*forests*

*Article*

# Modeling Cork Yield, Thickness, Price, and Gross Income in the Portuguese Cork Oak *Montado*

**Fernando Mata [1,*] and Maria Dos-Santos [2,3]**

1 CISAS—Center for Research in Agrifood Systems and Sustainability, Instituto Politécnico de Viana do Castelo, 4900-347 Viana do Castelo, Portugal
2 Escola Superior de Comunicação Social, Instituto Politécnico de Lisboa, 1549-014 Lisbon, Portugal; maria.jose.santos@iscte-iul.pt
3 Dinâmia-CET—Centre for Socioeconomic and Territorial Studies, ISCTE—Centro Universitário de Lisboa, 1649-026 Lisbon, Portugal
* Correspondence: fernandomata@ipvc.pt

**Abstract:** The cork oak (*Quercus suber* L.) woodlands, known as *montados* in Portugal, hold significant economic, cultural, social, and environmental value. They are found in the Mediterranean Sea basin, particularly in the Iberian Peninsula, and sustain various activities like silvopastoralism, with cork being a primary product. Despite its economic significance, challenges such as climate change threaten its sustainability. This study aimed to analyze the edaphoclimatic variables affecting cork yield, thickness, price, and gross income in the Alentejo region of Portugal. A total of 35 farmers were selected for the data collection included in this study. Multivariable linear regressions were performed to establish relationships between cork yield, thickness, price, and gross income as dependent variables, various edaphoclimatic factors, and tree densities. A higher tree density correlates with an increased cork yield but a decreased cork thickness. Soil pH affects cork yield and thickness, with a lower pH favoring higher cork yields but thinner cork. A higher clay and silt content in horizon soil C enhances cork thickness and raises the price but reduces the cork yield. Higher accumulated precipitation and temperatures contribute to higher yields and thicknesses of cork. It is concluded that the relationships between the dependent and the independent variables are complex but partially explainable. Understanding these relationships is paramount to ensure sustainable management practices are adopted that are capable of addressing issues raised in the current context of climate change.

**Keywords:** agroforestry; cork thickness; cork oak; cork yield; soil; *montado*; *suber*

check for updates

**Citation:** Mata, F.; Dos-Santos, M. Modeling Cork Yield, Thickness, Price, and Gross Income in the Portuguese Cork Oak *Montado*. *Forests* **2024**, *15*, 2163. https://doi.org/10.3390/f15122163

Academic Editors: Hongge Zhu, Shaopeng Zhang and Noriko Sato

Received: 3 October 2024
Revised: 28 November 2024
Accepted: 6 December 2024
Published: 8 December 2024



## 1. Introduction

Cork oak (*Quercus suber* L.) woodlands are commonly found in agroforestry systems of the Mediterranean Sea basin countries. The distribution of these landscapes is predominantly in the Iberian Peninsula, where they are known as *montado* (Portugal) and *dehesa* (Spain) [1]. A multitude of direct values and externalities relate to these agroforestry systems. Their economic value is derived from silvopastoral activities, including the use of acorns as a feed, firewood, and mainly cork [2]. Externalities include cultural, social, and environmental values: The *montado* is part of a tentative list of Portuguese places for inclusion in the UNESCO World Heritage List [3], and the cork oak woodlands and forests have a high conservation value for biodiversity [4,5]. Cork oak woodlands are explored not only for their cork but also to serve as a silvopastoral environment where diverse farm animal species can be kept [6,7]. Cattle can graze natural or sawn pastures, where intensification depends on factors such as tree density and slope [8–10]. Other grazing animals such as sheep, goats, and horses can also use these pastures, sometimes rotating between them [9,10]. Despite being more prominently known for feeding on the acorns produced by holm oaks, pigs can also feed on the acorns of cork oaks, to produce the famous Iberian hams [11]. Decades ago, raising turkeys on acorns was also a tradition in the *montado* of Alentejo, in Portugal. The practice has regained importance recently, and the Christmas turkey raised on acorns is now a delicacy [12].

Cork is the bark or outer periderm of the cork oak. Cork is produced by the secondary meristem, the phellogen, forming successive annual layers of cork during the trees' life [13]. The first cork harvested (virgin cork) is a hard, rough cork, irregular in density and thickness. According to Portuguese legislation, this extraction can only take place when 30 to 50% of the tree diameter reaches at least 70 cm [14]. The secondary cork is grown after the virgin cork extraction. After the first extraction, debarking occurs every 9 years, at least, to allow regrowth [13,15]. The secondary cork improves in quality and almost reaches the quality of the subsequent debarking (*amadia* or reproduction cork) [14].

The cork oak area in 2020 was around 2.123 million ha worldwide, of which 720 thousand (34%) were in Portugal and 574 thousand (27%) in Spain [16]. The world cork production in 2020 was around 187 million metric tons, of which 85 thousand (46%) were produced in Portugal and 61 thousand (33%) in Spain [16]. Despite being the largest producer, Portugal is the third-largest importer of cork due to the concentration of processing industries in the country, which later export in the form of end-user products. Portugal is the world leader in cork end-user production, with a share of 62.1%, totaling EUR 1016.1 million [16]. Therefore, the cork-related economy has a direct influence on the Portuguese trade balance by ensuring the maintenance of direct jobs, from production and extraction to the processing industry and commerce (8600), and many indirect jobs from the other industries and transport [17]. The importance of these agroforestry systems as carbon sinks has also been recognized [18].

Around 70% of the cork is still as stoppers for wine bottles [16]. Considering that cork products compete on the market with other substitutes from highly competitive industries with aggressive marketing aimed at satisfying new customer demands, the situation in the cork industry is perceived as challenging. In this industry, Portugal has long had expertise in the process of manufacturing cork products. There is, however, limited investment in research and development of new applications such as thermal insulation [19], lightweight aerostructures [20], or special composites [21,22].

The cork oak is an evergreen tree thriving in the Mediterranean basin and biome but is limited climatically in its spread by the thermo-Mediterranean and meso-Mediterranean bioclimatic belts [23]. The cork oak is the most selective oak species within the Mediterranean basin, concerning edaphic and climatic parameters such as temperature and precipitation [24]. Despite benefiting from water availability throughout the year, the cork oak is particularly susceptible to waterlogging [25]. In terms of temperature, the mean optimum is situated in the range of 13 °C to 19 °C, and the minimum tolerance is −5 °C [26]. This characteristic leaves the species susceptible to climate change, and therefore the study of its edaphoclimatic specificities has been prioritized [1,27–31]. Raising climatic temperatures together with extended drought periods have already been reported as a cause of the death of cork oaks in Tunisia [32]. The climate, combined with specific site characteristics, plays a crucial role in achieving balance within hydromorphic soil conditions. This balance, which hinges on the interplay between soil properties, topographical features, and water availability, is vital for the thriving growth of cork oak trees [25].

Cork oak decline has been reported [33] and is thought to result from a combination of primary (predisposing) factors and secondary (opportunistic) factors [34,35]. Among the primary causes, water availability is widely acknowledged as a significant contributor, given the resemblance between symptoms of cork oak decline and those associated with prolonged water stress [36]. Despite their strong adaptation to summer droughts and limited water resources [37], the distribution of cork oaks is closely tied to the severity of drought, hydromorphic soil conditions, and the interaction between soil, site characteristics, and water availability [38].

