

Irrigating cork oaks until maturity in the context of climate change: Current insights from long-term experimental plots

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ABSTRACT

Cork oak (*Quercus suber* L.) is of major importance in the coastal regions of the western Mediterranean basin. However, its widespread chronic decline is compromising the long-term sustainability of its main product, the cork. Fertilization has emerged as a potential strategy to accelerate growth and reduce the time to first cork harvest, being discontinued once trees reach their productive stage. This study synthesizes the rationale, methodology, and results from long-term experimental plots in Portugal, where cork oaks were subjected to different irrigation regimes, soil conditions, and management practices. Findings demonstrate that irrigation can advance the first cork debarking to around 14 years after plantation, while promoting more homogeneous stand development. Water requirements increase over time and may reach an efficient threshold of 140 m³ ha⁻¹ per week when trees are near the first debark. However, its success depends on edaphic suitability and adaptive management to prevent adverse outcomes, such as root dependence or pest pressure. Economic analyses indicate that fertilization is generally advantageous until the second harvest, except when installation and maintenance costs are exceptionally high. Irrigation suppression demonstrated that trees can adapt to rainfed conditions. From an environmental perspective, irrigation should be restricted to suitable soils and rely exclusively on surface water sources. Beyond productivity, irrigated cork oak stands provided broader ecosystem services, including carbon sequestration and biodiversity enhancement. Ultimately, fertilization should be considered a temporary support tool that strengthens cork oak establishment and competitiveness, paving the way for resilient and sustainable forests under Mediterranean climate change scenarios.

1. Introduction

The origins of the scientific fertilization projects with cork oak (*Quercus suber* L., Fagaceae) can be traced back to the experience of a private landowner in 2002, in Avis, Portugal. At that time, he was installing an intensive olive grove with fertilization. In one corner of the area, where some centuries-old cork oaks still stood, he decided to plant new cork oaks instead of olive trees. This small plantation occupied 1.6 ha. He maintained the olive grove spacing (3.5 m x 7 m) wherever possible. The cork oaks shared the same irrigation and fertilization system as the olive trees. Management followed similar

principles. Eight years later, in 2010, he harvested the first cork from a small sample of trees – within less than half of the expected time. The results caught the attention of private stakeholders in the cork industry, who began to question whether fertilization could support the establishment of cork oak plantations with faster growth. The goal was to shorten the time to first cork harvest. Fertilization would then be stopped, and trees would be managed under rainfed conditions. This interest led to a partnership between private stakeholders from the cork sector and research centers to develop afforestation techniques that make efficient use of fertilization, while ensuring water savings, minimizing environmental impacts and maintaining economic

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sustainability. The first scientific experiment with cork oaks under fertirrigation was established in 2014 – the REGASUBER plot. In 2017, the stand located in Avis was adapted into a scientific plot – the IRRICORK plot.

1.1. The cork oaks

1.1.1. Biogeography

Cork oak is a sclerophyllous evergreen tree native to the western Mediterranean Basin. It currently covers approximately 1.5 million hectares in Europe and about 1 million in North Africa. The largest forests are found along the Atlantic coast of the Iberian Peninsula. The species ranges from Morocco and the Iberian Peninsula to the western part of the Italian Peninsula. It is also found on the large Mediterranean islands, in parts of southern France, and in coastal and hilly regions of Morocco, Algeria, and Tunisia (Aronson et al., 2009). Cork oaks are strongly linked with the Mediterranean bioclimate area (Vessella et al., 2015). Cork oak typically occurs in regions with average annual precipitation above 600 mm and mean annual temperatures around 15 °C (Blanco et al., 1997). In Europe, its distribution appears limited by minimum winter temperatures. Cork oak avoids colder inland plateaus and prefers areas with oceanic influence in the south and southwest Iberia (Cano Carmona et al., 2024). It has an acidophilous and calcifuge character. Therefore, it mostly grows on acidic soils derived from siliceous substrates such as granite, schist, or sandstones (Serrasoltes et al., 2009); it is rarely found on limestone or neutral soils over dolomitic bedrock. Most stands occur on soils with pH values between 4.7 and 6.5. Cork oaks prefer loamy or sandy, well-aerated soils. They avoid compacted or seasonally flooded soils. These edaphic preferences, along with their adaptation to dry summers and mild, wet winters, define the species' ecological niche (Serrasoltes et al., 2009). Ecologically, *Q. suber* is often a dominant climax species in its range. Cork oak woodlands are classified as “habitat 9330” under the EU Habitats Directive. This habitat can be classified into four major biogeographic groups, defined by vegetation composition and climatic envelopes (Agrillo et al., 2018). Regardless of the biogeographic context, cork oaks demonstrate a remarkable capacity to withstand environmental extremes, provided a minimum level of moisture is available (Petroselli et al., 2013; Agrillo et al., 2018). Cork oak woodlands are, in fact, groundwater-dependent ecosystems, where access to groundwater buffers growth against seasonal fluctuations in precipitation and accounts for site-specific variations in cork production (Schmidt et al., 2009; Besson et al., 2014; Mendes et al., 2016). Nevertheless, the ability to survive summer droughts through groundwater uptake does not necessarily translate into high productivity. Growth is constrained by several edaphoclimatic factors. Climatic stressors such as evaporation and frost, together with edaphic parameters including soil texture, depth, etc., strongly influence site quality and the potential for cork oak exploitation (Costa et al., 2008; Paulo et al., 2015). In Portugal, edaphoclimatic regions relevant to cork oak productivity are classified in Regional Forest Management Plans (Macedo et al., 2019). This classification integrates a diagnostic assessment of Portuguese soil types, identifying specific limitations to optimal cork oak development (Gonçalves et al., 2004), alongside a bioclimatological diagnose for the species (Pinto Gomes and Ferreira, 2005).

Cork oaks may also be managed within traditional agro-silvopastoral systems—*montado* in Portugal and *dehesa* in Spain—classified under habitat 6310. These multifunctional systems combine evergreen oaks with pastures, supplying multiple products such as forage, acorns, wood, cork, and charcoal, while supporting high levels of biodiversity (Bugalho et al., 2011; Pinto-Correia et al., 2011; Moreno et al., 2018). Cork oak forests and their silvopastoral variants also play a crucial role in landscape conservation and wildfire prevention (Bugalho et al., 2011; Pinto-Correia et al., 2011).

1.1.2. Economic relevance

Cork itself is a remarkable tissue. It is formed by dead, suberized cells generated by the phellogen, a meristematic layer. Cork is renewable and sustainable, as trees are not felled for cork extraction. It is mainly composed of suberin (33 %–57 %), lignin (13 %–35 %), and smaller fractions of cellulose and hemicellulose (Pereira, 2015). Its unique combination of physical and chemical properties—lightness, elasticity, resilience, impermeability, insulation capacity, fire resistance, and durability—distinguish cork from other materials (Pereira et al., 2006; Silva et al., 2005; Pereira, 2015).

According to Portuguese law, cork can only be removed when the tree trunk reaches 70 cm in perimeter at 1.30 m height. Therefore, the timing of the first cork extraction depends on tree growth rate, which is influenced by edaphoclimatic conditions. The productive phase of a cork oak begins with the first debarking, after which cork can be harvested every 9–10 years throughout the tree's lifetime. The first harvest yields virgin cork, which is irregular. Subsequent extractions (usually from the third cycle onwards) yield reproduction cork, which is suitable for industrial uses, especially bottle stoppers (Pereira, 2015).

Portugal is the global leader in cork production and processing. The country has 720,000 ha of cork oak, representing 46 % of global cork production. Spain produces 33 %, Morocco 6 %, Algeria 5 %, and Tunisia 4 % (APCOR, 2020). The wine industry absorbs 73.5 % of all cork products, followed by construction materials (24.1 %). In 2019, cork accounted for 1.25 % of Portugal's GDP and nearly 10 % of national exports (APCOR, 2020).

