0001</i> )	-0.00128 ( <i>&lt;0.0001</i> )
	OC	4.8188	0.9606	0.001444 ( <i>&lt;0.0001</i> )	0.000584 ( <i>&lt;0.0001</i> )	0.962305 ( <i>&lt;0.0001</i> )	4.8049	0.9607	0.002709 ( <i>&lt;0.0001</i> )	1.624579 ( <i>&lt;0.0001</i> )	-0.29824 ( <i>&lt;0.0001</i> )
	pH	4.9018	0.9599	0.00297 (0.0002)	-0.00007 (0.5373)	0.955804 ( <i>&lt;0.0001</i> )	4.9011	0.9599	0.002566 ( <i>&lt;0.0001</i> )	0.755949 (0.0296)	0.036673 (0.5468)
	Cambisol	4.7964	0.9608	0.002075 ( <i>&lt;0.0001</i> )	0.00088 ( <i>&lt;0.0001</i> )	0.899264 ( <i>&lt;0.0001</i> )	4.7879	0.9608	0.002611 ( <i>&lt;0.0001</i> )	1.175977 ( <i>&lt;0.0001</i> )	-0.41669 ( <i>&lt;0.0001</i> )
	Luvisol	4.8915	0.96	0.002229 ( <i>&lt;0.0001</i> )	0.000618 (0.0302)	0.795557 ( <i>&lt;0.0001</i> )	4.8966	0.9599	0.002317 ( <i>&lt;0.0001</i> )	0.83688 ( <i>&lt;0.0001</i> )	-0.25771 (0.1415)
	Podzol	4.8252	0.9605	0.002119 ( <i>&lt;0.0001</i> )	-0.00093 ( <i>&lt;0.0001</i> )	0.654432 ( <i>&lt;0.0001</i> )	4.8192	0.9606	0.002089 ( <i>&lt;0.0001</i> )	0.638056 ( <i>&lt;0.0001</i> )	0.680378 ( <i>&lt;0.0001</i> )
	Regosol	4.8733	0.9601	0.00275 ( <i>&lt;0.0001</i> )	-0.00039 (0.0016)	0.963836 ( <i>&lt;0.0001</i> )	4.8793	0.9601	0.002606 ( <i>&lt;0.0001</i> )	0.910104 ( <i>&lt;0.0001</i> )	0.155758 (0.0051)
<i>Stand variables</i>	<b>Variable</b>	<b>MSE</b>	<b>R<sup>2</sup></b>	<b>k<sub>0</sub></b>	<b>k<sub>stand</sub></b>	<b>m</b>	<b>MSE</b>	<b>R<sup>2</sup></b>	<b>k</b>	<b>m<sub>0</sub></b>	<b>m<sub>stand</sub></b>
	N/100	4.9075	0.9599	0.003066 ( <i>&lt;0.0001</i> )	0.000075 (0.3634)	1.224674 ( <i>&lt;0.0001</i> )	4.8992	0.9599	0.002638 ( <i>&lt;0.0001</i> )	1.03927 ( <i>&lt;0.0001</i> )	-0.0322 (0.2708)
	Gu	4.8333	0.9605	0.001746 ( <i>&lt;0.0001</i> )	0.000044 ( <i>&lt;0.0001</i> )	0.816913 ( <i>&lt;0.0001</i> )	4.8432	0.9604	0.00237 ( <i>&lt;0.0001</i> )	1.097534 ( <i>&lt;0.0001</i> )	-0.01884 ( <i>&lt;0.0001</i> )
dudom	4.7101	0.9615	-0.00026 ( <i>&lt;0.0001</i> )	0.000018 ( <i>&lt;0.0001</i> )	-0.86909 ( <i>&lt;0.0001</i> )	4.7619	0.961	0.000829 ( <i>&lt;0.0001</i> )	0.853913 ( <i>&lt;0.0001</i> )	-0.027 ( <i>&lt;0.0001</i> )	

Table 6. Parameter estimates fitted with the iterative procedure for alternative models of the age-independent (ADE) with the asymptote fix (A=200).