Cork oaks occur naturally in Portugal all over the country. However, the traditional regions of cork production are Ribatejo and Alentejo. In recent decades, new plantations have also been located in northern regions of Beira-Baixa and Trás-os-Montes [39]. This partial relocation northwards may prevent the future survival of the species [39].

Despite the undeniable importance of the cork sector, persisting issues could compromise the position occupied by the sector in the medium and long term. Among the major challenges affecting the sector, those at the production level stand out, ranging from the undercrowding of cork oak forests to the lack of regeneration [40,41]. These aspects are further aggravated by overexploitation and unfavorable cultural practices [42]. Climate change is also seen as a future challenge to the species as the tendency for longer periods of concentrated rain or drought is expected [27]. The effect of prolonged periods of drought, caused by climate change, has also been identified as responsible for declining episodes of cork oaks, amplifying disease effects and causing sudden death [43].

Overall, there is a need to understand how different edaphoclimatic variables interact, to develop management techniques capable of mitigating the negative effects caused by the reduction in rain distribution, its seasonal concentration, and the extension of drought periods caused by climate change. To our knowledge, there are no previous studies including all the variables used in the present study, allowing for the study of their added effects. The present study set out with the objective of studying the main edaphoclimatic variables hindering the yield of cork, its thickness, price, and income. The aim was to identify constraints and advantageous natural factors allowing us to define strategies for cork oak woodland regeneration in the context of climate change.

## 2. Materials and Methods

### *2.1. Data Collection*

Data were collected through questionnaires using a sample of thirty-five farms located in the municipalities where *montado* occupies a prominent place in the Portuguese regional economy of Alentejo. These municipalities included Évora, Portalegre, Portel, Ponte de Sôr, Avis, Mora, and Montemor-o-Novo. Informed consent for the collection of data was obtained from the interviewees and anonymous answering was guaranteed. The questionnaire included questions to collect the data used in the present study and served this sole purpose. The interviews were conducted in November 2023 and all the interviewees extracted cork in at least one of their farm fields that year. All the data collected refer to those fields. In all these fields, the extraction was conducted after a regrowth period of nine years.

According to the World Reference Base for Soil Resources (WRB) classification, the majority (60%) of the soils where the samples were collected are podzols with arenites, and with coarse-grained acid igneous rock as the parent material (Municipalities of Ponte de Sôr, Mora, Alcaçer-do-Sal, and Aviz). The soil samples collected in the municipalities of Portalegre and Évora (23%) are classified as cambissols with granites as parent materials. The samples collected in the municipalities of Montemor-o-Novo and Gavião (17%) originated from Leptosols, with schist and graywacke as their parent materials.

The soil samples were collected by the authors, and the analysis was performed by technicians in the laboratory of agriculture chemistry at the University of Évora. The soil texture components were calculated using the hydrometer method, and the soil pH determination was performed using test strips (Universal Indicator Paper). The organic matter content of the soil was determined using the loss on ignition method, at 550 °C for 2 h. As there was no apparent division between horizons O and A in the soils sampled, the samples of horizon A may include any vestigial horizon O. The CEC was determined using the ammonium acetate method.

The density of the *montado* was determined using the aerial photography of SIP (Sistema de Identificação Parcelar), the system used in Portugal to identify and measure the fields in the Common Agricultural Policy. Soil sampling in horizon C of the soil was conducted after a tractor backhoe dug a hole. The meteorologic data were obtained from the register of the Direção Regional de Agricultura do Alentejo (the regional government agriculture services). The farmers gave all the other data.

The cork was initially piled in the respective field and was weighed within 2 months after extraction. The cork was weighed in a weighbridge when leaving the fields after being loaded on a lorry. The moisture content of the cork was not taken. The thickness of the cork was measured according to the procedure described by UNAC [44].

### 2.2. Variables Included in This Study

The following were chosen as dependent variables (DVs):

$Y_1$—Yield, cork production per ha. The original data were collected in *arroba* per ha. *Arroba* is a local weight unit equivalent to 15 kg. This variable was later translated into kg;

$Y_2$—Cork thickness, corresponding to the thickness of the board, expressed in millimeters.

$Y_3$—Price in euro per kg. The original data for the price were collected in euro per *arroba*, which was later translated into euro per kg;

$Y_4$—Gross income per ha. Obtained after multiplying the yield by the price.

The following were chosen as independent variables (IVs):

$X_1$—Density of the cork oak woodland. This variable may make an important contribution to explaining the production volume. In the area under study, there are generally low-density situations, characteristic of the Portuguese *montado* with an undercrowding of cork oaks. Defined as the number of trees per ha.

$X_2$—Cationic exchange capacity (CEC). This variable is expressed in cmolc/kg, as the number of cations necessary to neutralize negative loads of a unit quantity of soil under standardized conditions. The cation exchange capacity is extremely important in plant nutrition and correlates with other pedological parameters such as clay content, organic matter, and pH.

$X_3$—Soil organic matter (OM) content measured in horizon A of the soil, including horizon O. The total soil OM is a source of nutritional elements for plants, especially nitrogen, but has other beneficial roles such as increasing the CEC and retaining moisture.

$X_4$—Clay and silt content of the soil in horizon A.

$X_5$—pH of the soil in horizon A. There are strong correlations between pH values and plant nutrition and development. Extreme pH values, whether acidic or basic, can hinder the assimilation of some nutrients. To infer the influence of this parameter, we included it in the analysis.

$X_6$—Clay and silt content of the soil in horizon C. Horizon C is the deeper soil layer above bedrock or cemented soil.

$X_7$—Accumulated precipitation (mm) in the nonad of years preceding cork extraction from the oak.

$X_8$—Accumulated precipitation (mm) in the summers of the nonad of years preceding cork extraction from the oak.

$X_9$—Number of days with frost in the nonad of years preceding cork extraction from the oak.

$X_{10}$—Number of days with negative temperatures in the nonad of years preceding cork extraction from the oak.

$X_{11}$—Number of days with an average temperature above 25 °C in the nonad of years preceding cork extraction from the oak.

### 2.3. Statistical Procedure

In this cross-sectional study, the DVs were used individually in different models and fitted using all the IVs. The models used were generalized linear models for DVs presented as scale data, with an identity link function similar to multivariable linear regressions. The dataset was extended using a bootstrapping procedure to generate 1000 additional entries. Initially, the models were fitted with all the IVs, and a backward stepwise procedure was used for the elimination of all the non-significant IVs. The models were fitted without an intercept to allow for easier interpretation of the coefficients associated with the variables. The models were evaluated by the likelihood ratio chi-square test, and the variables in the models by the Wald chi-square test. Akaike's information criterion (AIC) for the models was also determined. Wald confidence intervals were produced for all the models' parameters. The assumption of independence between observations was immediately confirmed, and therefore, the assumptions were met. All levels of significance were set to $p < 0.05$. The procedures were implemented via the Generalized Linear Models routine from the statistical package SPSS® Statistics (IBM Corp.®, Armonk, NY, USA; version: 29.0.2.0 (20)). Descriptive statistics and correlations were also calculated for all the variables. The Kolmogorov–Smirnov test was used to check the normal distribution of variables.

