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ORIGINAL PAPER

Assessing the effect of cork oak fertigation on crown and root structure using electro-magnetic tracking system

Kristýna Šleglová[1]*, Constança Camilo-Alves[2, 3], Nuno Almeida Ribeiro[4, 5], Ana Poeiras[2, 3], José António Nunes[4], Peter Surový[1]

[1]*Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, CZ-165 00 Prague-Suchdol, Czech Republic*

[2]*MED – Mediterranean Institute for Agriculture, Environment and Development & CHANGE – Global Change and Sustainability Institute, Pólo da Mitra, Ap. 94, PT-7006-554 Évora, Portugal*

[3]*Institute for Advanced Studies and Research, University of Evora, Pólo da Mitra, Ap. 94, PT-7006-554 Évora, Portugal*

[4]*ICT – Institute of Earth Sciences, Rua Romão Ramalho, 59, PT-7002-554 Évora, Portugal*

[5]*University of Evora, School of Science and Technology, Department of Plant Science, Pólo da Mitra, Ap. 94, PT-7006-554 Évora, Portugal*

Abstract

Cork oak (*Quercus suber* L.) mortality events have spurred scientific research into new afforestation techniques, particularly the use of fertigation to accelerate tree growth and hasten the onset of the productive phase when cork stripping becomes feasible. This study examines the effects of fertigation on the development of root and aerial systems, with the objective of determining if fertigation can eventually be discontinued without compromising tree vitality. Six seven-year-old trees growing under natural conditions were selected for analysis, grouped into three pairs, each with similar crown sizes but subjected to different watering regimes – fertigation and rainfed. These trees were analyzed using the Fastrak Polhemus method, focusing on seven parameters: volume, area, length, root diameter, root-to-shoot ratio, shape area, and circularity. Analyses were conducted both graphically and using partial correlation statistics. The findings indicate that tree size accounted for the most significant differences in these parameters. Conversely, fertigation was associated with an increase in trunk volume, while rainfed conditions led to larger root diameters, likely as an adaptation to drought. The most pronounced differences were observed in smaller trees, where both groups exhibited unbalanced but opposing root-to-shoot ratios: rainfed trees invested more in root development, while fertigation trees prioritized aerial growth. The impact of irrigation on the development of below-ground and above-ground biomass in arid regions is crucial in the context of ongoing climate change, which will further intensify drought during the growing seasons.

Key words: Fastrak Polhemus; NPK-fertigation; 3D architecture; tree crown; root system; *Quercus suber* L.

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1. Introduction

In Portugal, cork oak is one of the most economically important cork oak (*Quercus suber* L.) species, occupying about 713,000 ha (ICNF 2015). Cork oak is a valuable non-woody forest product (Martínez De Arano et al. 2021), used primarily for the production of wine stoppers (Pereira 2007). Cork is the most profitable product from Portuguese forests, representing 1.84% of Portuguese exports of goods, 1.25% of Gross Domestic Product, and 1.86% of domestic employment (APCOR 2020).

Severe cork oak mortality events have repeatedly occurred within its range since the 1980s, disrupting the system in all its aspects (Camilo-Alves et al. 2013). In response to the observed decline in both the quantity and quality of raw materials derived from cork oak, new afforestation initiatives have been implemented to address issues of seedling mortality, enhance tree growth, and improve overall tree health (Camilo-Alves et al. 2020a, 2022). To meet these objectives, summer fertigation has been introduced in experimental plots. This approach is particularly relevant given the Mediterranean climate, character-

**Corresponding author. Kristýna Šleglová, e-mail: sleglova@fld.czu.cz*

ized by a significant evapotranspiration deficit during the summer months, when trees are heavily dependent on groundwater resources (Chirino et al. 2008; Disante et al. 2011). The new afforestation techniques represent a paradigm shift, with the use of fertigation from installation up to cork debarking. The research focuses on water conservation, environmental impact, and economic sustainability.

