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Soil conditions influence the advancement of first cork stripping in fertirrigated cork oaks

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Introduction: Fertirrigation in cork oak plantations is a novel approach intended to accelerate growth until trees reach productive maturity, after which they are expected to be managed under rainfed conditions. This study investigated how site quality influenced the timing of the first stripping in a fertirrigated stand.

Methods: REGASUBER is a 6-hectare experimental plot located in Coruche, Portugal, installed in 2014 with cork oaks planted with 4 × 4 spacing and subjected to four irrigation treatments. Trees height and diameter at breast height were annually measured, revealing the presence of two different site qualities, regular and inferior. Soil moisture was periodically monitored down to 1 meter deep at 10 locations per site. To access soil moisture at deeper layers, an exploratory electrical resistivity method was tested. The time to first stripping was modeled by irrigation treatment and site quality using nonlinear regression.

Results: Trees subjected to fertirrigation and located in regular site conditions showed the highest growth rates. Under these conditions, models predicted the first cork stripping at 13 to 15 years of age—about 10 years earlier than in rainfed trees on similar soils. Fertirrigation also contributed to more uniform growth across the stand, reducing uncertainty in stripping age. In inferior site conditions, fertirrigated trees were projected to reach the first stripping age between 20 and 25 years, which corresponds approximately to the age of rainfed trees in regular conditions. The resistivity method detected significantly higher soil moisture down to 4 meters in regular site quality, helping explain the observed growth differences.

Discussion: These results indicate that the benefits of fertirrigation for cork oak growth depend on soil water-holding capacity. Reliable methods to assess deep soil moisture are thus essential for forest managers considering this planting strategy.

KEYWORDS

***Quercus suber*, fertirrigation, site quality, tree growth, cork stripping, cork debark, irrigation**

1 Introduction

Cork oaks (*Quercus suber* L.) are Mediterranean trees with significant ecological, social, and economic importance (Pinto-Correia et al., 2011). Their primary economic value is linked to cork production (APCOR, 2020). According to the Portuguese law, cork can be removed when the tree trunk reaches a perimeter of 70 cm above the cork, at 130 cm height. Consequently, the timing of the first stripping varies depending on the tree's growth rate, which is intrinsically related to the edaphoclimatic conditions of the site. After the first stripping, cork can be removed every 9 to 10 years throughout the tree's life, irrespective of its growth rate. Among the various edaphoclimatic factors associated with cork oak growth, water availability has been identified as a key determinant of tree productivity (Paulo et al., 2015; Mendes et al., 2016). In fact, Mediterranean forests typically grow under water-limited conditions (Piñol et al., 1999). Exacerbating this constraint, increases in atmospheric evaporative demand combined with declining precipitation have been observed in the region (Spinoni et al., 2017; Ramos et al., 2018; Samaniego et al., 2018; Caloiero et al., 2018; Claro et al., 2023; Noto et al., 2023). Therefore, drought events have become more frequent and severe due to climate change, compromising not only cork oak growth but also tree vitality and natural/artificial regeneration (e.g., Nunes et al., 2016; Matías et al., 2019; González Romero et al., 2020; Touhami et al., 2020; Camarero et al., 2024). In response to these challenges, a limited number of studies have explored the use of irrigation under natural conditions to support cork oak regeneration (Vessella et al., 2010; Ceia et al., 2024; Mitique et al., 2025). Long-term research on cork oak fertirrigation is also being conducted, aiming not only to enhance seedling survival but also to accelerate tree growth and anticipate the first cork stripping (Camilo-Alves et al., 2020; Camilo-Alves et al., 2022). This objective is critical to the cork sector, which has experienced a reduction in cork quality and quantity due to the widespread of cork oak decline and lack of regeneration (Brasier, 1992, Ribeiro and Surovy, 2008, Camilo-Alves et al., 2013, Senf et al., 2020, Ritsche et al., 2021). Accordingly, the long-term scientific experiments on cork oak fertirrigation plots aim to find efficient fertirrigation to reduce time until cork stripping while advancing the fundamental understanding of how water availability influences the structural and physiological responses of trees. This understanding is crucial, as fertirrigation will be discontinued once productivity is achieved, requiring cork oaks to adapt to the subsequent rainfed conditions.

The studies on cork oak fertirrigation seek to provide forest producers with essential information to guide their decisions in this paradigm shift. Accordingly, the research aims to develop silvicultural models for cork oak that incorporate this technique, offering relevant guidelines on appropriate irrigation volumes and frequencies tailored to local conditions and tree age, as well as addressing proper management requirements, including vegetation control, formative pruning, planting spacing, thinning, and more. To date, published research provide information on the optimal water volume required to enhance growth while minimizing wastage, offering insights into the structural-functional responses of trees to water availability (Camilo-Alves et al., 2020; Camilo-Alves et al., 2022), including the effect on root development (Šleglová et al., 2025a; Šleglová et al., 2025b) and preliminary results on cork development (Poeiras et al., 2021; Poeiras et al., 2022a; Poeiras et al., 2022b). In addition to the scientific studies, reports and videos addressing the technical challenges and silvicultural interventions adapted to this context were also published (Go-Regacork, 2022; Regacork-Trade, 2023). The economic and financial evaluation was performed using the CORKFITS simulator (Ribeiro and Surovy, 2011), based on tree growth parameters from a fertirrigated plot established in 2002 on a very productive site, called IRRICORK (Camilo-Alves et al., 2025).

Nevertheless, the implementation of cork oak fertirrigation still remains subject to debate among forest producers, mainly due to uncertainties concerning the influence of edaphoclimatic factors on tree growth—that is, the site quality. Site quality is defined by the collective factors that determine the productivity potential of a forest area, and can be evaluated through direct or indirect methods (Mercker, 2006). When stand age is unknown, or in the absence of tree measurements for the species, it becomes necessary to employ indirect methods to estimate site quality using climatic and/or soil variables. For each Portuguese forest species, including the cork oak, Ferreira et al. (2001) classified site quality by employing a combination of climatic and soil conditions. They categorized site quality into three distinct classes: regular, optimal, and inferior. This classification was later used in the Regional Program for Forest Management (PROF) for Alentejo and Lisbon and Tagus Valley regions (Macedo et al., 2019). Although fertirrigation significantly enhanced tree growth in a stand classified as optimal for cork oak (Camilo-Alves et al., 2022) it remains necessary to test this technique in stands of differing site quality, in order to develop appropriate models. Accordingly, this study aims to evaluate the extent to which the timing of the first cork stripping can be anticipated through fertirrigation under site qualities other than optimal. Data was obtained from the first long-term scientific experimental cork oak fertirrigation plots, installed in 2014. The arenosol soil type across the plot is classified as of regular quality for cork oaks (Ferreira et al., 2001). However, notable differences in tree growth emerged across the plot, associated with spatial location. Those observation suggested the presence of two distinct soil types with different suitability for cork oak. Therefore, the covariate "site quality" was incorporated into the assessment of tree growth under fertirrigation in this study.