	MSE	ADE1		ADE2		ADE3		ADE4	
		R <sup>2</sup>	Estimate	Pr >  t	Estimate	Pr >  t	Estimate	Pr >  t	Estimate
<b>k</b>		3.530		3.562		3.506		3.525	
	R <sup>2</sup>	0.970		0.970		0.970		0.970	
	Parameter	Estimate	Pr >  t	Estimate	Pr >  t	Estimate	Pr >  t	Estimate	Pr >  t
	constant	0.008137	<0.0001	0.002223	<0.0001	0.005583	<0.0001	0.00513	<0.0001
	du/dudom	-0.00376	<0.0001					-0.00193	0.0021
	N/100			-0.00011	0.0025			-0.00015	0.0212
	100/N					0.000622	0.0018		
<b>m</b>		1.754038	<0.0001	0.692159	<0.0001	0.665369	<0.0001	1.195533	<0.0001
	du/dudom					1.782836	<0.0001		
	Luvi							-0.26846	0.0025
	Podzol							0.106351	0.0435

Table 7. Parameter estimates fitted with the iterative procedure for alternative models of the potential growth (IPOT) with the asymptote fix (A=200), and of the modifier (MDF).

	MSE	IPOT1		IPOT2		IPOT3	
		R <sup>2</sup>	Estimate	Pr >  t	Estimate	Pr >  t	Estimate
<b>k</b>		4.53		4.50		4.50	
	R <sup>2</sup>	0.96		0.96		0.96	
	Parameter	Estimate	Pr >  t	Estimate	Pr >  t	Estimate	Pr >  t
	constant	-0.00027	<0.0001	-0.0002	0.0218	-0.00018	0.0027
	dudom	0.000016	<0.0001	0.000016	<.0001	0.000014	<0.0001
	Gu	0.000727	0.0176	0.000827	0.0052		
<b>m</b>		-0.80831	<0.0001			-0.99006	<0.0001
	Prec			-0.00076	<.0001		
	Podzol					0.45805	0.0001

	MSE	MDF1		MDF2		MDF3	
		R <sup>2</sup>	Estimate	Pr >  t	Estimate	Pr >  t	Estimate
		3.70		3.70		3.68	
	R <sup>2</sup>	0.95		0.95		0.95	
	Parameter	Estimate	Pr >  t	Estimate	Pr >  t	Estimate	Pr >  t
	constant	0.632733	0.0019	0.74213	<0.0001	1.356885	<0.0001
	du/dudom	-0.95529	0.0004				
	BAL			-0.15268	<0.0001	-0.18727	<0.0001
	100/N					-0.38964	<0.0001

Table 8. Comparing the RMSE for the combination of the IPOT and MDF models in table 6.

	MDF1	MDF2	MDF3
IPOT1	2.627	2.618	2.608
IPOT2	2.591	2.577	2.563
IPOT3	2.740	2.739	2.739

Table 9. Prediction ability of the best candidate models, where ADE is the age-independent difference equation, IPOTxM is the potential times the modifier growth model, for each country dataset and for the all dataset.

Models	Iberian		Portugal (n=250)		Spain (n=518)	
	Mres	Mres	Mares	Mares	Mares	Mares
ADE3	0.1195	1.4180	-0.2438	1.7307	0.2948	1.2671
Estimated IPOT2 x MDF3	1.3253	1.8562	1.1845	1.9653	1.3933	1.8036
Calculated IPOT x MDF3	1.5282	2.0176	1.3797	2.0743	0.8403	0.9642