The studies are very promising; fertigation has been shown to significantly enhance tree growth (Camilo-Alves et al. 2020a), allowing the first cork stripping to occur as early as 8 years of age – substantially earlier than the typical 15 to 25 years expected under rainfed conditions (Camilo-Alves et al. 2022). This accelerated timeline is possible because cork can be stripped for the first time once the tree trunk reaches a perimeter of 70 cm at a height of 130 cm. Thus, the timing of the first cork stripping is directly influenced by the tree's growth rate. Fertigation is expected to be discontinued once the trees reach maturity, at which point they will need to thrive under rainfed conditions and withstand summer droughts. However, consistent water and nutrient availability during the fertigation period is expected to affect the trees' structure, such as the root-to-shoot ratio (Pardos et al. 2001; Dinis et al. 2014), as well as other morphological traits while trees are developing. Several published works support the hypothesis that whole-tree water use is more correlated with tree morphology than with environmental factors (Vertessy et al. 1995; Dawson 1996; Vertessy 1997). For example, transpiration has been shown to increase with increasing height and tree thickness (Tfwala et al. 2019). The authors showed that irrigation plus nutrient addition in a spruce stand modified stem shape, among other aboveground biomass characteristics (Wiklund et al. 1995). When water is scarce, plants often favor root growth overshoot growth, resulting in a lower root-to-shoot ratio. This phenomenon, similar to the response to nitrogen deficiency, shows that when water availability is limited, plants direct more assimilate to the roots because water, like nutrients, is crucial for growth. Nitrogen fertilization increased the inorganic nitrogen content in the soil and reduced its pH, accelerating the elongation of fine roots without affecting their seasonal patterns (Noguchi et al. 2013). This change is consistent with the concept of a balance between nitrogen and carbon, which affects how dry matter is partitioned between different parts of the plant. Thus, water deficiency affects growth more than photosynthesis, leading to a greater allocation of resources to the roots (Wilson 1988; Ericsson 1995; Ägren & Franklin 2003). This process is also consistent with the optimization hypothesis, which suggests that plants respond to limited resources to maximize their growth potential (Ägren & Franklin 2003). In light of these considerations, there is a possibility that water availability may alter cork oak development in a manner that imposes constraints on their vitality when transitioning to rainfed conditions. Most models of plant growth and architectural development are generally based on an open modular structure and its endogenous dynamics: birth, growth, senescence, typology, and geometry (White 1979; Ford & Ford 1990; Kellomäki et al. 1995). Functional-structural models of trees approach canopy development through shoot-level processes, using a framework of different interacting sub-modules that take into account both branch position in the canopy and light environment as relative factors for shoot morphology (Gavrikov et al. 1996; Kellomäki et al. 1999; Sievänen et al. 2000).

Therefore, to understand how cork oak responds to watering, it is necessary to gather the most accurate data on its architecture. The above-ground part of the trees is not simple in shape (Yoshimoto et al. 2014). The most accurate method to determine the 3D architecture of both the crown and roots is to use the Fastrak Polhemus magnetic digitizer to create 3D models (Danjon et al. 1999; Šleglová et al. 2024). The method for measuring three-dimensional tree architecture, which works at the branch level and simultaneously describes plant topology (branching), plant geometry, and branch morphology, combines a 3D digitizer (Colchester 2012) coupled with DiplAmi software for digitizer control and data acquisition management. This method has already been applied, for example, to the architectural description of a 20-year-old and 7m-tall walnut tree. The visual comparison between the tree photograph and the image synthesized from the digitization was then satisfactory in this case in both above- and below-ground components (Sinoquet 1997). Mutke et al. (2005) studied the correlation of topological and geometrical variables in individual trees. The correlation was confirmed only with the parameters of the parent shoot that had formed in the previous year. However, smaller plants, rather than mature trees, were examined using 3D digitizing equipment. Digitization of smaller plants has been addressed in a number of different studies, where the overall conclusion was that 3D models have the potential to demonstrate differences in structure and development between individuals and under different environmental conditions (Watanabe et al. 2005; Yoshimoto et al. 2014). Former studies have already highlighted the effect of fertigation on cork oak growth (Camilo-Alves et al. 2020a, 2022).