Additionally, to investigate the underlying causes of these differences in soil quality, an alternative technique for groundwater prospecting was employed. Geoelectrical prospecting is a geophysical method used to map the spatial distribution of subsurface electrical resistivity. While often applied in mineral exploration, soil resistivity is also valuable in agriculture for estimating variables such as fertilizer needs, water table depth, and soil moisture—topics covered by numerous studies (e.g., Afshar et al., 2015; Greggio et al., 2018; Olabode and San, 2023). The technique involves injecting an electric current (I) into the soil via two electrodes and measuring the resulting voltage (V) across another pair. Apparent resistivity is then calculated based on electrode positions (Kearey et al., 2002; Allred et al., 2008; Reynolds, 2011; Lowrie and Fichtner, 2020). Modern systems use multi-electrode arrays with automated switching to collect hundreds of measurements, which are processed through inversion algorithms to produce 2D resistivity profiles—an approach known as Electrical Resistivity Tomography (ERT).

In resume, this study aims to assess the extent to which fertirrigation can accelerate the timing of the first cork stripping under different site quality conditions Specifically, it seeks (1) to estimate the time required for the trees to reach the appropriate size for the first cork stripping, considering irrigation treatments and site quality; and (2) to investigate whether variations in site quality are related to differences in soil water holding capacity.

This is the first study to estimate the anticipated timing of first cork stripping across contrasting site qualities—an essential step toward evaluating the cost–benefit of fertirrigation in cork oak stands. By integrating long-term growth data with geoelectrical prospecting, the findings will contribute to the development of economic and silvicultural models to support decision-making in cork oak plantation management.

2 Materials and methods

2.1 Study area

The region of Coruche, Portugal, is characterized by a Mediterranean subhumid climate with hot and dry summers. According to the most recent climate normal (1981–2010) reported by the Portuguese Institute for Sea and Atmosphere, the average annual precipitation was 600.7 mm, and the average annual temperature was 16.2°C. Following the Regional Program for Forest Management (PROF) for Lisbon and Tagus Valley regions (Macedo et al. 2019b), the climatic aptitude for the region is considered superior for cork oak.

2.1.1 Study site and experimental design

In May 2014, the afforestation project was carried out on a former 6-hectare cropland designated for domestic use, within a farm dedicated to cork oak production. The experimental plot REGASUBER spans along a hill with a slope of approximately 7%, oriented 12° north. It covers a distance of 152 meters and a width of 404 meters (Figure 1). A detailed characterization of the experimental plot is available in Camilo-Alves et al. (2020). In short, the experimental design includes subsurface drip fertirrigation with four treatments plus a control, grouped into blocks with four to five irrigation lines. The treatment blocks were replicated four times and randomly distributed throughout the study site. Trees were planted at a 4 × 4 m spacing.

2.1.2 Fertirrigation treatments

Each year, the fertirrigation period takes place during the summer drought. All treatments initiate and end in the same weeks, with variations in weekly irrigation volume and frequency. Fertilizers were maintained equal across all treatments. Adjustments to irrigation volume and frequency, as well as fertilizers volume, were made in response to the plants' growth. The duration of the irrigation campaign varied depending on precipitation events in spring and autumn, ranging from 14 to 27 weeks. Total amount of fertirrigation is outlined in Table 1. Fertirrigation for the control group occurred in the first 2 years (2014, 2015) during initiation phase and intermittently—no more than 1 week a month—in the subsequent 2 years to enhance plants survival.

2.2 Site quality

Before planting, soil profile evaluation was carried out at eight random locations, down to 2 m. Soil was characterized as unstructured with sandy texture, loose tenacity and friability, non-stickiness, no plasticity and minimal compaction. More than 75% of the particles were classified was gross sand and organic matter content was very low (0.32%). No significant differences in soil profile were observed between the locations and no weathered parent material was reached (C horizon). According to the FAO classification, the soil is of the Arenosol type. Arenosols exhibit constraints in soil water holding capacity, resulting in regular soil quality for cork oak development (Ferreira et al., 2001). Significant variations in tree growth rate were observed in relation to their location within the plot (Figure 1). Although soil profile evaluations did not provide an explanation for these differences, trees located on the backslope of the hill exhibited significantly lower growth compared to those on the footslope.

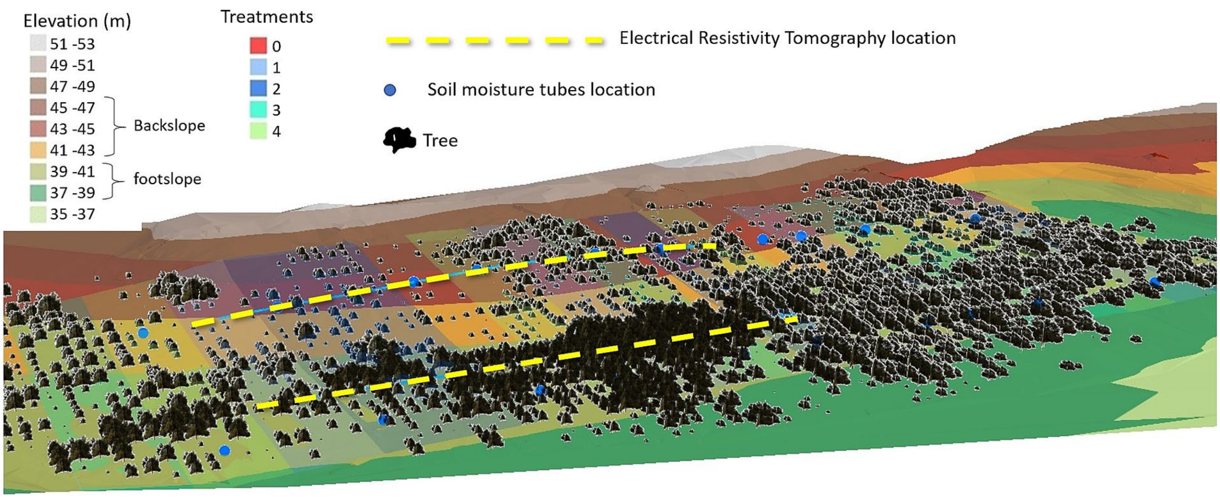

FIGURE 1
3D depiction of the REGASUBER experimental plot, Coruche, Portugal, measured on February 2023. Dimensions of the symbol "tree" are proportional to each tree diameter.