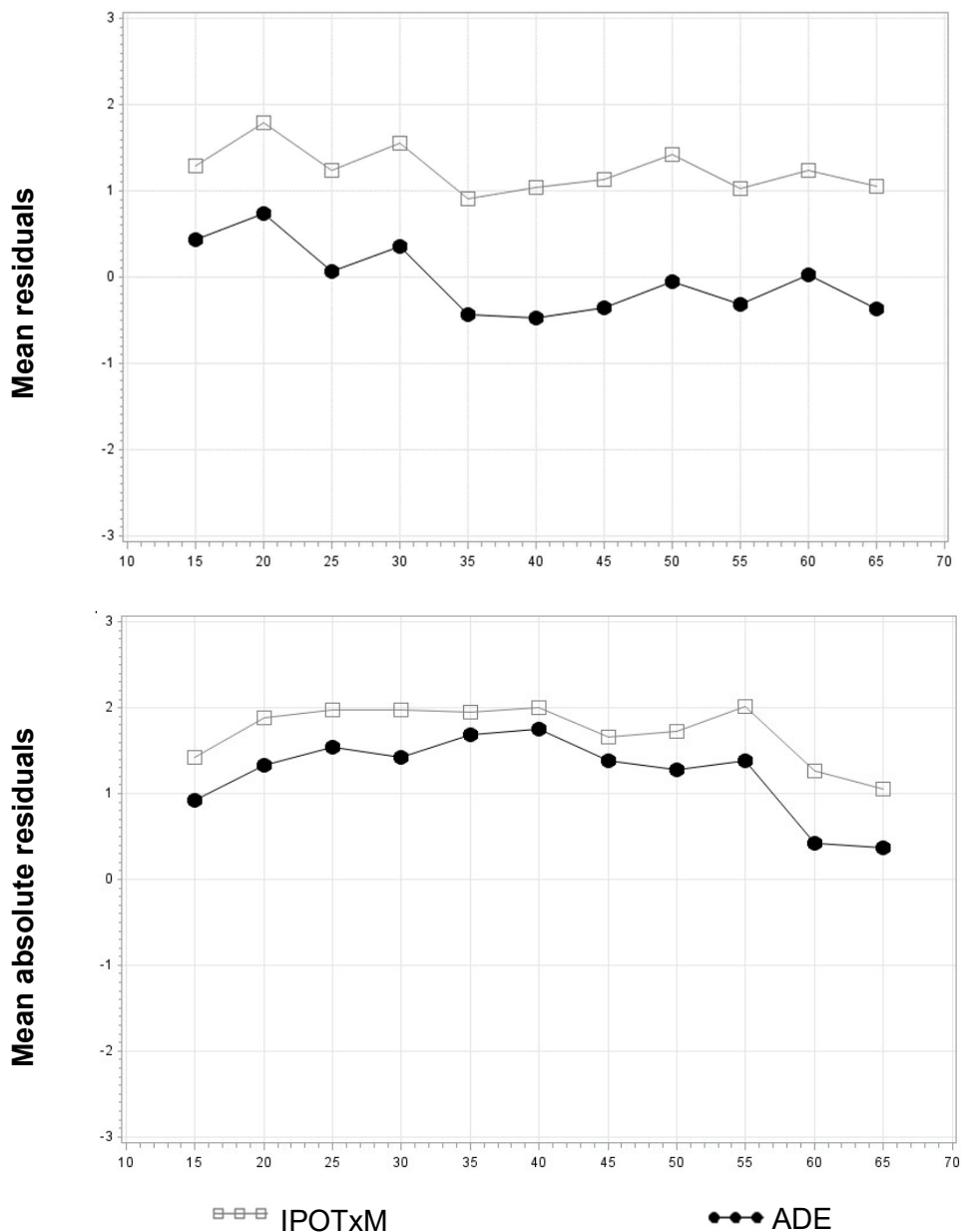


Figure 3. Mean of the residuals (Mres) and mean of the absolute value of residuals (Mares) with both final diameter growth models by diameter classes (central value in cm).