## 3. Results

### *3.1. Descriptive Statistics*

The descriptive statistics for the independent variables can be found in Table 1. Note that the minimum and maximum values determined by the sample limit the variability of these independent variables within the adjusted models that follow.

**Table 1.** Descriptive statistics of the dependent and independent variables used in the present study.

| | Variables | Minimum | Maximum | Mean | SD |
|---|---|---|---|---|---|
| Dependent variables | $Y_1$ Yield (kg/ha) | 750 | 2250 | 1414.28 | 341.07 |
| | $Y_2$ Quality (mm) | 27 | 47 | 36.33 | 6.43 |
| | $Y_3$ Price (euro/kg) | 1.53 | 2.40 | 1.94 | 0.19 |
| | $Y_4$ Gross Income (euro/ha) | 1388 | 4500 | 2744 | 725.48 |
| Independent variables | $X_1$ Density (trees/ha) | 20 | 100 | 46.29 | 20.38 |
| | $X_2$ CEC (meq/100 g) | 2.80 | 14.25 | 7.48 | 4.25 |
| | $X_3$ OM HA (%) | 0.44 | 3.43 | 1.01 | 0.88 |
| | $X_4$ Clay and Silt HA (%) | 3.1 | 16.3 | 6.9 | 3.6 |
| | $X_5$ pH HA | 5.0 | 6.4 | 5.9 | 0.43 |
| | $X_6$ Clay and Silt HC (%) | 0.0 | 55.0 | 27.37 | 15.44 |
| | $X_7$ Precipitation Total (mm) | 5501 | 7945 | 6073 | 442 |
| | $X_8$ Precipitation Summer (mm) | 226 | 453 | 314 | 70.7 |
| | $X_9$ Frost (number of days) | 5 | 40 | 19.43 | 12.52 |
| | $X_{10}$ Neg. Temp. (number of days) | 13 | 163 | 83.29 | 41.88 |
| | $X_{11}$ MD Temp. > 25 °C (number of days) | 1051 | 1410 | 1294 | 107 |

Note: $X_1$—density (number of cork oaks/ha), $X_2$—CTC (meq/100 g), percentage of organic matter in soil horizon A, $X_3$—organic matter on soil horizon A (%), $X_4$—clay and silt on soil horizon A (%), $X_5$—pH of the soil in horizon A, $X_6$—clay and silt content of the soil in horizon C, $X_7$—accumulated precipitation in the nonad of years (mm), $X_8$—accumulated precipitation in the summers of the nonad of years (mm), $X_9$—number of days with frost in the nonad of years, $X_{10}$—number of days with negative temperatures in the nonad of years, $X_{11}$—number of days with an average temperature above 25 °C in the nonad of years.

Of the DVs, the only one without a normal distribution is 'thickness', while for the IVs, the only one with a normal distribution is 'gross income'. Tables 2 and 3 give the correlation values, respectively, for the DVs and IVs.

**Table 2.** Matrix of correlations between the dependent variables. The variable gross income is not normally distributed; therefore, correlation values between any variable and gross income are calculated via a non-parametric test (Spearman's ρ) while the others are calculated via a parametric test (Person's r).

| Variable | Yield (kg/ha) | Thickness (mm) | Price (euro/kg) |
|---|---|---|---|
| Thickness (mm) | | | |
| Price (euro/kg) | | 0.654 *** | |
| Gross Income (euro/ha) | 0.923 *** | | 0.466 ** |

Note: Cells left blank have non-significant correlations; significance levels ** $p < 0.01$, *** $p < 0.001$.

These correlations highlight that the gross income is mainly driven by yields, but also by price, while the price is mainly driven by the cork thickness.

**Table 3.** Matrix of correlations between the independent variables. As the only variable with a normal distribution is quality, the correlation values correspond to Spearman's rho.

| Variable | $X_3$ | $X_4$ | $X_6$ | $X_7$ | $X_9$ | $X_{10}$ |
|---|---|---|---|---|---|---|
| $X_4$ Clay and Silt HA (%) | 0.377 * | | | | | |
| $X_5$ pH HA | | −0.754 ** | | | | |
| $X_8$ Precipitation Summer (mm) | | | −0.439 ** | 0.402 * | | |
| $X_9$ Frost (ner of days) | | | | −0.505 ** | | |
| $X_{10}$ Neg. Temp. (ner of days) | | | | | −0.635 *** | |
| $X_{11}$ MD Temp. > 25 °C (ner of days) | | | | | −0.510 ** | 0.476 ** |

Note: $X_3$—organic matter on soil horizon A (%), $X_4$—clay and silt on soil horizon A (%), $X_5$—pH of the soil in horizon A, $X_6$—clay and silt content of the soil in horizon C, $X_7$—accumulated precipitation in the nonad of years (mm), $X_8$—accumulated precipitation in the summers of the nonad of years (mm), $X_9$—number of days with frost in the nonad of years, $X_{10}$—number of days with negative temperatures in the nonad of years, $X_{11}$—number of days with an average temperature above 25 °C in the nonad of years; cells left blank have non-significant correlations; significance levels * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

### *3.2. The 'Yield' Model*

A model was successfully fitted to the data (likelihood ratio $\chi^2 = 160.54$, 6 df, $p < 0.001$) with Akaike's information criterion (AIC) at 457. The parameterization of the model is shown in Table 4.

**Table 4.** Parameters of the 'yield' model.

| Parameter | $\beta$ | SE | 95% Wald CI | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|
| | | | Lower | Upper | Wald $\chi^2$ | df | $p$-Value |
| $X_1$ Density (trees/ha) | 11.040 | 1.409 | 8.076 | 13.804 | 79.701 | 1 | <0.001 |
| $X_5$ pH HA | −472.814 | 63.853 | −612.348 | −361.739 | 63.479 | 1 | <0.001 |
| $X_6$ Clay and Silt HC (%) | −4.149 | 1.662 | −7.325 | −0.559 | 6.660 | 1 | =0.019 |
| $X_7$ Precipitation Total (mm) | 0.325 | 0.057 | 0.227 | 0.465 | 33.178 | 1 | <0.001 |
| $X_9$ Frost (ner days) | 8.147 | 2.348 | 4.096 | 13.195 | 15.712 | 1 | =0.004 |
| $X_{11}$ MD Temp. > 25 °C (ner days) | | 0.213 | 0.945 | 1.817 | 43.441 | 1 | <0.001 |

Note: $X_1$—density (number of cork oaks/ha), $X_5$—pH in soil horizon A, $X_6$—percentage of clay and silt in soil horizon C, $X_7$—accumulated precipitation (mm), $X_9$—accumulated frost (days), $X_{11}$—accumulated mean temperature > 25 °C (days).