TABLE 1 Quantification of water and nutrients inputs in the REGASUBER experimental plot, Coruche, Portugal, over 9 years, by treatments.

Inputs between Jun 2014–Jun 2023		Control	Treatments			
			1	2	3	4
Irrigation volume (m^3 ha^{-1})	Total	1 911	6 732	6 993	9 851	10 112
	Annual (mean)	159	561	583	821	843
	Week frequency		1x	2x	2x	1x
Nitrogen units (kg)	Total	109	320	320	320	320
	Annual (mean) average	9	27	27	27	27
Precipitation (m^3 ha^{-1})	Total	38 752 (= 3 875 mm)				
	Annual (mean)	4 323 (= 432 mm)				

Therefore, the plot was then divided into subplots according to dominant diameter at the base for the fertirrigated lines (Table 2).

Subplot with regular quality: the footslope of the hill, consisting of 22 plantation lines across the width, containing 1038 trees 8 years after planting.

Subplot with inferior quality: the backslope of the hill, consisting of 21 plantation lines across the width, containing 859 trees 8 years after planting.

2.3 Soil moisture

Two years after planting, 20 profile probe tubes (PR2, Delta-T Devices®) were installed at 10 locations distributed across two planting lines, with four locations per treatment (Figure 1). The two planting lines were spaced 80 meters apart, with one located in the subplot of regular site quality and the other in the subplot of lower site quality. The tubes were installed between the plant and the irrigation tube, spaced 30 cm apart. Volumetric water content (%) was measured every other month at each location, at six depths down to 1 meter, using a profile probe device, totaling 35 data collection events. As irrigation tubes were placed 40 cm deep, weighted average of the soil moisture was calculated for two classes: sub-surface (0 down to 40cm) and deep (40 cm to 100 cm deep).

Soil field capacity was assessed by selecting only the measurements collected during the rainy periods. To avoid soil saturation, measurements were taken 2 days after the rainfall events. Nine independent measurements across the 20 locations were used for this assessment. For the statistical analyses, a full factorial general linear mixed model was applied—using the Restricted Maximum Likelihood (REML) method and the Satterthwaite approximation for degrees of freedom- to analyze whether soil volumetric water content—measured over time—varied according to (1) irrigation period—as opposed to the field capacity; (2) treatments; (3) site quality. The random factor in this analysis was each tube where soil moisture was repeatedly measured over time.

2.4 Ground water exploration using electrical resistivity Schlumberger method

A PASI Electrical Imaging System Mod. 16G-N resistivity meter equipped with 32 electrodes was employed. Two parallel Electrical Resistivity Tomography (ERT) profiles were conducted, each extending 124 meters. One profile was located on the backslope, where soil moisture tubes were installed (site quality: inferior), and the other was positioned along a planting line at the footslope, intersecting the most productive cork oak patches (site quality: superior). These profiles were aligned between two planting lines and spaced 63 meters apart (Figure 1). Differential Spectra Precision Epoch 50 GNSS system was used to locate the profile ends accurately. The geoelectric surveys featured electrodes spaced 4m apart, and the system was configured to a Wenner-Schlumberger array with 12 scanning levels. The choice of the Wenner-Schlumberger array was motivated by its ability to provide results with good trade-off of horizontal and vertical resolution, particularly at shallower depths (Torrese et al., 2014; Hermawan and Putra, 2016). Data processing was executed using the RES2DINV inversion program from GeoTomo Software, that employ a smoothness-constrained least-squares method (Sasaki, 1992). The method was applied in June 2020, 9 days after the initiation of the fertirrigation period and a month following the spring rains.

2.5 Dendrometric measurements

All plants underwent annual measurements during the winter months (December–February). In the seedling phase, stem diameter at the base (Db) was measured with millimeter-precision using calipers, and total height (tH) was centimeter-accurate with a tape measure. As the trees grew, dendrometric measurements were performed using tree calipers and telescopic wands. Stand descriptors are in Table 2.

Perimeter at breast height (PB9) 9 years of age, only 19% of the trees had their PBH measured. Consequently, perimeter at the trunk base (PB) was used to infer the time until the first cork stripping. The relationship between PB and PBH was previously analyzed for trees within the experimental plot where both measurements were available (Supplementary Table S1). A general linear model was used to assess if irrigation treatments and site quality could potentially influence this relationship. The sampled trees were spatially scattered across the experimental area, therefore, spatial correlation within blocks was not expected. A significant ($p < 0.001$) and strong ($R^2 = 0.855$) allometric correlation was observed, independent of treatments and site quality (Figure 2; Supplementary Table S1). Based on this, the first cork stripping was projected to occur when the trunk perimeter at the base reached 98 cm. Additionally, it is important to note that the trunk perimeter above the cork is the key parameter for determining when

TABLE 2 Stand descriptor parameters of the 9 years' age REGASUBER experimental plot, Coruche, Portugal, by site quality subplots and by treatments.

Site quality	Regular					Inferior				
Treatment	Control	Fertirrigation				Control	Fertirrigation			
		1	2	3	4		1	2	3	4
Tree density (N. ha^{-1})	317	383	441	424	421	215	215	284	332	380
Basal area (m^2 ha^{-1})	2.52	7.97	7.67	8.54	8.17	0.85	3.07	1.97	2.60	2.92
Dominant TPB (cm)	35.8	54.4	57.3	61.2	81.7	27.8	35.7	31.9	36.1	33.9

N = 1215. TPB, Trunk perimeter at the Base.