In this study, the goal was to understand the effect of fertigation on the trees' structural development. Specific questions are: (1) Can an electromagnetic tracking system be used to record the structure of the underground and aboveground biomass of trees or to provide a 3D visualization? (2) How does the root-to-shoot ratio vary according to fertigation treatment? (3) How does tree morphology vary according to fertigation? This study aims to evaluate the possibility of removing fertigation from trees that have developed with water availability, examining whether morphological changes might compromise their ability to survive under rainfed conditions.

2. Materials and method

2.1. Study area

The study took place at "Herdade do Corunheiro", near Coruche, Portugal. The region is characterized by a typical Mediterranean subhumid climate with hot and dry summers. The average annual rainfall in the region is 704 mm, and the annual temperature averages 15.1 °C (1971–2000, according to data from the Portuguese Institute for Sea and Atmosphere). Cork oak covers 69% of the forested area in this region, representing the largest area occupied by this species in Portugal (Camilo-Alves et al. 2020b). The 6-hectare experimental plot was established in 2014 on former cropland for domestic use. Before planting, a soil profile evaluation was carried out at eight random locations, down to 2 meters. The soil was characterized as unstructured with a sandy texture, loose tenacity and friability, non-stickiness, minimal plasticity, and minimal compaction. More than 75% of the particles were classified as coarse sand, and the organic matter content was very low (0.32%). No significant differences in soil profile were observed between the locations, and no weathered parent material (C horizon) was reached. The plot has a slope of about 7%, facing north at 12 degrees. The experimental design is detailed in Camilo-Alves et al. (2020a). Briefly, four treatments plus a control, grouped into blocks with four to five irrigation lines, were replicated four times and randomly distributed throughout the study site. Initially, the soil was deep-ripped with a 1-meter ripper tooth in the W–E direction for the 4 × 4-meter planting lines. Subsurface drip irrigation was buried 40 cm deep and 60 cm east of the planting line for all the treatments and the control.

2.2. Data collecting

For the root structure study design, three pairs of trees were selected, each situated in adjacent treatment blocks: one receiving fertirrigation and the other serving as the rainfed. Each fertigation block received an average annual irrigation volume of 843 m^3 ha^{-1}, while the rainfed block received survival irrigation in the first two years, totaling 1,911 m^3 ha^{-1}. The 12-6-6 NPK fertigation corresponded to 27 kg ha^{-1} of nitrogen units annually. Trees in each pair were spaced 20 to 24 meters apart, and pairs were chosen based on their dimensions (Table 1). Since all the trees were the same age (seven years at the time of excavation), it was not possible to analyze root development over time. Therefore, three pairs of trees with different growth sizes were selected to represent age in terms of size (Table 1). Within each pair, however, trees were chosen to have similar development. For Pair 3, it was not possible to find a rainfed tree as developed as the fertigation tree, but it represents the most developed rainfed trees in the experimental plot. Since all fertigation trees in this study received the same water volume, differences in growth may be attributed to other factors.

The excavation was conducted to a depth of 1.5 meters, beyond which the roots were found to be very fragile and small, with the soil being too compact for further excavation with the air spade. The unexcavated roots represent a negligible fraction of the overall root system.

2.3. Fastrak digitizer

The Fastrak tracking system uses electromagnetic fields to determine the position and orientation of a remote object. The technology relies on generating near-field, low-frequency magnetic field vectors from a single assembly of three concentric, stationary antennas called a transmitter, and detecting these field vectors with a single assembly of three concentric, remote sensing antennas called a receiver. The sensed signals are input into a mathematical algorithm that computes the receiver's position and orientation relative to the transmitter.

The Fastrak system consists of a System Electronics Unit (SEU), one to four receivers, a single transmitter, a power supply, and a power cord. Static accuracy is 0.03 inches (0.08 cm) RMS for the X, Y, Z receiver positions, and 0.15° RMS for receiver orientation. Latency is 4.0 milliseconds from the center of the receiver measurement period to the beginning of the transfer from the output port. Outputs are software-selectable, including extended precision. Cartesian coordinates of position and Euler orientation angles are standard.