The 'yield' could be predicted based on the significant parameters shown in Table 4 and the corresponding variable values, as described in Equation (1).

$$Y_1 = 11.040X_1 - 472.814X_5 - 4.149X_6 + 0.325X_7 + 8.147X_9 + 1.307X_{11} \quad (1)$$

From (1), we could infer that while fixing all the other variables represented in the model, the yield of cork:

- Increases by 11.04 kg/ha when the cork oak tree density per ha varies between 750 and 2250;
- Decreases by 472.814 kg/ha when the pH scale value varies between 5 and 6.4;
- Decreases by 4.149 kg/ha when the percentage value of clay and silt in the soil horizon C varies between 0 and 55%;
- Increases by 0.325 kg/ha when the milliliters of accumulated precipitation in the nonad of years preceding extraction of cork from the cork oak trees vary between 5501 and 7945 mm;
- Increases by 8.147 kg/ha when the days of accumulated frost in the nonad of years preceding extraction of cork from the cork oak trees vary between 5 and 40 days;
- Increases by 1.307 kg/ha when the days with accumulated mean temperatures above 25 °C in the nonad of years preceding extraction of cork from the cork oak trees vary between 1051 and 1410 days.

### 3.3. The 'Thickness' Model

A model was successfully fitted to the data (likelihood ratio $\chi^2$ = 257.30, 7 df, $p$ < 0.001) with Akaike's information criterion (AIC) at 121. The parameterization of the model is shown in Table 5.

**Table 5.** Parameters of the 'thickness' model.

| Parameter | $\beta$ | SE | 95% Wald CI | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|
| | | | Lower | Upper | Wald $\chi^2$ | df | $p$-Value |
| $X_1$ Density (trees/ha) | −0.018 | 0.009 | −0.035 | −0.001 | 4.161 | 1 | =0.044 |
| $X_2$ CEC (meq/100 g) | 1.230 | 0.048 | 1.137 | 1.322 | 685.305 | 1 | <0.001 |
| $X_3$ OM HA (%) | −0.861 | 0.217 | −1.287 | −0.441 | 16.132 | 1 | <0.001 |
| $X_5$ pH HA | 2.357 | 0.419 | 1.536 | 3.167 | 32.518 | 1 | <0.001 |
| $X_6$ Clay and Silt HC (%) | 0.071 | 0.012 | 0.048 | 0.094 | 38.248 | 1 | <0.001 |
| $X_7$ Precipitation Total (mm) | 0.002 | 0.001 | 0.001 | 0.002 | 13.648 | 1 | <0.001 |
| $X_{11}$ MD Temp. > 25 °C (ner days) | | 0.001 | 0.000 | 0.006 | 4.158 | 1 | =0.044 |

Note: $X_1$—density (number of cork oaks/ha), $X_2$—CTC (meq/100 g), percentage of organic matter in soil horizon A, X3—organic matter in soil horizon A, $X_5$—pH in soil horizon A, $X_6$—percentage of clay and silt in soil horizon C, $X_7$—accumulated precipitation (mm), $X_{11}$—accumulated mean temperature > 25 °C (days).

The 'thickness' could be predicted based on the significant parameters shown in Table 5 and the corresponding variable values, as described in Equation (2).

$$Y_2 = -0.018X_1 + 1.230X_2 - 0.861X_3 + 2.357X_5 + 0.071X_6 + 0.002X_7 + 0.003X_{11} \quad (2)$$

From (2) we could infer that while fixing all the other variables represented in the model, the thickness (mm) of the cork extracted:

- Decreases by 0.018 mm when the cork oak tree density per ha varies between 750 and 2250;
- Increases by 1.23 mm when the value of cmolc/kg for CEC varies between 2.80 and 14.25;
- Decreases by 0.861 mm when the percentage value of organic matter in soil horizon A varies between 0.44 and 3.43%;
- Increases by 2.357 mm when the pH scale value varies between 5 and 6.4;
- Increases by 0.071 mm when the percentage value of clay and silt in soil horizon C varies between 0 and 55%;
- Increases by 0.002 mm when the milliliters of accumulated precipitation in the nonad of years preceding extraction of cork from the cork oak trees vary between 5501 and 7945 mm;
- Increases by 0.003 mm when the days of accumulated mean temperatures above 25 °C in the nonad of years preceding extraction of cork from the cork oak trees vary between 1051 and 1410 days.

### 3.4. The 'Price' Model

A model was successfully fitted to the data (likelihood ratio $\chi^2$ = 185.97, 4 df, $p$ < 0.001) with Akaike's information criterion (AIC) at 25.95. The parameterization of the model is shown in Table 6.

The 'price' could be predicted based on the significant parameters shown in Table 6 and the corresponding variable values, as described in Equation (3).

$$Y_3 = 0.016X_2 + 0.0129X_5 + 0.003X_6 + 0.0002X_7 \quad (3)$$

**Table 6.** Parameters of the 'price' model.

| Parameter | $\beta$ | SE | 95% Wald CI | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|
| | | | Lower | Upper | Wald $\chi^2$ | df | $p$-Value |
| $X_2$ | 0.016 | 0.007 | 0.003 | 0.028 | 6.361 | 1 | =0.013 |
| $X_5$ pH HA | 0.129 | 0.073 | 0.024 | 0.232 | 5.953 | 1 | =0.016 |
| $X_6$ Clay and Silt HC (%) | 0.003 | 0.002 | $1.336^{-4}$ | 0.006 | 4.239 | 1 | =0.042 |
| $X_7$ Precipitation Total (mm) | 0.0002 | $7.237^{-5}$ | $5.508^{-5}$ | $3.174^{-4}$ | 9.313 | 1 | =0.003 |

Note: $X_2$—CTC (meq/100 g). Percentage of organic matter in soil horizon A. $X_5$—pH in soil horizon A. $X_6$—percentage of clay and silt in soil horizon C. $X_7$—accumulated precipitation (mm).

From (3), we could infer that while fixing all the other variables represented in the model, the price of the cork extracted (euro/kg):

- Increases by EUR 0.016/kg when the value of cmolc/kg for CEC varies between 2.80 and 14.25;
- Increases by EUR 0.0129/kg when the pH scale value varies between 5 and 6.4;
- Increases by EUR 0.003/kg when the percentage value of clay and silt in soil horizon C varies between 0 and 55%;
- Increases by EUR 0.0002/kg when the milliliters of accumulated precipitation in the nonad of years preceding extraction of cork from the cork oak trees vary between 5501 and 7945 mm.

### *3.5. The 'Gross Income' Model*

A model was successfully fitted to the data (likelihood ratio $\chi^2$ = 135.00, 4 df, $p < 0.001$) with Akaike's information criterion (AIC) at 530. The parameterization of the model is shown in Table 7.