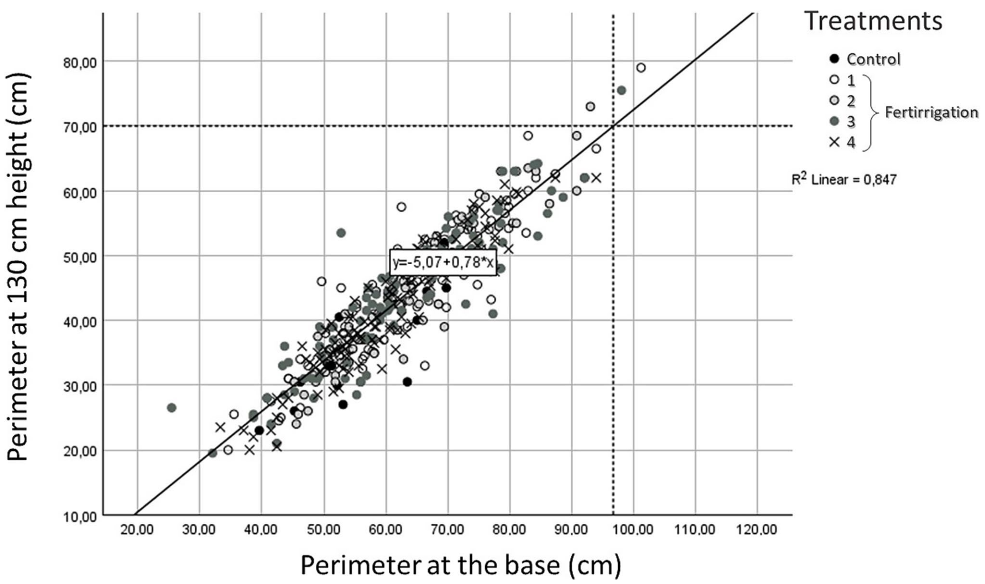

FIGURE 2
Allometric relationship between perimeter at the base and at 130 cm height, for the 9 years' age cork oaks from the REGASUBER experimental plot, Coruche, Portugal. *N* = 403. The dotted line indicates the perimeter at which cork can be removed.

trees are ready for debarking. Therefore, no estimation of cork thickness was required.

2.6 Tree growth analyses

For the tree growth analyses, plants belonging to the blocks' margins were discarded to reduce the influence of adjacent treatments on growth parameters. The remaining 663 trees from the regular site quality and 552 from the inferior site quality were included in the analyses. In a preliminary analysis, a general linear mixed model was applied using the Restricted Maximum Likelihood (REML) method and the Satterthwaite approximation for degrees of freedom, in order to evaluate differences in the perimeter of the 9 years 'age trees based on treatments and site quality (Supplementary Table S2). Random variables were blocks and trees within blocks. *Post-hoc* pairwise contrasts, performed using the Least Significant Difference (LSD) method, indicated no significant differences between treatments (Supplementary Table S2.4). Therefore, in subsequent analyses, trees were grouped by site quality and by rainfed vs. fertirrigated. For each group, the time until the first cork stripping—defined as the period required for the tree's perimeter at the base to reach 98 cm (serving as a proxy for 70 cm at PBH)—was estimated using a nonlinear regression analysis. This procedure was chosen considering that a growth curve is commonly divided into four stages, namely exponential, linear, logarithmic, and asymptotic (Figure 3A), related to the accelerated rate, constant velocity, decelerated rate, and no significant additional increment, respectively (Bahtiar and Iswanto, 2023). Graphical analyses showed that radial growth over time was in the exponential phase (Figure 3B). Given that the inflection point had not yet been reached (see Figure 3), it was explored four equations modeling exponential and linear growth, using the curve estimation regression procedure from SPSS software package:

$$\textbf{\textit{Linear}}: TPB = b0 + b1 * \text{year} \quad (1)$$

$$Power: TPB = b0 * year^{b1} \quad (2)$$

$$Growth: TPB = e^{(b0+b1*year)} \quad (3)$$

$$Exponential: TPB = b0 * e^{(b1*year)} \quad (4)$$

TPB: Trunk perimeter at the base.

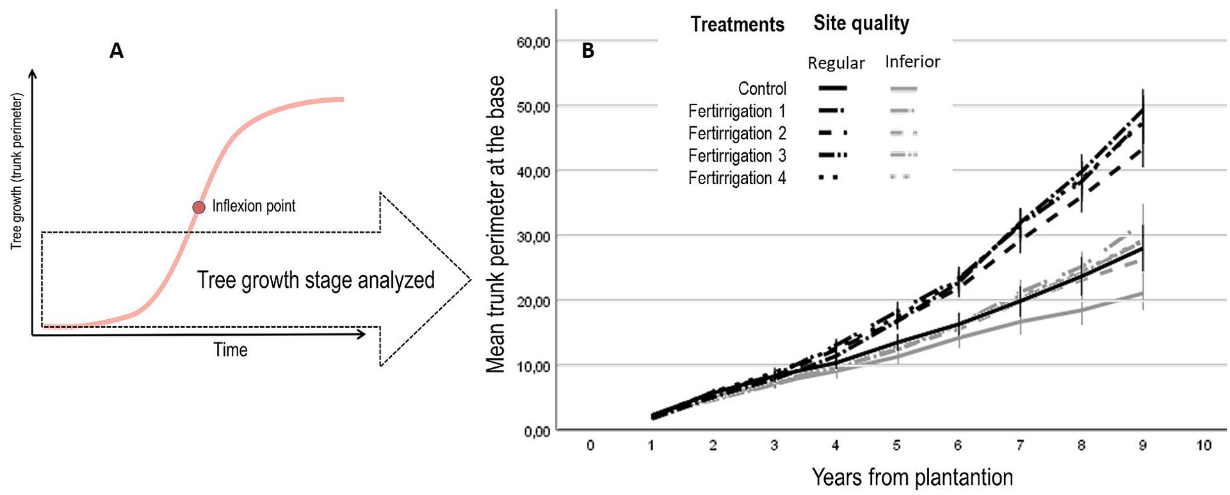

FIGURE 3
Cork oaks' mean and standard error of the trunk perimeter at the base by treatment and by site quality, in the REGASUBER experimental plot, Coruche, Portugal, **(A)** corresponding growth period and **(B)** tree growth over 9 years. N. trees = 1215.

b0: constant representing the intercept.

b1: constant representing the slope.

All models were statistically significant (Equations 1–4). ($p < 0.001$); however, the power equation exhibited the highest R^2 value and F-statistics (Supplementary Table S3) (Equation 2). As a result, this equation was used to estimate the time until the first cork stripping at the stand level, by treatment and site quality. Using the nonlinear regression procedure (SPSS v.28 package), the parameters of the power equation were iterated to construct the models (Equation 2). Random effects (trees within blocks) were deliberately excluded from the model, so that the full observed variability—both among individual trees within blocks and across blocks—would be incorporated into the residual error. This approach allows the confidence intervals for the predicted year in which trees reach a perimeter of 70 cm to reflect not only the average growth trend, but also natural variation.