1.2. The drivers behind the research on cork oak irrigation

Although abnormal cork oak mortality outbreaks have been reported in the Iberian Peninsula since the late 19th century (Baeta Neves, 1949), their severity increased significantly during the 1980s. In France and Italy, mortality was first noted after 1989 (DFCI, 1991; Ruiú, 2006). Around that time, the root pathogen *Phytophthora cinnamomi* was detected in declining stands (Brasier, 1992). This pathogen has since been linked to widespread cork oak mortality events across southern Europe. Subsequent studies highlighted the role of additional biotic and abiotic factors. These include prolonged droughts, soil limitations to root development, and inappropriate forest management practices (Moreira and Martins, 2005; Peñuelas et al., 2001; Ribeiro and Surový 2008; Camilo-Alves et al., 2013, 2020a). Currently, cork oak decline is seen as a result of multiple factors acting synergistically (Camilo-Alves et al., 2013; Marques et al., 2025). Root pathogens, prolonged droughts, and rising temperatures are central elements. These act more severely under adverse edaphic conditions, such as compacted soils or steep, south-facing slopes (Costa et al., 2010; Camilo-Alves et al., 2020a; Ribeiro and Surový 2008). Stand management also plays a critical role (Pinheiro et al., 2008). Cork oak is typically managed within agro-silvopastoral systems, whose sustainability has traditionally relied on the sub-optimization of resources over centuries (Joffe et al., 1999; Ribeiro et al., 2006).

However, recent decades have seen major changes. There has been a growing intensification of livestock grazing, particularly with cattle (Moreno et al., 2014; Godinho et al., 2016; Listopad et al., 2018). This is partly due to Common Agricultural Policy (CAP) incentives (Pinheiro et al., 2008; Pinto-Correia and Godinho, 2013; Pinto-Correia and Azeda, 2017). Overgrazing and intensive understory management—such as soil disking to control shrubs or install pastures—have harmful effects on tree vitality (Ribeiro et al., 2010; Acácio et al., 2021; Camilo-Alves et al., 2020a). These practices damage significant portions of the root system (Dinis, 2014).

This combination of factors—including livestock intensification, soil disturbance, *P. cinnamomi* spread, and increasing drought and heat—has been associated with the widespread cork oak decline observed since the late 1980s. This is particularly evident in more vulnerable edaphoclimatic zones.

While the overall cork oak area has remained stable due to considerable artificial regeneration efforts (Ribeiro et al., 2021), stand density has dropped sharply. From 1965–1990, canopy cover increased in many areas, but between 1990 and 2015, losses significantly outweighed gains. Over 70 % of the monitoring points showed canopy loss, while fewer than 9 % showed gains (Acácio et al., 2021). As a result, dense cork oak stands (canopy cover > 50 %) shrank from 314,000 ha in 1995–68,000 ha in 2015. At the same time, sparse stands (canopy cover < 30 %) expanded. Tree density, in particular the maintenance of crown cover, is a key factor on the sustainability of the cork oak system (Ribeiro et al., 2004, 2021). Additionally, a decline in stand density inevitably affects the cork industry. National inventories indicate that annual cork production fell from around 120,000 t in 1995–1998–30 % less within a decade (ICNF, 2025). The ongoing decline in cork yield raised concerns within the cork sector regarding future raw material supply. At this critical moment, the R&D department of a subsidiary of *Corticeira Amorim*—the world's leading cork processor—stepped in to explore long-term solutions. Among the proposed measures was the establishment of irrigated cork oak plantations. To ensure that such interventions were grounded in scientific evidence, a collaboration was initiated with a research team from the University of Évora. This group had already produced extensive work on mortality diagnosis and cork oak growth modeling, thereby offering management-oriented insights into the sustainability of cork oak ecosystems (Ribeiro et al., 2003a, 2003b, 2004, 2006, 2010, 2012; Pinheiro et al., 2008; Tenhunen et al., 2008; Ribeiro and Surový 2008, 2011; Surový et al. 2011; Camilo-Alves et al., 2013).

1.3. Possible constraints related to the phenology, physiology and development of cork oak

Growth of woody species has two components, one relating to increment of biomass, the other to the architectural arrangement of matter in space (Küppers, 1985). The latter is associated with budburst that occurs in early spring on cork oaks, followed by the development of leaves and shoots. At this time, leaf fall also occurs, concomitant with foliar renewal; shoot elongation may be limited during summer but often resumes in autumn (Oliveira et al., 1994; Pinto et al., 2011). Radial growth exhibits a well-defined seasonal pattern throughout the year, typically extending from March to October, with a peak in June–July and a marked decline during the summer (Costa et al., 2002; Costa et al., 2003). However, phenological development and radial growth are highly influenced by environmental conditions and the pronounced climatic seasonality (Bicho et al., 2024).

The main goal of irrigating cork oaks is to promote radial growth, as this is the key factor determining the feasibility of the first cork harvesting. Under typical rainfed conditions, a correlation has been observed between spring radial growth (of both cork and stem) and winter precipitation, as well as between autumn growth and rainfall from the previous month (Caritat et al., 1996; Costa et al., 2002). Summer temperature may also influence radial growth, but whether the effect is positive or negative depends on other factors (Caritat et al., 1996; Oliveira et al., 2016; Costa et al., 2016). Radial growth may be delayed, enhanced, or reduced depending on environmental conditions that constrain water availability (Costa et al., 2016). This suggests that water availability can indeed influence radial growth, potentially increasing the annual increment. However, other studies highlight that under adverse summer conditions — with high temperatures and solar radiation — photosynthesis may be limited by factors not directly related to water stress. In such conditions, midday depressions in the photosynthetic apparatus have been reported (Faria et al., 1996; Larcher, 2000). This down-regulation of photosynthesis acts as a protective mechanism in response to multiple stress factors on hot, cloudless days (Larcher, 2000). Therefore, even with adequate water supply through irrigation, the physiological responses to high temperatures and radiation may inhibit photosynthesis and consequently limit growth.

Another possible constraint involves changes in root development

caused by water availability, both in terms of root architecture and root-to-shoot biomass allocation. In the juvenile phase, cork oaks develop a deep taproot that is essential for survival. In adult trees, a large part of the root system is superficial and horizontal, from which thin vertical sinker roots emerge (David et al., 2013; Dinis, 2014). It is these deep roots that enable cork oaks to access water at depth and maintain transpiration rates during the summer — a typical drought avoidance mechanism (David et al., 2004; Pinto et al., 2014). Constant surface irrigation could potentially alter this deep root development, making trees more dependent on the surface wet bulb. Moreover, the root-to-shoot biomass ratio may also shift with increased water availability (Sharp and Davies, 1989; Chaves et al., 2003; Ramírez-Valiente et al., 2019). As a result, upon irrigation suppression, trees may be less able to adapt to rainfed conditions and access deep soil water.

1.4. Irrigation removal

The central issues in prolonging irrigation during the productive phase, beyond the environmental costs of exploiting a scarce resource in the Mediterranean—water—are the potential loss of resilience and the related economic implications. While irrigation can deliver multiple benefits, its prolonged use may foster increased dependence, ultimately rendering the system more vulnerable to failure (Zweifel et al., 2020; Bose et al., 2022). Accordingly, discontinuing irrigation prior to thinning operations, which should be carried out shortly after the onset of productivity (Serrão et al., 2019a), is recommended. Trees retained after thinning will face reduced competition for limiting resources (Gracia et al., 2011) despite no longer benefiting from irrigation. Also, from the economic cost perspective, prolonged irrigation may also be disadvantageous. Even the highest-quality driplines have an average lifespan of 15–20 years (Jawalekar, 2024). If the dripline is the largest cost component of the irrigation investment (Thompson et al., 2016), replacing it will significantly increase system costs. For these reasons, the proposal to withdraw fertirrigation once the trees enter their productive phase appears to be the most viable strategy.