**Table 7.** Parameters of the 'gross income' model.

| Parameter | $\beta$ | SE | 95% Wald CI | | Hypothesis Test | | |
|---|---|---|---|---|---|---|---|
| | | | Lower | Upper | Wald $\chi^2$ | df | $p$-Value |
| $X_1$ Density (trees/ha) | 24.703 | 3.011 | 19.389 | 31.086 | 52.740 | 1 | <0.001 |
| $X_5$ pH HA | −662.798 | 160.582 | −969.540 | −325.127 | 19.245 | 1 | <0.001 |
| $X_7$ Precipitation Total (mm) | 0.579 | 0.126 | 0.282 | 0.799 | 14.325 | 1 | <0.001 |
| $X_{11}$ MD Temp. > 25 °C (ner days) | | 0.567 | 0.600 | 2.852 | 8.511 | 1 | <0.01 |

Note: $X_1$—density (number of cork oaks/ha), $X_5$—pH in soil horizon A, $X_7$—accumulated precipitation (mm), $X_{11}$—accumulated mean.

The 'gross income' could be predicted based on the significant parameters shown in Table 7 and the corresponding variable values, as described in Equation (4).

$$Y_4 = 24.703X_1 - 662.798X_5 + 0.579X_7 + 1.559X_{11} \quad (4)$$

From (4), we could infer that while fixing all the other variables represented in the model, the 'gross income' (euro/ha):

- Increases by EUR 24.703/ha when the cork oak tree density per ha varies between 750 and 2250;
- Decreases by EUR 662.798/ha when the pH scale value varies between 5 and 6.4;
- Increases by EUR 0.579/ha when the milliliters of accumulated precipitation in the nonad of years preceding extraction of cork from the cork oak trees vary between 5501 and 7945 mm;
- Increases EUR by 1.559/ha when the days of accumulated mean temperatures above 25 °C in the nonad of years preceding extraction of cork from the cork oak trees vary between 1051 and 1410 days.

## 4. Discussion

Within the density range of the present study (20–100 trees/ha), and according to our models, an increase in tree density results in higher yields and gross incomes, despite a lower cork thickness.

Corona et al. [45] conducted a study in Sardinia, Italy, and found a positive correlation between the mass of cork produced and the number of trees in a stand (for stands with densities between 350 and 800 trees/ha). The authors also discovered that the density (within the studied range) does not affect cork mass production per tree. Therefore, if cork mass production per tree is not affected at these densities, within the range of densities observed in our study, we can expect the same. As a result, an increase in yields, and consequently gross income, is justified.

Fonseca et al. [46] utilized self-thinning dynamics to estimate optimum cork oak densities in Portugal and found that the current densities of Portuguese *montado* are not a limiting factor for yields. However, should the goal of a *montado* be cork production only, the authors argue that increasing densities should be considered. Therefore, within the low-density range of the sample used in the present study (20–100 trees/ha), our models show that higher densities result in increased cork yields and cork gross income per hectare.

Arosa et al. [47] argued that low densities in the Portuguese *montados* are not due to management with that purpose. The authors concluded that this is a result of high densities of livestock and ploughing, as these do not allow natural regeneration. Decreasing livestock densities and spacing soil work with a minimum of five years would allow natural regeneration. Protecting regenerating trees from both mechanical work and grazing animals would also be important to allow the densification of trees [42,48].

Our models show that yield and gross income decrease with the pH, while cork thickness and price increase with the pH. The cork oak is considered an acidophilous tree, occurring in siliceous soils and showing intolerance to high-pH and therefore silt-rich soils. Cork oak thrives in soils with a pH between 4.7 and 6.5 [49]. The pH of the soils in the present study ranged between 5 and 6.4 (within the announced tolerance interval), explaining the results. It is also known that cork oak has the unusual ability to decrease the soil pH around the rhizosphere [49]. The uptake of calcium in addition to the leaching of other alkaline cations is the mechanism responsible for a decrease in pH from bottom to top in cork oak forest soils [49,50]. The cork thickness model is negatively affected by higher levels of OM in soil horizon A. Pestana and Gomes [51] found that soils with richer organic matter and a higher cation exchange capacity correlate negatively with cork thickness, which is corroborated by our results.

Despite the increase in yield, according to our models, lowering the pH may result in a lower thickness of cork. The result agrees with that obtained by Pestana and Gomes [51], who found a positive correlation between the caliber of cork and the quantities of calcium available in the soil, and therefore, higher pHs (within the acidic range). Nevertheless, within the pH range of our study, a higher pH has been shown to favor price but not gross income. Such a fact may be explained by the higher yields obtained at lower pH values in the range of our study (5.4 to 6). Cork thickness and density may also be affected by intraspecific competition, with higher competition resulting in a lower caliber and higher cork density [52]. The results also agree with those obtained by Pestana and Gomes [51], where a higher porosity was also found in cork produced in soils richer in alkaline cations, mainly magnesium, and therefore, with higher pHs. The decrease in yield is, however, the main predictor for a decrease in gross income in soils with higher pH values.

Our models show that a higher percentage of clay and silt in horizon C of the soil relates to lower yields, thicker cork, and higher prices.

The cork oak prefers loamy to sandy soils, with good aeration, no compaction, and therefore good drainage [49,53]. Climate change has brought more frequent droughts and episodes of severe precipitation, which has been pointed out as a reason for some decline in cork oaks in areas more susceptible to floods. Root infection with the fungi *Phytophthora cinnamomic* is used to explain this maladaptation [53]. A higher percentage of clay and silt in soil horizon C is associated with poorer permeability, which may explain the decrease in yields observed in our model. Particularly in our study, when we found up to 55% clay and silt in soil horizon C, our models showed that loss of yield was compensated for by thicker cork and therefore a better price. This argument is also supported by the fact that our models showed higher values of CEC to be related to greater cork thicknesses and higher prices.

According to our models, more accumulated precipitation in the nonad or years preceding the extraction of cork correlates with a higher yield, thicker cork, higher prices, and higher gross income. Despite disliking poor drainage and resisting periodic draughts, cork oaks benefit very much from regular precipitation, and cork growth has shown synchrony with accumulated precipitation [54]. Spring cork oak growth is favored when there is winter rain, and autumn growth when there is summer rain [55]. Precipitation in winter and spring (November to June) is highly relevant for cork growth, and summer precipitation also has some importance [54]. Years of drought or lower-than-average winter rainfall have a negative influence on cork oak growth and need to be considered when estimating yields and quality [56].

The fitted models showed that concerning the accumulated number of days with mean temperatures above 25 °C in the nonad of years preceding extraction, the higher the accumulation, the higher the yield, thickness, and gross income. The cork oak is a tree that thrives in the Mediterranean climate with hot summers and mild winters and that handles elevated temperatures very well [57]. The tree possesses several anatomical and physiological adaptations spanning from the capacity to control evapotranspiration through leaf stomata [58] to the capacity to obtain moisture from a deep rooting system [37,59]. It is also known that the growth of new leaves in cork oaks occurs with elevated temperatures in the summer, especially if there is moisture available in reach of the rooting system [60–62]. Cork growth is dependent on the warmer summer temperatures, and during this season, only severe drought or superficial rooting systems are limiting factors [63], as stomatal closure, leaf osmotic adjustment, and deep-water uptake adjust evapotranspiration [60]. High temperatures in June are correlated with cork oak radial growth [55].