3 Results

The initial tree density was 625 trees per hectare; however, seedling mortality was substantial during the first 2 years. Typical mounds and bore holes in the plants' vicinity, as well as severe scarifications signs on root collars, pointed to rodent attacks by *Microtus duodecimcostatus* or *M. lusitanicus,* impacting at least 13% of the seedlings. Over time, dieback became more concentrated in the subplot with inferior site quality under the control treatment, as indicated by the inferior tree density by hectare (Table 2). Basal area and dominant tree perimeter were superior in fertirrigated subplots, however, influenced by site quality (Table 2).

3.1 Soil moisture

Soil volumetric water content below the sub-irrigation drip varied in relation to the field capacity and site quality (Table 3.1; Figure 4).

TABLE 3.1 General linear mixed model results applied to the dependent variable "deep soil volumetric water content" in 20 locations, in the REGASUBER experimental plot, Coruche, Portugal, measured six times per year over 9 years in 20 locations.

Independent fixed effects				
Parameters	Z-value	df1	df2	Sig.
Corrected Model	32.818	19	851	**< 0.001**
Treatments	0.656	4	851	0.623
Field capacity	563.534	1	851	**< 0.001**
Site quality	5.036	1	851	**0.025**
Treatment * Field capacity	0.760	4	851	0.552
Treatment * Site quality	0.603	4	851	0.660
Field capacity * Site quality	0.101	1	851	0.751
Treatments * Field capacity * Site quality	1.675	4	851	0.154

N = 871. Probability distribution: Normal. Link function: Identity. df1, Numerator degrees of freedom; df2, Denominator degrees of freedom. Values in bold indicate statistical significance at $p \leq 0.05$.

No significant differences were observed across the treatments, nor was there any interaction between the factors. During the irrigation period deep soil moisture was about 9% less compared to the field capacity. Furthermore, locations at the backslope (inferior site quality) showed less 4% of water content when compared to the location at the footslope (regular site quality). Most of the unaccounted variance was primarily due to differences in the values measured over time (Table 3.2) and secondly across the 20 locations (Table 3.3).

3.2 Electrical resistivity tomography

Figure 5 displays the two ERT sections processed using the aforementioned method. Both sections exhibit resistivity values consistent with sandy soils (Pandey et al., 2015; Datsios et al., 2017;

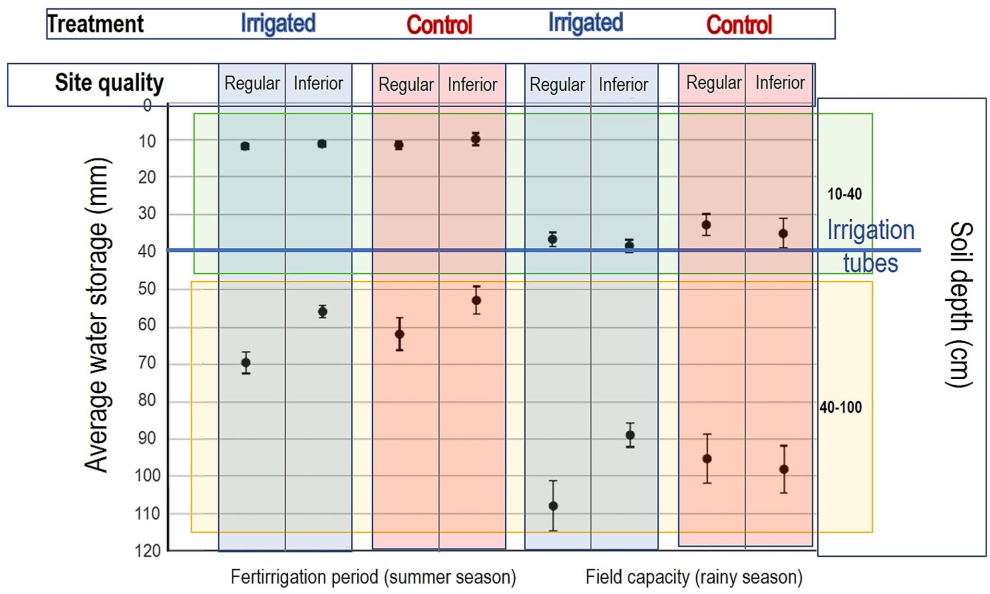

FIGURE 4
Average (points) and confidence intervals (bars) of the soil volumetric water content at two depth classes, by treatments, site quality, and period of the measurements in the experimental plot REGASUBER, Coruche, Portugal, measured over 9 years in 20 locations. *N* = 871.

TABLE 3.2 General linear mixed model results applied to the dependent variable "deep soil volumetric water content" in 20 locations, in the REGASUBER experimental plot, Coruche, Portugal, measured six times per year over 9 years in 20 locations.

Residual effects						
Residual effect	Estimate	Std. error	Z-value	Sig.	95% Confidence interval	
					Lower	Upper
AR1 Diagonal	21.867	1.483	14.745	< 0.001	19.145	24.976
AR1 Rho	0.524	0.032	16.309	< 0.001	0.458	0.584

Covariance Structure: First-order autoregressive.

TABLE 3.3 General linear mixed model results applied to the dependent variable "deep soil volumetric water content" in 20 locations, in the REGASUBER experimental plot, Coruche, Portugal, measured six times per year over 9 years in 20 locations.

Random effect						
Random effect covariance	Estimate	Std. error	Z-value	Sig.	95% Confidence interval	
					Lower	Upper
Var(Intercept)	16.438	6.696	2.455	0.014	7.398	36.523

Covariance Structure: Variance components.

Gerscovich and Vipulanandan, 2023). At the section with regular site quality, the resistivity pattern is characterized by low values (depicted in green and blue colors) in a shallow layer with variable thickness, ranging from 2 to 10 meters. Within this layer, some spots with higher resistivity values (depicted in red and yellow colors) are detected but with no apparent correlation with treatments or tree size (Figure 5). The deeper layers of this section show high resistivity. On the other hand, the resistivity distribution at the section with inferior site quality follows a different overall pattern. It includes a superficial thin layer (down to 4 meters deep) with high resistivity values, irrespectively of treatments except where the road is located. An intermediate layer of low resistivity (falling within the range of values of the surface layer at the footslope section) with variable thickness, and finally, a third layer in the lower part of this section with high resistivity. This lower layer exhibits a geometry profile similar to the base layer of the previous section. In summary, the consistently high resistivity within the first 4 meters of soil in the section with inferior site quality indicates—for sandy soils—a very low soil moisture availability.