1.5. The goals

While the results were promising, there was no guarantee that cork oak fertirrigation would succeed under soil conditions different from those of the specific stand located in Avis. Additionally, it was essential to define the most appropriate irrigation and fertilization regimes. Namely, those that would promote growth with minimal water input — i. e. the functional threshold (Fig. 1) — without inducing major structural or physiological changes that would impair the trees' ability to survive without summer irrigation in the future. Recognizing the need for a sound scientific basis, the industry engaged with an academic institution to develop research projects on this topic.

In response to this challenge, scientific field plots were established to

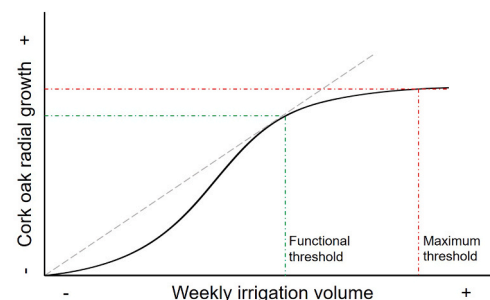


Fig. 1. Theoretical scheme of the relationship between cork oak radial growth and the amount of water supply. Maximum threshold: the water supply beyond which the tree does not increase in size. Functional threshold: the point at which the water supply and radial growth rate are optimally balanced.

answer four key questions:

1. Does annual summer fertirrigation reduce time to the first cork debarking?
2. If Goal 1 is true, what is the minimum water input required to stimulate radial growth?
3. Does development under irrigation compromise the tree's ability to adapt to rainfed conditions?
4. Is the additional cost of fertirrigation offset by the earlier onset of productivity, and under which soil conditions?

This article aims to explain the rationale behind the development of scientific studies on cork oak fertirrigation, initiated in 2014. It also presents the results obtained so far, the main challenges encountered, and future perspectives—particularly in the context of climate change in the Mediterranean region.

2. Methodology applied to the studies on irrigated cork oaks

Although assisted irrigation was already used in some new cork oak plantations, scientific studies published before 2014 were anecdotal and focused on seedlings during the establishment phase (Gómez-Aparicio et al., 2008; Vessella et al., 2010; Gonzalez-Rodriguez et al., 2012). This highlighted the need for long-term studies, ideally covering different soil conditions.

2.1. First long-term scientific experimental plots on fertirrigated cork oaks

2.1.1. REGASUBER

In 2014, the first long-term scientific cork oaks fertirrigation plot was installed (Camilo-Alves et al., 2022b). The REGASUBER plot is located near Coruche, Portugal, in a cork oak forest region (Table 1). The

6-hectare site, formerly used as cropland for domestic purposes, has Arenosol soils, considered of average quality for cork oaks (Gonçalves et al., 2004). Subsurface irrigation was selected to allow understory management without herbicides or the need to remove irrigation lines. The experiment included four irrigation treatments and a control. Further technical details are described in Camilo-Alves et al. (2020b). The REGASUBER plot was designed to test different combinations of water volumes and irrigation frequencies. Fertilization levels were kept constant in the irrigated treatments. The focus was on water, and a minimum level of fertilization was used only to compensate for the poor nutrient status of the sandy, degraded soil.

The plot was equipped with a meteorological station and soil moisture sensors installed down to 1 m. Intensive monitoring was carried out. All plants were measured annually for basal diameter, height and crown radii. Physiological data was collected, including water potential, stomatal conductance, gas exchange and fluorescence. The architectural development was analyzed at two time points—when trees were 2 and 9 years old. At 9 years, analogue and digital dendrometers were installed, along with sap flow sensors. Aerial imagery from RGB and multispectral drone cameras was also collected periodically to assess stand structure and vegetation indices. Leaf and soil samples were analyzed for nutrient status. All management interventions—such as shrub control or formative pruning—were planned and recorded.

2.1.2. IRRICORK

The second scientific experimental plot—IRRICORK—was established in the 1.6 ha cork oak stand located in Avis (Table 1). This was the same stand planted in 2002 that initially caught the cork industry's attention. By 2015 cork harvest was monitored in this plot, and in 2017 the experimental design was applied (Camilo-Alves et al., 2022c). The sandy loam luvisol at this site is considered to have higher suitability for cork oak growth. Four treatments were installed with different water

Table 1

Description of the first two scientific research plots with irrigated cork oaks.

		PLOTS	IRRICORK	REGASUBER	
		Location	Avis, Portugal	Coruche, Portugal	
		Plantation year	2003	2014	
		Total area (ha)	1.6	6	
		Spacing (m)	7 × 3.5	4 × 4	
		Soil type	Low-Saturated Gleyic Luvisol	Arenosol	
Normal 1991 2020		Soil characterisation	Structured sandy-loam	Deep, non-structured sandy soil	
		Annual precipitation (mm)	534	556	
		Average temperature (°c)	16.6	16.4	
Scientific plot characterization		Installation year	2017	2016	
		Area (ha)	1	4	
		irrigation system	Surface drip irrigation. 2,1 L drip emitters spaced 0,75 m along the tubes	Sub-surface drip irrigation. 1.6 L drip emitters spaced 1 m along the tubes	
		Treatments	3 irrigation volumes + irrigation suppression	Combination of 2 irrigation volumes and 2 irrigation frequencies + control (rainfed)	
Monitoring	Continuous	Meteorological parameters	yes	yes	
		Soil moisture	yes	yes	
		Tree sap flow	since 2017	since 2023	
		Radial increments (digital dendrometers)	yes	yes	
		Annual dendrometric measurements	yes	yes	
	Periodic	Radial growth (dendrometric tapes)	yes	since 2023	
		RGB and multispectral aerial images	yes	yes	
		Physiological parameters (gas exchange, fluorescence, stomatal conductance, water potential)	yes	yes	
		punctual	Root excavation		20 two-year-old seedlings
			Root excavation and tree 3D architecture	1 tree	6 trees
	Soil electrical resistivity (to infer soil moisture in depth)		3 tomographic maps	3 tomographic maps	
		Nutrients	soil	leaf and soil	
		Floristic diversity		2024	
	Cork production	since 2015	since 2024		
	Cork quality	secondary and reproduction cork			

volumes and scheduling. Details can be seen in (Camilo-Alves et al., 2022e). For the control treatment – no fertirrigation – the key question was to infer if trees exhibited normal physiological responses after irrigation withdrawal. These trees had developed under conditions of surface water availability, which may have led to structural changes—such as in root architecture—and physiological traits that could exacerbate drought stress once irrigation was permanently withdrawn.

The same monitoring protocols used in REGASUBER were applied in IRRICORK. In this case, trees were already mature enough for installation of sap flow sensors and dendrometers. Also, a complete excavation and digitization of a single tree were carried out to generate an empirical 3D model.

The existence of this stand allowed to study the effect of irrigation withdrawal in cork oaks' vitality. Since some trees were already producing their second cork, it also allowed evaluation of the effects of water on cork development.

2.1.3. Mature pilot plots

As part of an EIP-AGRI Operational Group project launched in 2018, additional experimental plots were established (Go-Regacork, 2018). Two of these were installed in stands of rainfed adult cork oaks that have been monitored since 1996, included detailed dendrometric data and cork samples from two to three consecutive harvests (Camilo-Alves et al., 2022d). The experimental plots underwent two treatments – fertirrigation and control. The goal of these plots was to deepen the fundamental understanding of how water availability affects the physiological and structural responses of cork oaks, particularly regarding the development of reproduction cork. Since cork samples from previous harvests were available, they could be used for comparative analysis. A sample of trees was monitored using equipment such as sapflow sensors and dendrometer tapes.

Within the same project, five other private partners also established irrigated cork oak stands. These were designed for productive purposes and served as recipients of the knowledge generated in the pilot plots.

In the following year, a Spanish consortium with similar objectives was created. It brought together research and technology partners to support the implementation of fertirrigation in cork oak stands in the Extremadura region (Go-Fertirriego, 2018). The pilot plot —Rueda Chica—covers 1 hectare and was planted in 2004. Irrigation was applied during the establishment phase for seven years. The use of clonal material from selected provenances makes this plot unique and of great scientific interest. In addition, three more plots were installed for long-term monitoring.