The device should not be used in enclosed spaces, as large metallic objects, such as desks or cabinets, located near the transmitter or receivers may adversely affect the system's performance. Many walls, floors, and ceilings also contain significant amounts of metal. The optimal operating temperature is between 10 °C and 40 °C, with a relative humidity of 10% to 95% non-condensing (Colchester 2012).

SEU – The System Electronic Unit is a stand-alone unit that can be located conveniently near the work area, AC power source, and host computer. It includes the necessary input and output connectors and controls to sup-

Table 1. Basic cork oak tree characteristics and treatments of the analyzed pair of trees, measured with dendrometric instruments before excavation.

Tree characteristics	Pair 1		Pair 2		Pair 3	
	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6
	rainfed	fertigation	rainfed	fertigation	rainfed	fertigation
Diameter at the base (cm)	11.3	10.6	5.0	6.0	12.5	20.2
Height (cm)	296	276	189	118	257	443

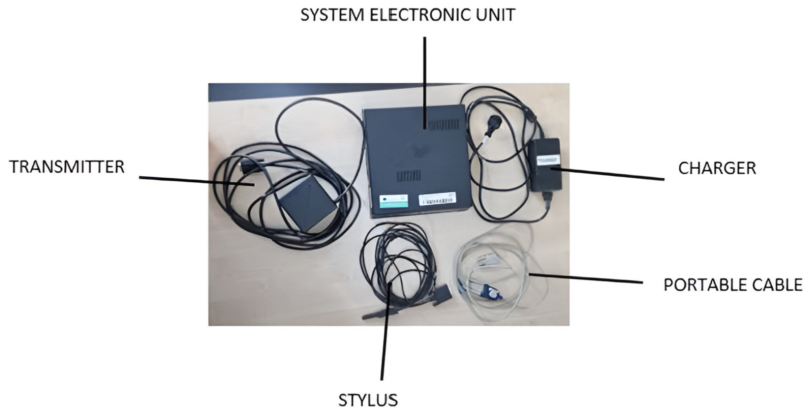

Fig. 1. Main parts of Fastrak Polhemus device (electro-magnetic tracking system).

port up to four receivers, a single transmitter, and both RS-232 and USB output ports.

TRANSMITTER – The transmitter generates the electromagnetic field and serves as the reference for position and orientation measurements of the receivers. It is typically mounted in a fixed position on a non-metallic surface or stand, close to the receivers.

STYLUS – The stylus is a pen-shaped device with a receiver coil assembly built inside and a push-button switch on the handle to facilitate data output. Position measurements are relative to the tip of the stylus, due to precise factory calibration. The stylus functions as a receiver, with the electrical center offset from the tip via software (Colchester 2012). The software output files are in XML format and allow for additional notes to be entered directly into the spreadsheet, such as branch diameters and text notes.

The general procedure followed during the digitization process was as follows:

1. Digitize the main stem (axis) from the bottom to the top of the sapling.
2. Digitize the first-order branches from their point of insertion on the main stem to the tip, then proceed to second- or third-order branches if present. This process starts with the lowest branches and moves upwards along the sapling's main axis.

To avoid missing a branch or measuring it twice, the idea of transpiration of water can be used as an aid. For each measured point, the thickness in the given section is also measured and entered into a table in the Fastrak Digitizer software. The series are also recorded in the software.

2.4 Investigated tree species

First-order branches grow directly from the trunk. Second-order branches originate from first-order branches, while third-order branches grow from second-order branches, and so on. Below ground, first-order roots grow directly from the lignotuber. The first-order root closest to the surface is designated as P1. Second-order roots derive from the first-order roots, with the one closest to the P1 origin labeled as P1/P1, and the next as P1/P2, and so on. This hierarchical branching pattern continues similarly for subsequent orders.

Since roots are cleaned gradually and cannot be exposed all at once, the use of reference points is necessary.