Finally, the last studied fact affecting yield is the accumulated number of days with frost in the nonad or years preceding extraction, with a higher accumulated number of days associated with a higher yield. The cork oak is a tree that dislikes freezing temperatures. Light-energy harvesting is limited by low temperatures because of the reduced photochemical efficiency of photosystem II [64], limiting, therefore, photosynthesis. As such, this result is difficult to explain and may result from the interaction of other variables not considered in this model.

## 5. Conclusions

The fitted models reveal the intricate relationship between the edaphoclimatic factors with an influence on cork oak yield, thickness, price, and gross income. Higher tree densities within the studied range lead to increased yields and gross incomes despite thinner cork. Soil pH plays a critical role, with a lower pH associated with higher yields but potentially thinner cork. The presence of clay and silt in soil horizon C influences yield, thickness, price, and gross income, highlighting the complex effect of soil composition on cork oak productivity. Climatic factors such as precipitation and temperature significantly impact cork oak growth and yield, with warmer temperatures and adequate moisture favoring higher yields and thicker cork. However, the influence of frost days on yield warrants further investigation. Understanding these multifaceted relationships is crucial for optimizing cork oak management practices and ensuring sustainable cork production under the current circumstances of climate change.

Soon, cork trees may face numerous challenges, including prolonged droughts and concentrated rainfall, an issue in itself, as cork oaks are sensitive to excess water. The Alentejo region, a lowland area without significant elevations, contrasts with northern regions like Beiras, which have steeper terrains and poorer, often rocky soils. These differences greatly impact the suitability of cork oaks in the area, making the relocation of this species to northern Portugal, to the extent existing in the south, challenging. Additionally, while climate change advances rapidly, ecological adaptation cannot keep pace. Even if cork oak forests could be shifted northward, several critical factors remain, such as the lengthy growth cycle of cork oaks, which require up to 40 years before the first cork can be harvested. Furthermore, the local human and ecological heritage associated with these forests is deeply rooted and would be nearly impossible to transfer.

**Author Contributions:** Conceptualization, M.D.-S.; methodology, F.M. and M.D.-S.; validation, F.M. and M.D.-S.; formal analysis, F.M.; investigation, F.M. and M.D.-S.; resources, F.M. and M.D.-S.; data curation, F.M. and M.D.-S.; writing—original draft preparation, F.M. and M.D.-S.; writing—review and editing, F.M. and M.D.-S. All authors have read and agreed to the published version of the manuscript.

**Funding:** We extend our gratitude to Foundation for Science and Technology (FCT, Portugal) for financial support to CISAS—Centre for Research and Development in Agrifood Systems and Sustainability (UIDB/05937/2020 (https://doi.org/10.54499/UIDB/05937/2020)); and UIDP/05937/2020 (https://doi.org/10.54499/UIDP/05937/2020)).

**Data Availability Statement:** The data presented in this study are available on request from the corresponding author due to confidentiality.

**Acknowledgments:** We extend our gratitude to the farmers who contributed and allowed the collection of data for this work.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## References

1. Vizinho, A.; Príncipe, A.; Vasconcelos, A.C.; Rebelo, R.; Branquinho, C.; Penha-Lopes, G. Using and Creating Microclimates for Cork Oak Adaptation to Climate Change. *Land* **2023**, *12*, 531. [CrossRef]
2. Campos, P.; Álvarez, A.; Oviedo, J.L.; Mesa, B.; Caparrós, A.; Ovando, P. Environmental Incomes: Refined Standard and Extended Accounts Applied to Cork Oak Open Woodlands in Andalusia, Spain. *Ecol. Indic.* **2020**, *117*, 106551. [CrossRef]
3. UNESCO. Cultural Landscape. Available online: https://whc.unesco.org/en/tentativelists/6210/#:~:text=The%20cork%20oak%20forest%20zones,municipalities%20of%20Crato%20and%20Portalegre (accessed on 10 March 2024).
4. La Riccia, L.; Voghera, A.; Salizzoni, E.; Negrini, G.; Maltoni, S. Planning Ecological Corridors: A Cost Distance Method Based on Ecosystem Service Evaluation in the Sardinian Cork Oak Forests. In *International Conference on Innovation in Urban and Regional Planning*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 301–310.
5. Mexia, T.; Lecomte, X.; Caldeira, M.C.; Bugalho, M.N. Conservation Zones Increase Habitat Heterogeneity of Certified Mediterranean Oak Woodlands. *For. Ecol. Manag.* **2022**, *504*, 119811. [CrossRef]
6. Moreno, G.; Rolo, V. Agroforestry Practices: Silvopastoralism. In *Agroforestry for Sustainable Agriculture*; Burleigh Dodds Science Publishing: Sawston, UK, 2019; pp. 119–164.
7. Pereira, M.S.; Quintas, A.; Coelho, I.S.; Belo, C.C. Types of Land Use in the Montado (Dehesa) Production System. In *Silvopastoralism and Sustainable Land Management, Proceedings of the an International Congress on Silvopastoralism and Sustainable Management Held in Lugo, Spain, April 2004*; CABI Publishing: Wallingford, UK, 2005; pp. 64–65.
8. Carneiro, J.P.; Simões, N.; Maçãs, I.D.; Tavares-de-Sousa, M. Pasture Improvement in Montado Extensive Farming Systems. *Opt. Méditerr. Ser. A* **2008**, *79*, 193–197.
9. Crespo, D.G. The Role of Pasture Improvement in the Rehabilitation of the "Montado/Dehesa" System and in Developing Its Traditional Products. In *Animal Products From the Mediterranean Area*; Wageningen Academic: Wageningen, The Netherlands, 2006; pp. 185–195, ISBN 9086865682.
10. De Dios Vargas, J.; Huntsinger, L.; Starrs, P.F. Raising Livestock in Oak Woodlands. In *Mediterranean Oak Woodland Working Landscapes: Dehesas of Spain and Ranchlands of California*; Springer: Dordrecht, The Netherlands, 2013; pp. 273–310.
11. Rodríguez-Hernández, P.; Martín-Gómez, A.; Cardador, M.J.; Amaro, M.A.; Arce, L.; Rodríguez-Estévez, V. Geographical Origin, Curing Plant and Commercial Category Discrimination of Cured Iberian Hams through Volatilome Analysis at Industry Level. *Meat Sci.* **2023**, *195*, 108989. [CrossRef]
12. Fonseca, A.; Themudo-Barata, F. Use of substitute foods in the "montados" of Alentejo during the second and third quarters of the twentieth century. *Rev. História E Econ.* **2018**, *21*, 67–81.
13. Costa-e-Silva, F.; Correia, A.C.; Pinto, C.A.; David, J.S.; Hernandez-Santana, V.; David, T.S. Effects of Cork Oak Stripping on Tree Carbon and Water Fluxes. *For. Ecol. Manag.* **2021**, *486*, 118966. [CrossRef]
14. Santos, A.; Carvalho, A.; Barbosa-Povoa, A. An Economic and Environmental Comparison between Forest Wood Products–Uncoated Woodfree Paper, Natural Cork Stoppers and Particle Boards. *J. Clean. Prod.* **2021**, *296*, 126469. [CrossRef]
15. Teixeira, R.T. Cork Development: What Lies Within. *Plants* **2022**, *11*, 2671. [CrossRef]