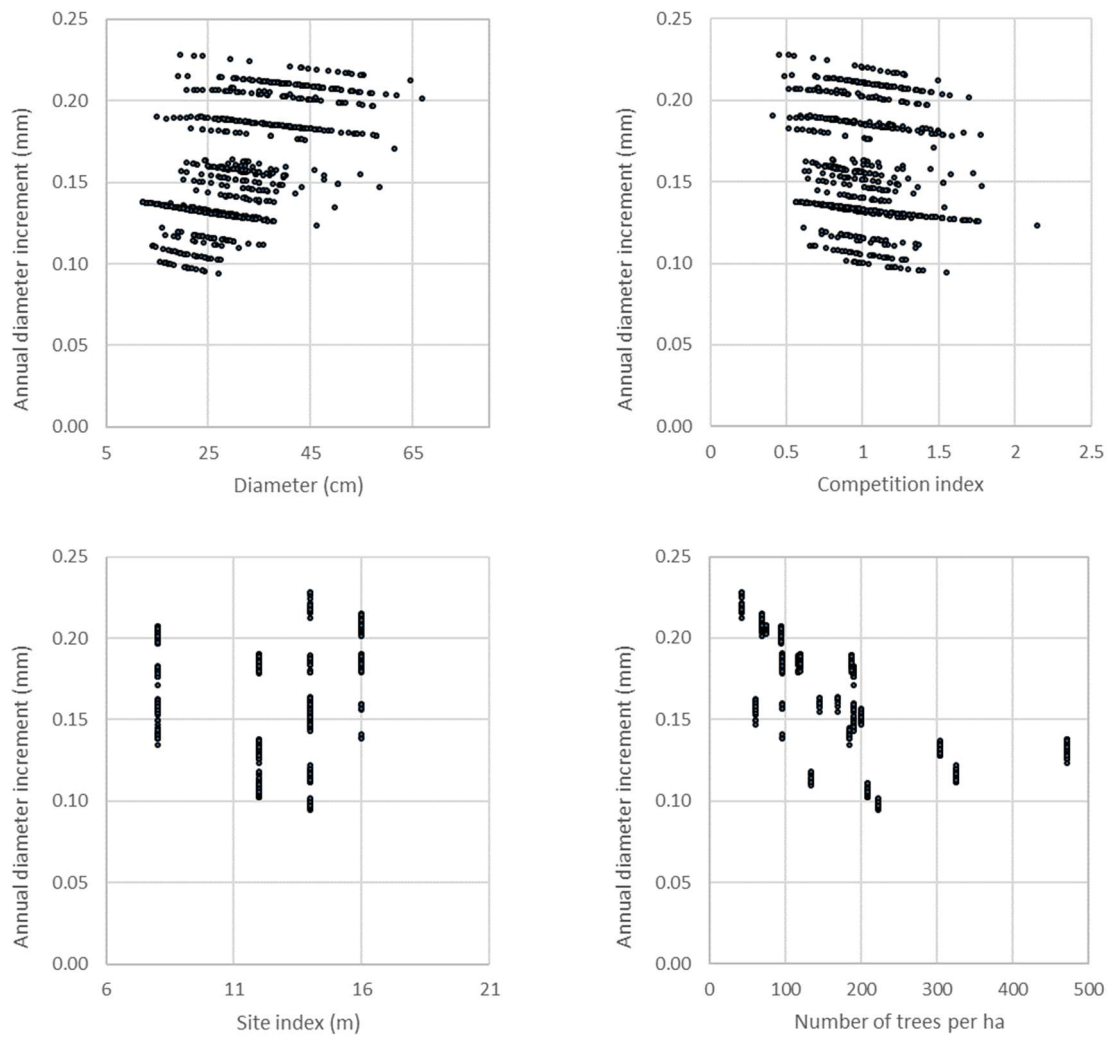


Figure 4. Predicted annual diameter increment with ADE final model over each one of the tree growth drivers selected.

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#### **IV. CONCLUSIONS**

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This manuscript research focused on the tree and cork growth, assessing the impact of the understory management and inter-tree competition. This chapter aim is to associate the six presented studies outcomes, which were individually discussed in each subchapter.

### **VI.1. Effect of understory management alternatives on tree and on cork growth**

In subchapter II.1 (Faias *et al.* 2018), tree radial growth and cork annual growth were compared between two distinct understory management treatments established in *Montargil* trial, within a cork debarking cycle of 9 years. The results indicate no effect on cork growth, as well as, on wood increment, for the trees growing along the complete cork rotation under lupine periodical seeding after the understory removal. However, differences were found regarding cork annual growth between this treatment and the maintenance of spontaneous shrubs on one of the blocks, evidencing the need for further research. Therefore, in subchapter II.1 (Faias *et al.* 2019), the former dataset was extended including cork samples from trees with a different cork debarking cycle within the trial period. This detail allowed studying the interaction between cork ring age with understory removal and lupine periodical seeding. The data analysis showed that integrating distance-dependent competition indices did not contribute to explain the variability of cork width when the model contains other known explanatory variables, such as, cork age, precipitation of the previous growing year, and understory management related variables. As a final point, when analysing the eight complete cork rings from a cork cycle (Faias *et al.* 2018), the lupine seeding did not show an effect, although comparing cork rings of different age within the cork cycle (Faias *et al.* 2019) a negative effect was found in the first half of the cork rotation – cork age around 5 years. On the other hand, the cork ring growth seem to benefit from the maintenance of spontaneous shrubs, for these specific shrubs species, until the middle of the cork rotation – cork age around 6 years.