Altogether, these two Operational Groups led to the installation of 116 ha of irrigated cork oaks. In parallel, other private producers in both Spain and Portugal have independently adopted fertirrigation systems for production purposes.

The installation of the long-term experimental plots contributed to deepening our understanding of the effects of water availability on the physiology and development of cork oak. This knowledge is essential to determine the most appropriate irrigation strategies to meet both production and resilience goals.

3. Results from the experimental plots

3.1. Does annual summer fertirrigation reduce time to the first cork debarking?

3.1.1. Cork oak growth

As addressed in 1.3, cork oak photosynthesis can be down-regulated under adverse environmental conditions, such as high temperatures and solar radiation (Faria et al., 1996; Larcher, 2000). In such cases, soil water availability alone may not be sufficient to increase carbon sequestration. However, irrigated cork oaks exhibited substantial plasticity coping with fluctuations in water supply. Every 15 days, radial growth responded closely to different water volumes, resulting in a

linear increase up to 2 mm day⁻¹ (140 m³ ha⁻¹ week⁻¹) of irrigation (Camilo-Alves et al., 2022e). During summer, rainfed trees exhibited reduced growth as the air vapor pressure deficit rose. In contrast, fertirrigated trees were less sensitive to these adverse conditions, sustaining higher carbon assimilation rates, which in turn resulted in greater growth. That is why irrigation was estimated to shorten the time to first debarking by approximately 5–10 years in both experimental plots (Camilo-Alves et al., 2025a), bringing it to around 14 years after plantation establishment. Beyond advancing the onset of productivity, fertirrigation also narrowed the confidence interval, indicating a more homogeneous entry into production across stands rather than a prolonged and uneven transition.

Remarkably, in REGASUBER's regular soil quality for cork oaks — where plot installation without irrigation would have been challenging — tree growth approached that of irrigated trees in IRRICORK, which had better-structured, superior soil quality for cork oak. The first cork harvest in REGASUBER was estimated to occur between 13 and 15 years after plantation (Camilo-Alves et al., 2025), and by year 11 (in 2025), 8 % of the irrigated trees had already been debarked. In IRRICORK, 64 % of trees were debarked at age 15. After this, gains in the percentage of trees entering production became marginal (10 % over 6 years). However, growth of secondary cork (second harvest) and reproduction cork (third harvest) was rapid. This may indicate that the smaller undebarbed trees are suppressed, and eventually increased water availability or other forest management actions could improve their growth. The key point is that under adequate edaphoclimatic conditions the average first cork harvest in fertirrigated stands occurs at about 13–15 years. For comparison, growth simulations for the best rainfed conditions suggest first cork harvest at 17–21 years (Sánchez-González et al., 2005; Ribeiro et al., 2010; Camilo-Alves et al., 2025). Such rainfed conditions are rare, as they require optimal soils and rainfall, which typically overlap with areas prioritized for agriculture.

3.1.2. Limitation to growth

Although promising, fertirrigation is not a panacea and cannot compensate for all limiting conditions. Some areas of REGASUBER have soils with inferior quality for cork oaks, particularly lacking water retention capacity down to 4 m, as revealed by deep electrical resistivity surveys (Camilo-Alves et al., 2025a). In these areas, growth is severely limited, and mortality rates were higher. Similar issues were observed in a few stands managed by other project participants. Cork oak irrigation success thus requires addressing limiting edaphic factors, including deep soil moisture prospection and evaluating whether irrigation can mitigate them. For successful establishment, new plantations must be located in areas naturally suitable for cork oak survival under rainfed conditions. Irrigation should serve only as a temporary supplement for early survival and rapid growth. It must not be used to establish plantations in sites unsuitable for the species.

3.1.3. Cork development

Regarding cork development, preliminary studies have explored quality parameters by comparing reproduction cork from mature trees in IRRICORK with cork from a representative rainfed stand located 35 km away (Poeiras et al., 2021, 2022a, 2022b). These studies were preliminary because, at the time, no reproduction cork from rainfed trees was available in the plot, so there was no real control group. However, it is worth noting that porosity and density from irrigated trees remained within the normal range for natural cork stopper production (Poeiras et al., 2021). More recent studies (Poeiras et al. submitted) performed with corks obtained from the mature plots indicate that cell walls become thicker with irrigation, but the lumens remained the same size. Cork is currently being processed to assess porosity and density, important parameters for its quality.

Another aspect to be considered is the increase in cork growth rates. Six-year-old fertirrigated reproduction cork (harvested with legal authorizations) had an average thickness of 2.61 ± 0.22 cm, compared

with the 2.13 ± 0.55 cm of the nine-year-old cork from the representative rainfed stand (Poeiras et al., 2021). Given the legal nine-year growth cycle, excessive thickness may compromise quality and reduce industrial efficiency. Therefore, the proposal to withdraw fertirrigation once the trees enter their productive phase appears to be the most viable strategy.

3.2. What is the minimum water input required to stimulate radial growth?

3.2.1. Irrigation monitoring

Water management is well developed for agricultural species. It can be based on climatic parameters, where potential evapotranspiration is calculated and the crop coefficient is used to estimate the amount of water to be replaced. This requires knowing the crop coefficient — the water use of the plot, which includes both transpiration by the species and evaporation from the system. Several crop coefficients may occur throughout the life cycle of a crop. During the seedling stage, when the soil is highly exposed and if irrigation is applied at the surface, this method can be useful. At this stage, evapotranspiration is more related to evaporation losses than to plant transpiration (Allen et al., 1998). For later stages, several studies will be needed to calculate reliable crop coefficients. One study has already addressed the calculation of the crop coefficient for cork oak (Lima, 2008). Another practical approach is management based on the soil water balance. Several commercial devices allow continuous monitoring down to 1.5 m depth. For more structured soils, this is a good approach to ensure that stored soil water remains within the values required for the yield threshold. However, this approach was tested in the REGASUBER plot, and the sandy soils' inability to maintain a wet bulb made this type of management unfeasible. No differences in soil water content were detected down to the sensor depth, although plants showed different growth increments depending on the applied treatments (Fig. 2). This highlighted the importance of water availability at depths greater than 1 m, even for plants only two years after planting (Camilo-Alves et al., 2020b). Plant physiological parameters, particularly stomatal conductance, indicated the effect of irrigation and helped define irrigation efficiency. Plants with adequate water supply showed higher values for these parameters compared to control or deficit-irrigated plants. For in-field adjustments, it is more advantageous to have at least two differentiated sectors, allowing comparison of physiological parameters between plants. As plants grow, a reliable indicator of irrigation efficiency becomes radial growth measurements using dendrometers (Camilo-Alves et al., 2022e). The use of dendrometric tapes with 0.1 mm precision allowed monitoring variations in radial growth every 15 days, as a function of irrigation. Alternatively, digital dendrometers allow monitoring at the scale

of one micrometer, enabling the detection of daily variations. This facilitates precision monitoring, indicating the minimum water required to improve growth. Analysis of digital dendrometer data is still ongoing, aiming to compare it with sap flow measurements and meteorological conditions, so that this parameter can be used to support precision irrigation.