16. APCOR. *Cork Yearbook 2020*; APCOR: Lisbon, Portugal, 2020.
17. Castro, A.; Avillez, F.; Rodrigues, V.; Silva, F.G.; Santos, F.; Rebelo, F.; Jorge, M.N.; Aires, N. *The Cork Sector: From the Forest to the Consumer*; APCOR: Lisbon, Portugal, 2020.
18. Coelho, M.B.; Paulo, J.A.; Palma, J.H.N.; Tomé, M. Contribution of Cork Oak Plantations Installed after 1990 in Portugal to the Kyoto Commitments and to the Landowners Economy. *For. Policy Econ.* **2012**, *17*, 59–68. [CrossRef]
19. Yay, Ö.; Hasanzadeh, M.; Diltemiz, S.F.; Kuşhan, M.C.; Gürgen, S. Thermal Insulation with Cork-Based Materials. In *Cork-Based Materials in Engineering: Design and Applications for Green and Sustainable Systems*; Springer: Berlin/Heidelberg, Germany, 2024; pp. 3–15.
20. Silva, J.; Gardi, A.; Sabatini, R. Integration of Naturally Occurring Materials in Lightweight Aerostructures. In *Sustainable Aviation Technology and Operations: Research and Innovation Perspectives*; John Wiley & Sons: Hoboken, NJ, USA, 2023.
21. Martins, C.I.; Gil, V. Processing–Structure–Properties of Cork Polymer Composites. *Front. Mater.* **2020**, *7*, 297. [CrossRef]
22. Li, X.; Liu, R.; Long, L.; Liu, B.; Xu, J. Tensile Behavior and Water Absorption of Innovative Composites from Natural Cork Granules and Bamboo Particles. *Compos Struct.* **2021**, *258*, 113376. [CrossRef]
23. Rivas-Martínez, S.; Penas, A.; González, T.E.D.; Prieto, I. *Bioclimatic Map of Europe: Thermoclimatic Belts*; Universidad de León, Secretariado de Publicaciones: León, Spain, 2006; ISBN 8497732766.
24. Aronson, J.; Pereira, J.S.; Pausas, J.G. *Cork Oak Woodlands on the Edge: Ecology, Adaptive Management, and Restoration*; Island Press: Washington, DC, USA, 2012; ISBN 161091130X.
25. Firmino, P.N.; Paulo, J.A.; Lourenço, A.; Tomé, M.; Campagnolo, M. How Do Soil and Topographic Drivers Determine Tree Diameter Spatial Distribution in Even Aged Cork Oak Stands Installed in Average to High Productivity Areas. *New For.* **2024**, *55*, 1475–1496. [CrossRef]
26. Pérez-Girón, J.C.; Díaz-Varela, E.R.; Álvarez-Álvarez, P. Climate-Driven Variations in Productivity Reveal Adaptive Strategies in Iberian Cork Oak Agroforestry Systems. *For. Ecosyst.* **2022**, *9*, 100008. [CrossRef]
27. Camarero, J.J.; Gazol, A.; Valeriano, C.; Colangelo, M.; Rubio-Cuadrado, Á. Growth Responses to Climate and Drought in Relict Cork Oak Populations as a Benchmark of the Species Tolerance. *Forests* **2023**, *15*, 72. [CrossRef]
28. Duque-Lazo, J.; Navarro-Cerrillo, R.M.; Ruíz-Gómez, F.J. Assessment of the Future Stability of Cork Oak (*Quercus suber* L.) Afforestation under Climate Change Scenarios in Southwest Spain. *For. Ecol. Manag.* **2018**, *409*, 444–456. [CrossRef]
29. Vessella, F.; López-Tirado, J.; Simeone, M.C.; Schirone, B.; Hidalgo, P.J. A Tree Species Range in the Face of Climate Change: Cork Oak as a Study Case for the Mediterranean Biome. *Eur. J. For. Res.* **2017**, *136*, 555–569. [CrossRef]
30. Paulo, J.A.; Firmino, P.N.; Faias, S.P.; Tomé, M. Quantile Regression for Modelling the Impact of Climate in Cork Growth Quantiles in Portugal. *Eur. J. For. Res.* **2021**, *140*, 991–1004. [CrossRef]
31. Leite, C.; Oliveira, V.; Miranda, I.; Pereira, H. Cork Oak and Climate Change: Disentangling Drought Effects on Cork Chemical Composition. *Sci. Rep.* **2020**, *10*, 7800. [CrossRef]
32. Touhami, I.; Chirino, E.; Aouinti, H.; El Khorchani, A.; Elaieb, M.T.; Khaldi, A.; Nasr, Z. Decline and Dieback of Cork Oak (*Quercus suber* L.) Forests in the Mediterranean Basin: A Case Study of Kroumirie, Northwest Tunisia. *J. For. Res.* **2020**, *31*, 1461–1477. [CrossRef]
33. Costa, A.; Pereira, H.; Madeira, M. Analysis of Spatial Patterns of Oak Decline in Cork Oak Woodlands in Mediterranean Conditions. *Ann. For. Sci.* **2010**, *67*, 204. [CrossRef]
34. Cabral, M.; Lopes, F.J. *Determinacao Das Causas de Morte Do Sobreiro Nos Concelhos*; AGRIS—International System for Agricultural Science and Technology: Rome, Italy, 1992.
35. Thomas, F.M.; Blank, R.; Hartmann, G. Abiotic and Biotic Factors and Their Interactions as Causes of Oak Decline in Central Europe. *For. Pathol.* **2002**, *32*, 277–307. [CrossRef]
36. Kurz-Besson, C.; Otieno, D.; Lobo do Vale, R.; Siegwolf, R.; Schmidt, M.; Herd, A.; Nogueira, C.; David, T.S.; David, J.S.; Tenhunen, J. Hydraulic Lift in Cork Oak Trees in a Savannah-Type Mediterranean Ecosystem and Its Contribution to the Local Water Balance. *Plant Soil* **2006**, *282*, 361–378. [CrossRef]
37. Oliveira, G.; Correia, O.A.; Martins-Loução, M.A.; Catarino, F.M. Water Relations of Cork-Oak (*Quercus suber* L.) under Natural Conditions. In *Quercus ilex L. Ecosystems: Function, Dynamics and Management*; Springer: Dordrecht, The Netherlands, 1992; pp. 199–208.
38. Kabrick, J.M.; Dey, D.C.; Jensen, R.G.; Wallendorf, M. The Role of Environmental Factors in Oak Decline and Mortality in the Ozark Highlands. *For. Ecol. Manag.* **2008**, *255*, 1409–1417. [CrossRef]
39. Paulo, J.A.; Palma, J.H.N.; Gomes, A.A.; Faias, S.P.; Tomé, J.; Tomé, M. Predicting Site Index from Climate and Soil Variables for Cork Oak (*Quercus suber* L.) Stands in Portugal. *New For.* **2015**, *46*, 293–307. [CrossRef]
40. Príncipe, A.; Nunes, A.; Pinho, P.; Aleixo, C.; Neves, N.; Branquinho, C. Local-Scale Factors Matter for Tree Cover Modelling in Mediterranean Drylands. *Sci. Total Environ.* **2022**, *831*, 154877. [CrossRef] [PubMed]
41. Fennane, M.; Rejdali, M. The World Largest Cork Oak Maamora Forest: Challenges and the Way Ahead. *Fl. Medit.* **2015**, *25*, 277–285.
42. Mechergui, T.; Pardos, M.; Boussaidi, N.; Jacobs, D.F.; Catry, F.X. Problems and Solutions to Cork Oak (*Quercus suber* L.) Regeneration: A Review. *iForest Biogeosci. For.* **2023**, *16*, 10–22. [CrossRef]
43. Gentilesca, T.; Camarero, J.J.; Colangelo, M.; Nolã, A.; Ripullone, F.; Nole, A. Drought-Induced Oak Decline in the Western Mediterranean Region: An Overview on Current Evidences, Mechanisms and Management Options to Improve Forest Resilience. *IForest* **2017**, *10*, 796–806. [CrossRef]