3.3 Dendrometric measurements

Overall, fertirrigation yielded similar outcomes across treatments, but its effectiveness appeared constrained under inferior site quality (Figure 3B). The absence of significant differences among the fertirrigation treatments allowed the development of only one model for fertirrigated trees by site quality (Table 4). The power model indicated that fertirrigated trees at the subplot with regular site quality are estimated to be debarked between 13 to 15 years of age (Figure 6A). In contrast, debarking for the control trees is expected to initiate, on average at 27 years of age

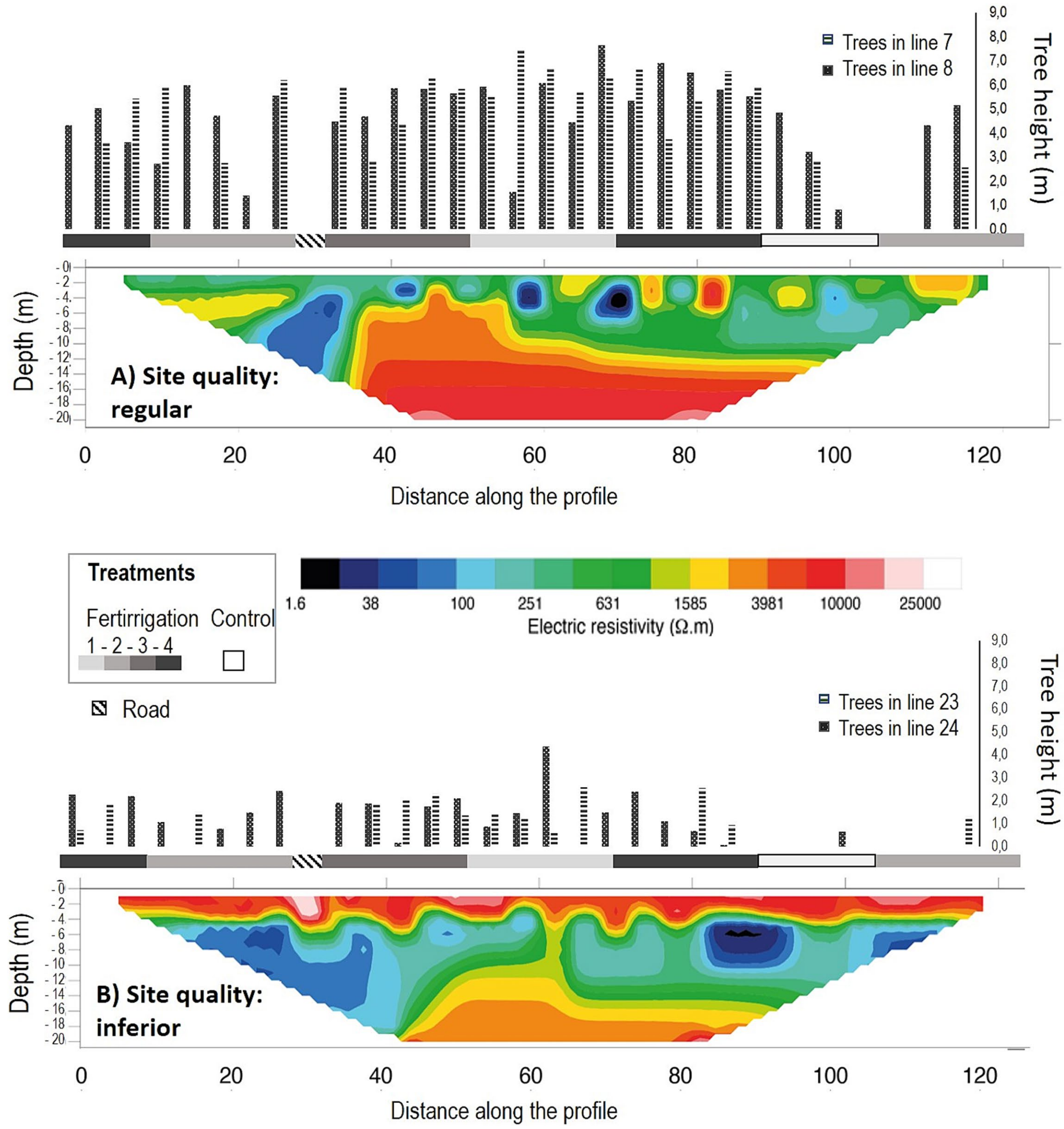

FIGURE 5
Electrical Resistivity Tomography sections reaching depths of up to 20 meters in the soil, conducted at one location with **(A)** regular site quality and another location with **(B)** inferior site quality within the REGASUBER experimental plot. Above these sections, individual tree heights are graphically represented by vertical bars, and the corresponding treatments are indicated by horizontal bars. Lines 7, 8, 23, 24: plantation lines bordering the ERT section at a 2 m distance.

(Figure 6A). As for the trees located at the inferior site quality, fertirrigated ones are expected to be debarked between 16- and 24-years of age. (Figure 6B). Additionally, the parameters' 95% confidence interval indicated a high level of uncertainty for the control trees.

4 Discussion

The investigation into cork oak fertirrigation originated from an experiment conducted by a private landowner, who planted cork oak seedlings on the edge of an olive grove to take advantage of its fertirrigation system (Camilo-Alves et al., 2022). The first cork removal occurred at 8 years post-planting, drawing considerable interest from the cork industry. A key concern raised by forest producers pertains to the conditions under which this technique would significantly accelerate growth, specifically, the relationship between the combined effects of edaphoclimatic conditions and fertirrigation. The experimental plot, REGASUBER, was established as a long-term scientific experiment aimed at evaluating the feasibility of this technique across various dimensions.

4.1 Site quality

The REGASUBER plot was installed in an arenosol, a soil type considered to be of regular quality for cork production, due to its limited water-holding capacity. However, as the plants developed over time, differences in growth and survival indicated that the plot could be subdivided into two site quality classes: regular and inferior. Dominant diameter was chosen as a proxy for site quality, given that

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TABLE 4 Power equation' parameters estimates of the annual trunk perimeter growth by treatment within site quality in the REGASUBER experimental plot, Coruche, Portugal, measured over 2016–2022.

Site quality	Treatment	Parameter	Estimate	Std. error	95% Confidence interval		ANOVA R squared
					Lower bound	Upper bound	
Inferior	Control	b0	2.106	0.283	1.552	2.661	0.495
		b1	1.166	0.068	1.033	1.300	
	Fertirrigated	b0	1.271	0.068	1.137	1.404	0.517
		b1	1.637	0.026	1.585	1.689	
Superior	Control	b0	2.285	0.278	1.739	2.831	0.453
		b1	1.011	0.062	0.888	1.134	
	Fertirrigated	b0	1.584	0.088	1.412	1.756	0.634
		b1	1.318	0.028	1.263	1.372	

N = 1215.