3.2.2. Irrigation regimes

The experimental plots proved valuable in defining the water requirements of cork oak trees. It was possible to estimate not only the minimum amount of water needed during the establishment phase (Camilo-Alves et al., 2020b) but also the optimal irrigation frequency for the sandy soils of the REGASUBER plot (Camilo-Alves et al., 2022b). Compared to the more complex soils of the IRRICORK plot, water application strategies must differ according to soil type. In the sandy soils of REGASUBER, the wet bulb did not persist, whereas in the IRRICORK soils, which contain higher percentages of clay and loam, the opposite effect was observed — a more stable and long-lasting wet bulb was formed. Therefore, in sandy soils, irrigation should be applied more frequently and in smaller doses — that is, lower volumes applied at reduced intervals, such as two to three times a week. In contrast, in clay-rich soils, the key is to prevent the wet bulb from drying out, as their lower infiltration rate hinders the redistribution of water in depth (Hao et al., 2007; Effegem et al., 2020; Ali et al., 2024). In IRRICORK, irrigation once a week was sufficient to maintain the superficial wet bulb and also to allow water percolation for deeper roots. The influence of soil type on irrigation efficiency has been widely studied in agronomy, however, it remains to be seen whether the same irrigation principles used for agricultural crops should be applied to cork oak trees. Surface water availability is crucial for cork oak radial growth, especially when deep water reserves are located below 2.5 m (Otieno et al., 2006; Mendes et al., 2016). Nevertheless, roots must develop in depth. Thus, cork oak irrigation should aim to support deep root development — essential for resilience under rainfed conditions — while maintaining a moist surface wet bulb, where water uptake is more efficient for radial growth.

3.2.3. Water requirements

One major question is how much water is needed to significantly enhance cork oak growth, important for both irrigation system dimensioning and for its environmental cost. From the two main experimental plots, the most efficient water amounts ranged from about 3.12 mm per week in the sandy soil of REGASUBER for 2-year-old plants, up to 14 mm per week for 15-year-old trees in the more complex soil of IRRICORK, with 90 % canopy cover. However, the increase in water needs is non-linear. At early stages, water waste is higher, especially with drip lines

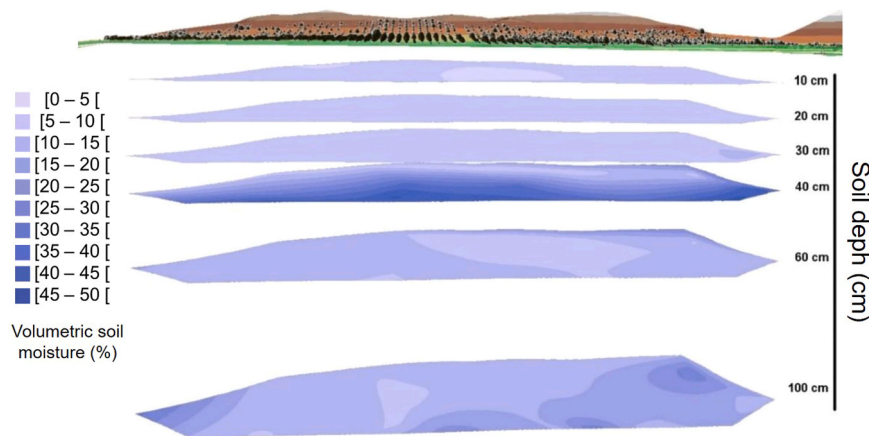


Fig. 2. Filled contour plot based on 20 soil moisture profiles measured at six depths during the irrigation period. Covered area: 1.5 ha. Irrigation tubes were buried at approximately 30 cm depth, with higher moisture observed just below 40 cm.

using spaced emitters. As plants grow, their root system occupies a larger soil volume, allowing better water uptake.

We calculated the actual amounts used in both pilot plots. In REGASUBER, water may have been supplied in excess for efficient growth, as it was an experimental setting. In IRRICORK, treatments with reduced water volumes were tested. In Fig. 3, we show the weekly average irrigation per hectare for all irrigated treatments, highlighting optimal values identified for two growth stages. For the other stages, variations in irrigation treatments were not statistically linked to differences in growth, likely due to variations in soil water storage capacity (Camilo-Alves et al., 2025). Under the highest water-demanding stage - when trees obtain the appropriate trunk radial dimensions for the first cork debark - about $140 \text{ m}^3 \text{ ha}^{-1} \text{ week}^{-1}$ is expected using surface drip irrigation. Thus, taking into account the maximum water requirements during the typical four-month Mediterranean summer irrigation period, the total annual volume reaches approximately $2400 \text{ m}^3 \text{ ha}^{-1}$ with a surface drip irrigation. Such a figure aligns closely with the surface drip irrigation requirements estimated for intensive olive orchards in the region (DGADR, 2023; Santos et al., 2024) - The landowner managing the IRRICORK stand showed considerable foresight in anticipating such water demands. However, considering the water use in REGASUBER, it is likely that subsurface irrigation could lead to water savings, as reported for some crops where reductions of up to 25 % have been achieved due to lower evaporative and percolation losses (Lamm et al., 2021). Continued monitoring of these experimental plots will be essential to confirm this potential.

3.2.4. Water management under prolonged droughts

One of the characteristics of the Mediterranean climate is its unpredictability, caused by the high variability in precipitation (Vicente-Serrano et al., 2025). In Fig. 4, the variability in monthly precipitation measured by the weather station installed in the REGASUBER experiment is shown over a 12-year period. Winter and spring rainfall are particularly important for cork oak growth in the following season (Costa et al., 2002), as they recharge groundwater reserves. It is not always the total amount of precipitation that matters, but also its distribution throughout the year.

For instance, in 2017, corresponding to the 15th year of tree growth

in IRRICORK, was the driest year within this scientific experiment. Precipitation in the region was 68 % below the 1970–2000 average, concentrated almost entirely in February and March. The irrigation campaign therefore had to start very early and extend into autumn, resulting in 27 weeks of irrigation. At IRRICORK, the weekly irrigation averaged $109 \text{ m}^3 \text{ ha}^{-1}$ (by that time, there was only one irrigation treatment, similar to the intensive olive groves), totaling $2851 \text{ m}^3 \text{ ha}^{-1}$ of water volume. This was lower than the ideal ($3360 \text{ m}^3 \text{ ha}^{-1}$) for the trees' size ($\alpha 70 \text{ PBH}$) but still promoted growth comparing with non-irrigated trees ($> 60 \%$ radial increment for trees with virgin cork). These results, combined with growth measurements taken every 15 days (Camilo-Alves et al., 2022e), indicated that when ideal irrigation is not possible, trees will still grow but proportionally less.

3.3. Does development under irrigation compromise the tree's ability to adapt to rainfed conditions?

3.3.1. Functional responses

The effect of irrigation suppression in trees that grew 15 years under irrigation - applied in some lines from IRRICORK plot - is being monitored in terms of the functional responses and growth. Decrease in predawn leaf water potential was observed, as expected in rainfed trees as drought extends over summer. However, recovery in autumn with the sap flow as well as in the leaf water potential were observed throughout the years (Vaz et al., 2022). Those cork oaks showed expected functional and growth responses for rainfed trees (Camilo-Alves et al., 2022e; Vaz et al., 2022).

In 2022, after an extremely dry autumn and winter (Fig. 4), except for a rainfall peak in March, IRRICORK had no water available in the reservoir for irrigation from June onwards. Trees responded physiologically as expected, with predawn water potentials decreasing on average from -1.2 ± 0.1 to $-1.6 \pm 0.1 \text{ MPa}$, and photosynthetic rates dropping from 5.95 ± 0.62 to $1.35 \pm 0.60 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in July, with no differences between treatments. A patch of trees progressively lost their leaves (Fig. 5), which is a typical response to severe drought to avoid xylem cavitation and embolism (Chaves et al., 2003). In August, the landowner provided water manually using a tank truck directly to the irrigation tubes. Therefore, control (rainfed) trees were not watered.