44. UNAC—União da Floresta Mediterrânica. *Guia de Comercialização de Cortiça No Campo. Corknow—How: Conhecimento Suberícola Em Rede*; UNAC: Lisbon, Portugal, 2013.
45. Corona, P.; Quatrini, V.; Schirru, M.; Dettori, S.; Puletti, N. Towards the Economic Valuation of Ecosystem Production from Cork Oak Forests in Sardinia (Italy). *iForest Biogeosci. For.* **2018**, *11*, 660. [CrossRef]
46. Fonseca, T.; Monteiro, L.; Enes, T.; Cerveira, A. Self-Thinning Dynamics in Cork Oak Woodlands: Providing a Baseline for Managing Density. *For. Syst.* **2017**, *26*, e006. [CrossRef]
47. Arosa, M.L.; Bastos, R.; Cabral, J.A.; Freitas, H.; Costa, S.R.; Santos, M. Long-Term Sustainability of Cork Oak Agro-Forests in the Iberian Peninsula: A Model-Based Approach Aimed at Supporting the Best Management Options for the Montado Conservation. *Ecol. Modell.* **2017**, *343*, 68–79. [CrossRef]
48. Pausas, J.G.; Marañón, T.; Caldeira, M.C.; Pons, J. *Natural Regeneration*; Island Press: Washington, DC, USA, 2009.
49. Serrasolses, I.; Pérez-Devesa, M.; Vilagrosa, A.; Pausas, J.G.; Sauras, T.; Cortina, J.; Vallejo, R. *Soil Properties Constraining Cork Oak Distribution*; Island Press: Washington, DC, USA, 2009.
50. Cabral, M.T.; Lopes, F.; Sardinha, R.M. Determinação Das Causas Da Morte Do Sobreiro Nos Concelhos de Santiago Do Cacém, Grândola e Sines. Relatório Síntese. *Silva Lusit* **1993**, *1*, 7–24.
51. Pestana, M.N.; Gomes, A.A. The Effect of Soil on Cork Quality. *Front. Chem.* **2014**, *2*, 80. [CrossRef] [PubMed]
52. Pizzurro, G.M.; Maetzke, F.; Veca, D.S.L.M. Differences of Raw Cork Quality in Productive Cork Oak Woods in Sicily in Relation to Stand Density. *For. Ecol. Manag.* **2010**, *260*, 923–929. [CrossRef]
53. Moreira, A.C.; Rodrigues, A. Effect of Soil Water Content and Soil Texture on Phytophthora Cinnamomic Infection on Cork and Holm Oak. *Silva Lusit.* **2021**, *29*, 133–160. [CrossRef]
54. Caritat, A.; Gutiérrez, E.; Molinas, M. Influence of Weather on Cork-Ring Width. *Tree Physiol.* **2000**, *20*, 893–900. [CrossRef]
55. Costa, A.; Pereira, H.; Oliveira, Â. Influence of Climate on the Seasonality of Radial Growth of Cork Oak during a Cork Production Cycle. *Ann. For. Sci.* **2002**, *59*, 429–437. [CrossRef]
56. Tomé, M.; Coelho, M.B.; Lopes, F.; Pereira, H. Modelo de Produção Para o Montado de Sobro Em Portugal. In Proceedings of the European Conference on Cork Oak and Cork, Lisboa, Portugal, 25 May 1998; Centro de Estudos Florestais: Lisboa, Portugal, 1998; pp. 22–46.
57. Ghouil, H.; Montpied, P.; Epron, D.; Ksontini, M.; Hanchi, B.; Dreyer, E. Thermal Optima of Photosynthetic Functions and Thermostability of Photochemistry in Cork Oak Seedlings. *Tree Physiol.* **2003**, *23*, 1031–1039. [CrossRef]
58. David, T.S.; Ferreira, M.I.; Cohen, S.; Pereira, J.S.; David, J.S. Constraints on Transpiration from an Evergreen Oak Tree in Southern Portugal. *Agric. For. Meteorol.* **2004**, *122*, 193–205. [CrossRef]
59. Méthy, M.; Damesin, C.; Rambal, S. Drought and Photosystem II Activity in Two Mediterranean Oaks. In Proceedings of the Annales des Sciences Forestières; EDP Sciences: Les Ulis, France, 1996; Volume 53, pp. 255–262.
60. Besson, C.K.; Lobo-do-Vale, R.; Rodrigues, M.L.; Almeida, P.; Herd, A.; Grant, O.M.; David, T.S.; Schmidt, M.; Otieno, D.; Keenan, T.F. Cork Oak Physiological Responses to Manipulated Water Availability in a Mediterranean Woodland. *Agric. For. Meteorol.* **2014**, *184*, 230–242. [CrossRef]
61. Costa, A.; Madeira, M.; Oliveira, Â.C. The Relationship between Cork Oak Growth Patterns and Soil, Slope and Drainage in a Cork Oak Woodland in Southern Portugal. *For. Ecol. Manag.* **2008**, *255*, 1525–1535. [CrossRef]
62. Vaz, M.; Pereira, J.S.; Gazarini, L.C.; David, T.S.; David, J.S.; Rodrigues, A.; Maroco, J.; Chaves, M.M. Drought-Induced Photosynthetic Inhibition and Autumn Recovery in Two Mediterranean Oak Species (*Quercus ilex* and *Quercus suber*). *Tree Physiol.* **2010**, *30*, 946–956. [CrossRef] [PubMed]
63. Costa, A.; Barbosa, I.; Roussado, C.; Graça, J.; Spiecker, H. Climate Response of Cork Growth in the Mediterranean Oak (*Quercus suber* L.) Woodlands of Southwestern Portugal. *Dendrochronologia* **2016**, *38*, 72–81. [CrossRef]
64. Adams, W.W., III; Demmig-Adams, B. The Xanthophyll Cycle and Sustained Thermal Energy Dissipation Activity in Vinca Minor and Euonymus Kiautschovicus in Winter. *Plant Cell Environ.* **1995**, *18*, 117–127. [CrossRef]