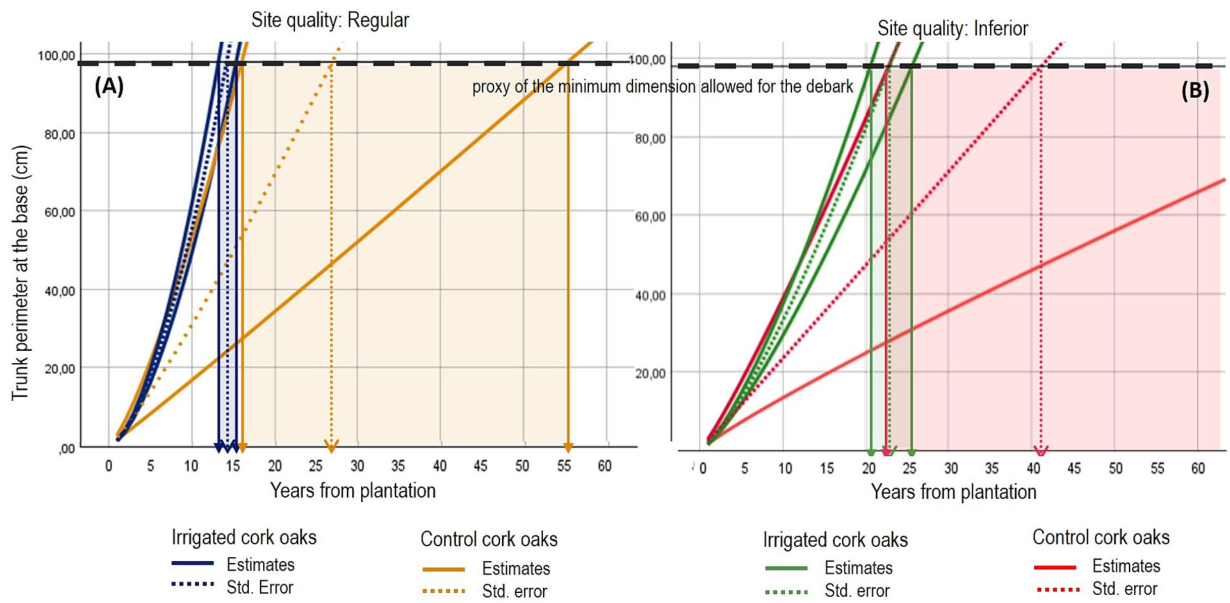

FIGURE 6
Curve growth estimates of the cork oaks trunk perimeter at the base according to treatments and site quality in the REGASUBER experimental plot, Coruche, Portugal at the **(A)** regular site quality and **(B)** inferior site quality.

productive age is defined by the point at which radial stem growth reaches the threshold required for cork stripping.

4.2 Site quality and soil water holding capacity

Based on soil moisture retention curves from the literature (Evett et al., 2008), for soils reaching field capacity at 10 and 27%—such as those at the REGASUBER (Figure 4)—the wilting points are observed at 4 and 12%, respectively. Therefore, during the irrigation period, soil moisture above the irrigation tubes was close wilting point, while some water was available to plants below the tubes (Figure 4). However, differences between irrigation treatments could not be detected in the soil moisture profiles (Table 3.1). This can be explained by the low water-holding capacity of the sandy soil at REGASUBER. Previous measurements already had already indicated that the wet bulb fail to extend horizontally the 30 cm from the drip point to the soil moisture measurement tubes (Camilo-Alves et al., 2020). Minor variations in moisture retention were also detected based on site quality (Table 3.1), indicating improved soil texture for water retention down the hill. However, these differences were marginal, amounting to 4%. Given that cork oak roots can extend several meters deep to access groundwater (Otieno et al., 2006; David et al., 2007; Dinis, 2014), soil moisture measurements limited to a depth of 1 meter are insufficient to fully account for the water available to these trees. Indeed, during the excavation of six trees within the plot Šleglová et al. (2025a) observed that some roots extended beyond the 2-meter excavation depth. This highlights the need for the prospection of deeper water sources. The electrical resistivity method allowed the assessment of resistivity distribution down to a depth of 20 meters. Assuming similar soil composition in both areas, and considering the established correlation between soil moisture and resistivity (Ozcep et al., 2009; Jong et al., 2020), observed differences in resistivity can be interpreted as indicative of variations in soil water content. Accordingly, the higher resistivity observed down to 4 meters in the subplot with inferior site quality may be attributed to very low moisture. Conversely, this pattern was reversed in the subplot with regular site quality, possibly linked to higher surface water content in that section. These differences could be associated with variations in soil texture at deeper layers. Differences in ERT align with differences in mortality rate and tree development according to site quality. The surviving plants in areas with inferior site quality, facing drier conditions, may be allocating resources toward root system development (Padilla and Pugnaire, 2007; Ramírez-Valiente et al., 2019). Consequently, it is expected that their aerial development will occur once their root systems reach groundwater at depths below 4 meters. Further investigation through the long-term study within the experimental plot will confirm this hypothesis. Nevertheless, the use of electrical resistivity was a helpful tool to explaining differences in site quality across the plot. Water availability for cork oaks is not solely dependent on water supply; rather, the soil's water-holding capacity and access to groundwater are also crucial factors (Pinto et al., 2014; Mendes et al., 2016). In this study, a preliminary prospecting test was conducted; however, further tests utilizing this technique should be performed over time to evaluate the spatiotemporal variability of soil moisture and optimize irrigation management.

4.3 Trees' growth under different irrigation treatments

Radial growth was lower in trees from the control lines; however, no statistically significant differences were detected across the irrigation treatments (Supplementary Table S1). This result contrasts with previous findings in the same plot (Camilo-Alves et al., 2020), as well as with results from the IRRICORK plot (Camilo-Alves et al., 2022). In both studies, growth increments were directly related to the applied water volume. A likely explanation lies in the temporal, structural and technical differences between the two experimental periods and sites, reinforced by the studies on root development in both plots (Šleglová et al., 2025b). While the earlier REGASUBER results reflected the initial response of young trees with localized root systems, the current analysis covers a later stage, when root systems have expanded further in depth. When water is supplied through subsurface drip irrigation in coarser soils, it is likely to result in water percolation and more homogeneous deep-water availability across treatments over time. In contrast, in IRRICORK, the loam to sandy clay loam soil texture combined with surface drip irrigation enables the formation of a stable superficial wet bulb near each tree, which supports a high density of fine roots within the irrigated area, allowing for a stronger treatment response, even in more mature trees. Further research using Electrical Resistivity Tomography (ERT) could provide valuable insights into water movement within the soil profile."