In order to contribute with more information regarding understory management, the trees within one of the trial's block were continuously followed considering three different treatments. The study present in subchapter II.3 focused on how the trees respond to the three distinct understory management alternatives assessing the tree diameter increment and the nutrients' content in the leaves. Differences were found for the N and P foliar content on the plot distinguish by NP fertilization into the soil. Concerning the intra-annual diameter increment, results also indicate a positive effect in the following year after fertilization for the trees that were earlier debarked, or in other words, trees in the middle of the cork rotation.

## VI.2. Assessing inter-tree competition on tree growth

The study in chapter III.2 focusing on undebarked cork oak plantations, analysed the relationship between stand characteristics and tree growth efficiency. Evaluating the stands competitive status based on several methodologies, the study points out to an absence of inter-tree competition before the first cork extraction for the common stand densities observed in young plantations. However, signs of competition were found in older stands never debarked and with high density when analyzing the relationship between diameter relative growth rate and tree size. Stand crown cover is traditionally used as measure for defining stocking limits in cork oak stands according to the management objectives. Based on the results, it is suggest the use of a relative spacing threshold between 0.6 and 0.8 as an alternative management measure, since it does not require the tree crown measurement. Additionally, by providing visual information of the study sites competitive status it points out that understanding the stand growth pattern will support management decisions, such as, the first thinning potential timing and severity. The forest manager depending on the stand characteristics decide to retain trees until the second cork debarking, and be able to take into account the selection of the trees to be removed according to their cork features.

In subchapter III.1 (Paulo *et al.* 2016), two models differing in the methodologic approach were developed to predict crown diameter. The models included a competition index that takes into account the effect of the tree position in the stand structure. Model evaluation highlighted that the fixed-effect model should be used over the mixed-effect model, when there is no available data to perform the calibration procedure. Applying the fixed-effect model to the two last Portuguese forest inventory dataset, results indicated a decrease in crown cover, evidencing the risk of cork production sustainability in Portugal.

The study in subchapter III.3 compared two approaches to predict diameter growth for the Iberian Peninsula. For each model was tested the inclusion of stand variability associated to climate and soil site conditions. Two models were developed ADE, an aged-independent difference equation method, and IPOTxM, a potential growth function multiplied by a modifier function bounded between 0 and 1 to express inter-tree competition. Competition indices were included in both final models with a negative correlation with diameter increment. A stand density measure was included in the ADE model but none of the tested site variables were significant. Only precipitation was positively correlated with diameter increment in the potential growth equation. The ADE model revealed a better predictability for the diameter increment, but when considering the wood diameter increment prediction the IPOTxM was less biased and more precise for Spain.

### VI.3 Final Remarks

Forest simulators are crucial tools to provide forest managers with forecasts regarding stand growth under different management alternatives. However, these tools are being continuously updated in order to include new contributions from research and/or to answer technical questions raised by practitioners that need specific outputs to support their management decisions.

The research conducted under this thesis contributes to the understanding on how neighbourhood vegetation affects tree and cork growth. The developed models for crown width and diameter increment are more accurate and integrate distance-dependent competition indices, which express the tree relative dimension. These new models can now be incorporated in the existing growth and yield model for pure cork oak stands, the SUBER model (Tomé 2004, Paulo 2011).

Other outcomes, regarding inter-tree competition and understory management, can be implemented in the silvicultural parameters and/or in the time of operations occurrence. To define stocking limits in cork oak stands, a relative spacing range was suggested as an alternative measure to the spacing coefficient that is computed from the stand crown cover. The first thinning time and/or severity may be schedule after assessing the stand competitive status in order to maintain trees until the second cork extraction. At the second debarking it is possible to make the decision about which trees should be selected to be removed based on the current cork features. The understory management depending on its spontaneous species may take into the account the clear interaction between the understory presence and cork age. It was found a different impact depending on whether the operations is performed at the middle or at the beginning of the cork rotation cycle.

Forests have a long-term response to anthropogenic interventions. Thus, to conduct forest research it is extremely important the existence of a network of permanent plots but also their monitoring throughout the years. Furthermore, sharing data between institutions regardless of the region or the country is a promising path to account for regional variability within the climate change framework.

Multidisciplinary research studies conducted for the main Portuguese forest species have been performed using data collected on pure stands. However, mixed stands are valuable ecosystems regarding functions and services with a role in adaptive forest management. Their importance have been an increasing topic in forest research, however there is still a gap in knowledge regarding their management, which is attached to pure stands strategies and/or recommendations.

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