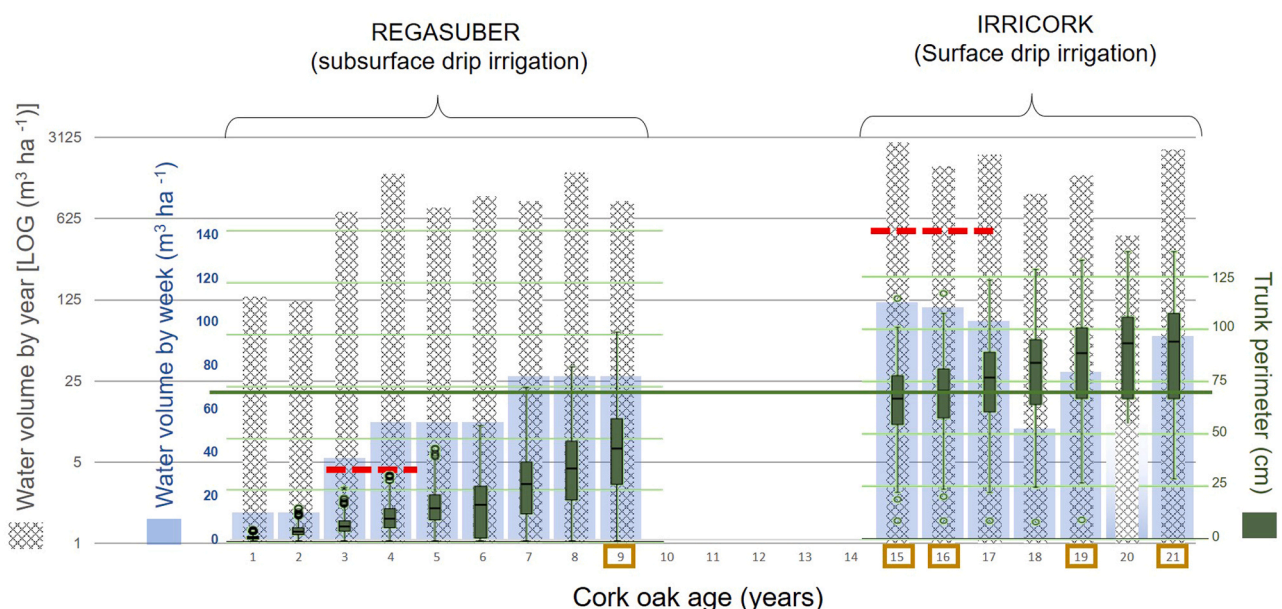


Fig. 3. Relationship between tree radial growth (boxplots, green right axis) and water volume applied weekly (solid blue bars, left blue axis) and annually (hatched bars, left grey axis) in the REGASUBER and IRRICORK plots. Water volumes correspond to the total amount applied in the irrigated treatments for each plot. Solid black line: minimum perimeter required for the first cork harvest. Dashed red line: estimated optimal weekly irrigation volume for that tree age. No significant differences between treatments were observed for other ages. Brown squares on the cork oak age axis indicate cork harvest events.

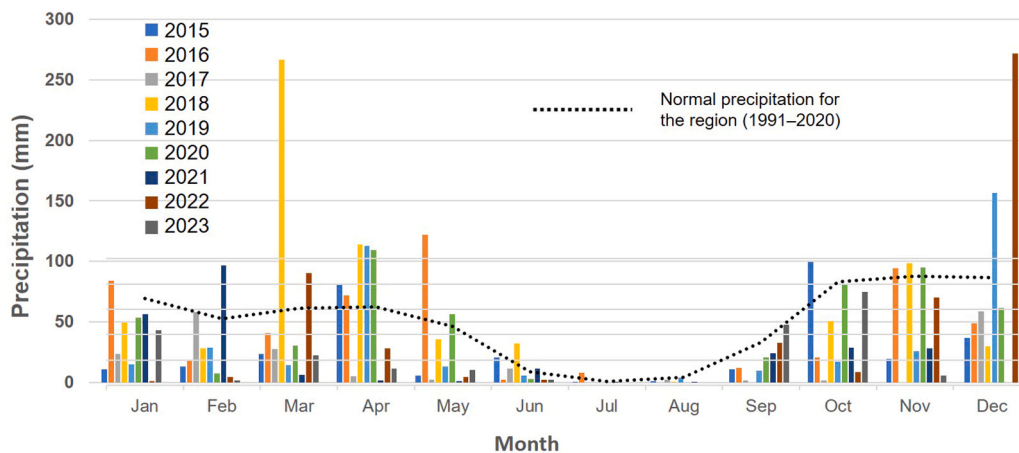


Fig. 4. Monthly precipitation variation between 2015 and 2020, measured by the weather station at REGASUBER.

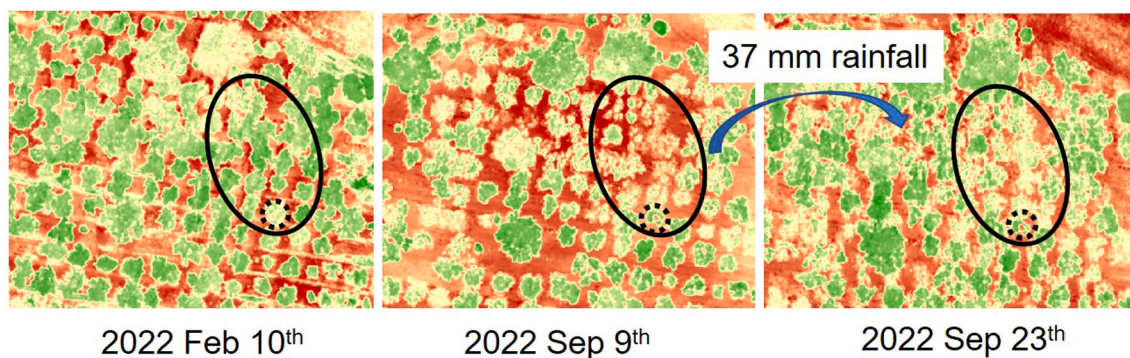


Fig. 5. NDVI from multispectral drone images acquired on the indicated dates at IRRICORK. Irrigation was not possible during the summer, and a patch of cork oaks showed defoliation (solid black circle). Between 9 and 23 September, 40 mm of precipitation occurred, resulting in foliar recovery. One tree (non-irrigated treatment) did not recover (dashed black circle).

The total volume was 115 m³, averaging 658 L per tree. After the first rains (37 mm between September 12 and 15), new leaf development resumed. In the next year (2023), one non-irrigated tree failed to recover and was later cut down (Fig. 5). Thus, of all trees with irrigation suppression since 2017, only one did not survive the 2022 drought, a situation that may also occur in trees grown entirely under rainfed conditions. These results indicate that developing under water availability did not impair the trees to cope with summer droughts over time after irrigation withdrawal.

3.3.2. Structural adaptations

Root development and architecture play an important role in irrigation suppression success. Trees must be able to access deep groundwater and to support the needs of the aerial part. At the start of the REGASUBER experiment, excavations of 20 two-year-old plants revealed that root architecture was independent of dripper location (Dinis et al., 2018). However, after seven years, excavations of seven trees (6 in REGASUBER and 1 in IRRICORK) suggested a relationship between root development and wet bulb formation, influenced by soil type and irrigation method (surface or subsurface) (Šleglová et al. 2025b). Only in IRRICORK, where the wet bulb formed closer to the surface, was there a clear tendency for more roots in the irrigation-influenced area: half of the roots were located in the wet bulb quadrant, and the other half were distributed among the remaining three quadrants.

Root-to-shoot ratio was more related to tree size, yet there was a tendency for fertirrigated trees to exhibit lower ratios (Šleglová et al. 2025a, 2025b). This pattern is expected, as the ratio is influenced by

drought conditions and because fertirrigation promotes aboveground growth rather than reducing root development (Coyle and Coleman, 2005). The largest pair measured had a ratio of 1.04 for the rainfed tree (DBH = 39 cm) and 0.56 for the fertirrigated tree (DBH = 63 cm). By contrast, the irrigated IRRICORK tree (20 years old, DBH = 50 cm) had a volumetric ratio of approximately 1.