4.4 Trees' growth and first cork stripping under fertirrigation across different site quality

Young trees from both the control and treatment groups were observed to be growing freely, showing no significant signs of having reached the inflection point. This is reflected in the power-type growth pattern, indicating continued and unrestricted growth at the age of 9 years. Thus, using the power model, estimates indicated that the first stripping will occur on average between 13 to 15 years' age under the optimal conditions, i.e., 12 years earlier than rainfed trees in similar soil conditions. It is expected that, in areas with optimal and regular site quality, trees reach the appropriate dimensions for the first cork removal at around 20 years of age. In contrast, in areas classified as having inferior site quality, tree growth is diminished, and the cork stripping may be delayed by more than 10 years (Lacambra et al., 2010; Ribeiro et al., 2010; Sánchez-González et al., 2005). As comparison, diameter growth models based on stem analysis data from two of the main cork producing areas in Spain indicated that the age at which cork oak trees can be debarked for the first time is about 20 years for the best site quality (Sánchez-González et al., 2005), but considering a perimeter of 60 cm over virgin cork (Spanish legislation). Using the CORKFITS simulator, based or radial growth data from one of the main productive areas from Portugal (Ribeiro and Surovy, 2011), adjusting the potential modifier for the best site quality, and performing 100 simulations for a cork oak stand with a 4 ×4 spacing, the result indicated the trees could be debarked for the first time at an age of 19 ± 2 years.

These differences in the timing of the first cork stripping underscore the influence of year-round water availability and tree growth. Indeed, Camilo-Alves et al. (2022) demonstrated that radial growth is significantly sustained during summer drought in trees subjected to fertirrigation, even under conditions of high atmospheric vapor water deficit. Fertirrigation allowed the trees to achieve their full radial growth potential. Moreover, fertirrigation enhanced productivity in the subplot located on the backslope of the hill, effectively improving site quality from inferior to regular. In addition to the anticipation of the first cork stripping, another compelling outcome was the reduction of its uncertainty. Fertirrigation contributed to uniform tree growth throughout the stand, consequently enhancing productivity at the stand level. Conversely, on the control lines, variations in the access to water—and subsequently, nutrient availability—may lead to variations in tree growth. The first cork stripping is expected to be more gradual in rainfed conditions for the same soil conditions.

The findings from this study underscore the role of water availability—by means of irrigation during the drought periods—on site quality improvement in arenosols. This study also highlights the importance of soil water holding capacity and consolidate the mid-run impact of fertirrigation in tree growth. However, it is important to note that the model was specifically designed to estimate the time required to reach the first cork stripping. Future research should focus on developing tree growth and cork productivity models (e.g., Ferreira and Oliveira, 1991; Fonseca and Parresol, 2001; Ribeiro and Tomé, 2002; Ribeiro et al., 2003; Ribeiro et al., 2006; Tomé, 2004; Sánchez-González et al., 2007; Pasalodos-Tato et al., 2018) that incorporate modifiers for water availability, adapted to the conditions of the experimental plots.

4.5 Fertirrigation in the Mediterranean context

Lastly, a note on the use of irrigation to enhance yield in sectors not directly linked to food production, particularly in regions prone to water scarcity: The Mediterranean climate, characterized by a summer water deficit, presents challenges for sustainable resource management. Therefore, the viability of cork oak irrigation is dependent on the existence of ponds to collect winter rainwater for use during the summer drought, thereby avoiding reliance on deepwater tables. Irrigation of approximately 700 m^3/ha/year in the REGASUBER plot was sufficient to reach tree growth potential. This water volume represents 16% of the average annual precipitation in the stand and is considerably lower than the 2500 m^3/ha/year used in intensive olive groves within the country. This approach is not intended to substitute rainfed stands. Instead, it is an alternative technique designed for specific conditions, aimed at providing a competitive edge over exotic tree species or over the intensification of the agro-pastoral systems associated with cork oaks. The enhancement of tree growth and canopy cover provides additional benefits, including increased carbon sequestration and biodiversity improvement. For instance, the rapid expansion of canopy cover was linked to greater floristic diversity in the REGASUBER plot (Raposo et al., submitted). Other studies have highlighted the role of high canopy cover in enhancing tree resilience and protecting regeneration in the face of climate change (Ribeiro et al., 2024a; Ribeiro et al., 2024b). Future analysis of a limited irrigation period (15–25 years) aimed at establishing productive cork oak stands more rapidly should also consider its effects on ecosystem services, such as carbon sequestration, water cycle, soil recovery; biodiversity, etc., particularly under climate change scenarios.

5 Conclusion

Annual cork oak fertirrigation between 561 and 843 m^3 ha^{-1} in a stand with sandy soil significantly enhanced tree stem growth, particularly in the regular site quality. Estimates indicate a 12-year anticipation of the first cork stripping and a substantial improvement in productivity at the stand level, with trees recruited for cork stripping within a narrower interval. In the inferior site quality, however, the high variability and uncertainty dilutes the effect of fertirrigation. Thus, potential constraints associated with this innovative technique were identified. Prior to implementing cork oak fertirrigation, it is crucial to conduct thorough soil prospecting at potential sites, combining conventional soil moisture assessment methods with groundwater prospecting to infer soil water holding capacity. This study supports the positive impact of fertirrigation in anticipating the first cork stripping, providing valuable information for the economic assessment of this technique.

Data availability statement

The datasets presented in this article are not readily available because of Legal restrictions. Requests to access the datasets should be directed to calves@uevora.pt.

Author contributions

CC-A: Data curation, Formal analysis, Funding acquisition, Investigation, Resources, Writing – original draft, Writing – review & editing. BC: Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. JN: Data curation, Methodology, Writing – review & editing. AP: Data curation, Methodology, Writing – review & editing. JR: Data curation, Methodology, Writing – review & editing. MM: Data curation, Methodology, Writing – review & editing. MV: Conceptualization, Supervision, Writing – review & editing. JB: Conceptualization, Supervision, Validation, Writing – review & editing. MT: Conceptualization, Resources, Software, Supervision, Visualization, Writing – review & editing. NA-R: Conceptualization, Formal analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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