The effect of irrigation on tree development has been studied in fruit trees for decades (e.g., Levin et al., 1979; Fernández Luque et al., 1991), including the appropriate irrigation management to avoid undesirable patterns (Bravdo et al., 1992). To withdraw irrigation when cork oaks enter production, one could adapt irrigation so that surface roots are less dependent on the wet bulb, for example, by installing irrigation lines on both sides of the tree. Nevertheless, deep sinker roots, which are highly functional for water uptake at depth, were always found in excavated trees (Figs. 6 and 7). This means that trees can access deep water once irrigation is withdrawn. Early in planting, deep ripping can stimulate vertical root growth (Dinis et al., 2018). Later, irrigation can be adjusted so that the wet bulb remains deeper in the soil. Monitoring the wet bulb can help identify areas where root density is likely to increase, although roots also extend beyond the wet bulb. This knowledge allows adjustment of water volumes, irrigation frequency, and irrigation placement to promote both uniform surface rooting and deeper root development. Finally, a gradual reduction in total summer water volumes can further facilitate the transition to rainfed conditions.



Fig. 6. Images of tree roots excavated in REGASUBER and IRRICORK, showing sinker roots originating from the horizontal root system.

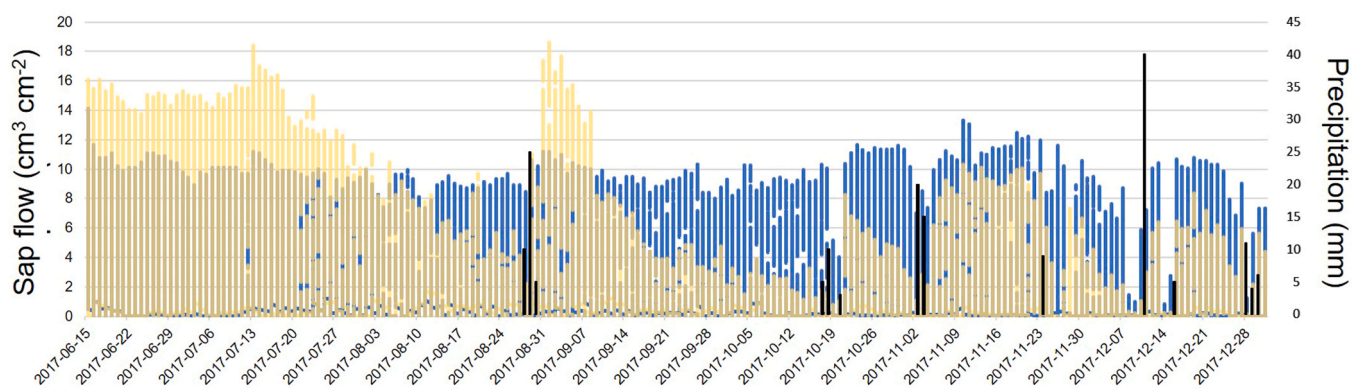


Fig. 7. Daily sap flow of irrigated cork oaks (blue bars) and cork oaks under irrigation suppression (yellow bars), together with precipitation events (black bars), during 2017 (15-year-old trees) at IRRICORK. Bars are superimposed. Note the reduction in sap flow of non-irrigated trees and the increase following precipitation events, whereas irrigated trees maintained a more stable flow.

3.4. Is the additional cost of fertirrigation offset by the earlier onset of productivity, and under which soil conditions?

The costs of fertirrigation comprise not only the installation and maintenance of the irrigation system, but also electricity and water expenses (when applicable), as well as adjustments in stand management arising from increased intervention needs. Accelerated growth rates inevitably require more frequent silvicultural operations, particularly understory control and formative pruning.

A cost–benefit analysis was conducted using data from IRRICORK (good site quality, 4×4 m spacing, cork stripping starting 12 years after plantation establishment), with real cost data provided by project partners. Results indicated that fertirrigation would only be economically disadvantageous under the most expensive scenario recorded (installation = €6700 ha⁻¹; annual maintenance = €750 ha⁻¹; Camilo-Alves et al., 2025b). In such cases, irrigation should be discontinued once the stand reaches 300 @ ha⁻¹ of cork (4500 kg ha⁻¹), which may occur only after the second stripping. Although the simulations targeted maximum system productivity, most projects reported lower installation and maintenance costs than those in the high-cost scenario. Achieving such productivity levels depends on ensuring that the site meets the suitability criteria outlined in chapter 3.1, and that planting is carried out at 4×4 m spacing, or even 3×3 m. The 4×4 m spacing is also recommended in silvicultural models for rainfed systems (Serrão et al., 2019a), yet it is often underused due to lack of familiarity or confusion

with the agro-silvopastoral model. Closer spacings—such as 3×3 m, already implemented in a partner plantation—offer clear advantages: higher productivity, enhanced growth in trunk height (favorable for cork production), and reduced understory management needs through faster canopy closure. In irrigated stands, such configurations allow more efficient water use. Once trees enter production, competition can be managed through thinning.

At the installation stage, costs are influenced by the opportunity cost of each component within their specific context: whether existing ponds can be utilized or must be constructed; whether energy is available or solar panels are required; and whether to adopt surface or subsurface irrigation. During the maintenance phase, management approaches varied among partners. Some opted for a more agronomic strategy, with intensive interventions such as plant protectors, staking, foliar fertilization, or strict understory control. Conversely, in the REGASUBER plot, a more restrained approach was used, significantly reducing maintenance costs. Trees were neither staked nor protected, and understory control was gradually phased out after five years. Investment focused on formative pruning, as irrigated trees not only grew faster but also developed abundant branching, requiring annual pruning to develop a tall, straight trunk. Findings from REGASUBER highlighted three key factors for success of this technique: (1) investment in high-quality irrigation materials, thereby reducing maintenance costs; (2) the use of subsurface irrigation, which suppressed weed growth and facilitated understory management; and (3) correct application of

formative pruning techniques (Rodrigues, 2023), which maintained high growth rates and produced tall trunks suitable for quality cork planks.

In summary, effective stand management is fundamental to the economic success of cork oak irrigation. Irrigated forest systems, unlike rainfed ones, require continuous monitoring and annual maintenance. However, they need not be managed as intensive agronomic systems; rather, success depends on the careful selection of key interventions that have a decisive influence on outcomes.

3.5. Additional aspects of cork oak irrigation

3.5.1. Adverse outcomes

Pest attacks, especially by voles (*Microtus duodecimcostatus* and *M. lusitanicus*), were a problem in some of the fertirrigated stands. In REGASUBER, up to 25 % of seedlings were affected during the first five years (Camilo-Alves et al., 2022a). Thus, the early-stage survival benefits of irrigation, observed here and in others studies (Vessella et al., 2010; Ceia et al., 2024; Mitique et al., 2025), can be offset. Vole abundance is linked to dense vegetation, particularly in irrigated plots, where densities can reach 390 individuals per hectare, and in extreme cases up to 1500 per hectare (Palencia, Spain) (EPP0, 2002). Although these species do not show strong preferences for sandy soils (Monarca et al., 2019), attacks occurred precisely on such soils. To manage the pest population, vegetation in the REGASUBER plot was cleared annually in spring, without soil mobilization in order to prevent root damage. Newly transplanted seedlings were protected by enclosing their root balls in metallic nets. However, during the subsequent years, some of those seedlings presented root destruction caused by voles. Additional measures to mitigate vole attacks may include maintaining or enhancing predator dens. Chemical control is feasible in agronomic systems, although it may not be adequate in forest contexts. In REGASUBER, pest damage was markedly reduced five years after plantation establishment, primarily due to tree growth. Excavation revealed that vole activity continued to affect the roots, although the trees exhibited no visible signs of stress. Consequently, in the presence of vole outbreaks, new plantations are expected to undergo a critical vulnerability period, after which vole damage becomes negligible.

No other pests or diseases caused significant damage. *P. cinnamomi* can, however, pose a problem, particularly in compact soils prone to waterlogging (Moreira and Martins, 2005). Nevertheless, it is important to note that a healthy tree can defend itself against biotic agents, including *P. cinnamomi*. Cork oak is moderately susceptible to this root disease, which typically requires the combined action of other stress factors acting synergistically to cause a decline in vitality (Camilo-Alves et al., 2013).

To prevent future problems, soil assays for root pathogens should be conducted prior to stand establishment. Moreover, the effective establishment and growth of cork oak require the implementation of pest prevention and control strategies.

3.5.2. Environmental cost-benefit under climate change conditions

Water use in the Mediterranean context is a sensitive issue, as the defining feature of this climate is the summer dry period. In the Alentejo region, Portugal, the reference evapotranspiration averages 5 mm day⁻¹ during summer (1971–2000 climatological normal), with mean maximum temperatures exceeding 26 °C and monthly precipitation below 30 mm. In fact, Mediterranean forests typically grow under water-limited conditions (Piñol et al., 1999) and exhibit a wide range of adaptations to such constraints (Pereira et al., 2009). More concerning, however, is the progressive intensification of adverse summer conditions in several areas across the distribution range of cork oak. For example, a comparison between the 1971–2000 and the 1991–2020 climatological normal for Central Alentejo—the region hosting the largest cork oak stands in Portugal—shows, for summer (June–September), increases in maximum temperature, a decline in precipitation

in June and July, and a higher frequency of days above 30 °C (IPMA, 2025). In the Mediterranean region, climate change is projected to exacerbate constraints on tree growth and vitality by increasing atmospheric evaporative demand in parallel with declining precipitation (Spinoni et al., 2017; Samaniego et al., 2018; Caloiero et al., 2018). Although precipitation must be interpreted with caution due to its inherently high interannual variability, rising temperatures appear to be a robust trend of climate change (Noto et al., 2023; Vicente-Serrano et al., 2025), leading to higher evapotranspirative demand. This environmental stress has already hampered natural regeneration of the species (Gómez-Aparicio et al., 2008; Arosa et al., 2015; Ribeiro et al., 2024).

Technical guidelines commonly recommend irrigation support during the first three years after plantation ((Barros and Sousa, 2006) as also stated in the official website of the Portuguese Forest Service (ICNF, 2025) and supported by European funding instruments (PEPACC, 2025). Nevertheless, such recommendations refer to mobile water tanks rather than to permanent irrigation systems. These institutions thus acknowledge the crucial role of water in securing successful cork oak establishment, under the assumption that the long-term benefits outweigh the natural resource costs.

Fertirrigation projects propose to extend irrigation beyond the establishment phase, maintaining it throughout the juvenile stage until trees reach maturity (ca. 15 years) or the second cork harvest (ca. 20 years). Based on calculations of efficient water use (Fig. 3), and considering a maximum allocation of 140 m³ ha⁻¹ week⁻¹ from year 14 onwards, the average water use over a 20-year irrigation period would be 93 m³ ha⁻¹ week⁻¹. This is equivalent to a traditional olive grove under drip irrigation. During the peak demand phase, particularly in the final five years, water use approaches the requirements of intensive olive orchards—a crop widely represented in Portugal. Given the scarcity of water, such use for non-food production should only be considered when supplied from surface sources (dams or ponds) and never from groundwater. Ideally, fertirrigation should be implemented in areas adjacent to irrigated crops or within agroforestry systems that integrate irrigated pastures and fodder. Also, irrigation should not be used to establish cork oak stands in areas with edaphoclimatic constraints to these forests, but rather only to overcome difficulties during reforestation.

Beyond supporting timber or cork production, irrigation can also deliver important ecosystem services, including carbon sequestration and land restoration. In the REGASUBER plot, accelerated tree growth promoted ecological succession and increased floristic biodiversity. This recovery was closely associated with canopy closure rather than with soil chemical parameters (Raposo et al., 2025). In addition, a mature stand with high canopy cover is expected to be more resilient to climate change (Ribeiro et al., 2024a), as well as to support higher regeneration survival (Ribeiro et al., 2024b). Thus, cork oak irrigation may contribute to climate change adaptation by supporting tree growth until the system becomes resilient, while also assisting in climate change mitigation by enhancing carbon sequestration through increased tree growth.

Finally, it is important to emphasize that irrigation in cork oak forestation should not be seen as competing with rainfed systems, but rather as a strategy to provide a competitive advantage over fast-growing exotic species (e.g. *Eucalyptus globulus*) or agro-pastoral intensification, which often provide quicker economic returns (Camilo-Alves et al., 2025). Irrigation is intended only as a temporary support until trees reach the production stage, ultimately yielding a resilient and biodiverse forest ecosystem under natural conditions.

3.6. The future

Much remains to be learned from the cork oak irrigation plots. Irrigation provides a unique opportunity to examine cork oak physiology under conditions of water availability, both at the physiological and structural levels. Ongoing studies on crown architecture are expected to

yield valuable insights into the structural development of cork oaks. Formation pruning, when properly carried out, is an essential management practice for ensuring tree vitality and productivity; the knowledge generated through these experimental plots may help to define and strengthen this methodology. With regard to cork production, current studies aim to clarify the role of water in cork development and its quality parameters.

All this information on cork oak structural–functional adaptation to water availability can support the establishment of cork oak stands in areas with higher precipitation. Although potentially suitable for the species, they remain underutilized due to the lack of appropriate silvicultural models. As cork oak suitability is projected to shift towards such regions (Serrão et al., 2019b), proactively establishing productive stands there represents a strategy to adapt forests in advance to climate change.

In terms of ecosystem services, these stands also offer the opportunity to investigate the role of cork oak forests in the water cycle, through monitoring deep water dynamics, rainfall infiltration, and evaporative demand. This will allow linking the cost of water use by trees with the contribution of forests to soil water recharge.

Regarding fertilization, these experimental plots focused primarily on assessing water requirements, with nutrient inputs maintained at the minimum necessary to compensate for soil deficiencies. Cork oak nutrition remains poorly understood, and studies are underway to develop reference thresholds based on foliar parameters.

Finally, several methods are being evaluated to improve monitoring of water requirements, ranging from drone imagery to precision instruments. The ultimate goal of these experimental plots is to develop decision-support and monitoring tools that enable fast and accurate management of irrigated cork oak stands until maturity, relying only on efficient water use and interventions that also enhance the environmental services provided by these forests.

4. Conclusions

Irrigation represents a promising, context-dependent approach to promote cork oak survival and growth. Results from experimental plots confirm its capacity to significantly shorten the juvenile phase, enhance radial growth, and promote earlier and more uniform productivity. Nonetheless, its effectiveness is contingent upon site selection, particularly water retention capacity, and requires integration with sound silvicultural practices, notably formative pruning and pest control. Water requirements throughout the irrigation period remain lower than for typical irrigated crops; during the most demanding stages - which may last up to five years - requirements may approach those of intensive olive orchards, at approximately $140 \text{ m}^3 \text{ ha}^{-1}$ per week. From an economic perspective, irrigation is viable provided that installation and maintenance costs remain within reasonable thresholds and that management practices are adjusted to accelerate growth dynamics. Environmentally, fertirrigation should only rely on surface water resources and be applied as a temporary measure until stands reach maturity, thereby avoiding long-term dependence. Beyond economic returns, irrigated cork oak stands offer opportunities to improve ecosystem services, including carbon sequestration and biodiversity recovery. As cork oak suitability shifts under climate change, fertirrigation can also serve as a proactive adaptation strategy, enabling the establishment of productive stands in regions with higher precipitation but a lack of silvicultural models. In conclusion, fertirrigation should be viewed as a strategic tool to increase competitiveness and ensure the resilience and sustainability of cork oak forests in a changing Mediterranean landscape.

CRedit authorship contribution statement

Nuno Almeida-Ribeiro: Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Barroso João Mota:** Writing – review & editing,

Validation. **Constança Camilo-Alves:** Writing – original draft, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Margarida Vaz:** Writing – review & editing, Validation. **Poeiras Ana Patricia:** Writing – review & editing, Formal analysis.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used CHAT GPT in order to review and correct the English. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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