2.5 Data analysis

For better visualization of the architecture, 3D models were created (Fig. S1). The data was processed in Fastrak Digitizer. The output files from the software were further enhanced by including the diameter of individual

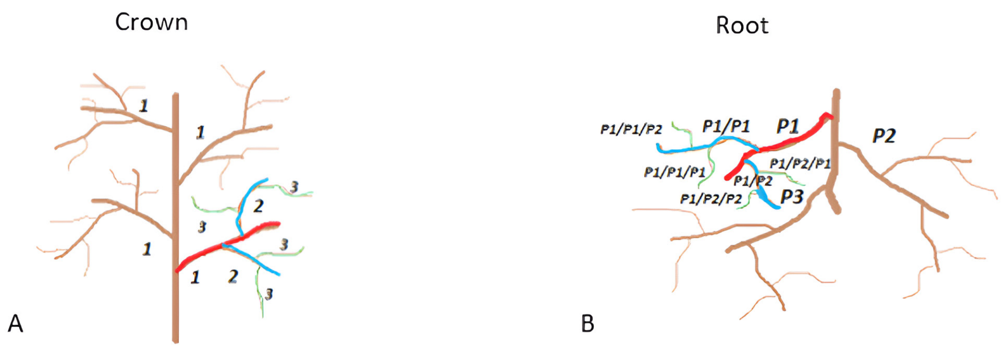

Fig. 2. Description of the measured parts of the (A) crown: 1 – first-order branches; 2 – second-order branches; 3 – third-order branches; and the (B) root system in cork oak.

Fig. 3. The red arrows indicate cut points on the roots of the cork oak, serving as reference points for measurement.

segments, as well as descriptions of the crown and roots. Additional mathematical methods were used to calculate branch lengths and the total branch length for all three orders. The length of each segment was determined using the following formula:

$$L = \sum_{i=1}^{n} \sqrt{(x_{i\_s} - x_{i\_e})^2 + (y_{i\_s} - y_{i\_e})^2 + (z_{i\_s} - z_{i\_e})^2} \qquad [1]$$

where L – branch length; n – number of branch segments; i – order number; [$x_{i\_s}1$, $y1_{i\_s}$, $z_{i\_s}1$] – coordinates of the segment start point; [$x2_{i\_e}$, $y2_{i\_e}$, $z2_{i\_e}$] – coordinates of the segment final point.

To determine the length of individual segments, a mathematical expression was developed, which was then added up for each individual branch and order separately:

$$V = \frac{\pi}{4} \cdot \frac{d_0^2 + d_n^2}{2} \cdot L \qquad [2]$$

where V is the segment volume, d_0 is first diameter segment, d_n is second diameter segment, L is the segment length (Hansson et al. 2013).

2.6. Structural analyses

Each tree was separated into its components: roots and collar root, representing the belowground (root) system, and the trunk and branches of the aerial (crown) system. For each component, seven basic structural parameters were analyzed: volume (m^3), surface area (m^2), length (m), average diameter (cm), root order classification, shape area (area explored by the systems, in m^2), and circularity of the systems.

Length and volume formulas are explained above. Volume was also used to calculate the root-to-shoot ratio. The weighted average root diameter was calculated as the average product of diameter and length for each segment. The sum of all these products was then divided by the total length.

The fifth important index was the comparison of the area explored by the roots and by the crown. To determine this, the Minimum Bounding Geometry function and the Convex Hull subfunction from ArcGIS 3.11 were used. This function creates the simplest shape that can enclose a given set of geographic features, producing the total area occupied by the root system and the crown (Fig. S2).

The sixth parameter was the order of branches and roots. Branches and roots were divided into orders, and then the percentage of each order relative to the total length of roots and branches for each tree was calculated. These values were visualized in a radar diagram. The circularity of the crown and roots was determined using a grazing artifact. The formula for calculating circularity was used as follows:

$$C = \frac{4 * PI\,(A)}{p^2} \qquad [3]$$

where C = circularity, A = area, P = length.
Circularity is a geometric measurement that determines how closely the shape of an object resembles a circle. In this study, circularity was calculated for the canopies and root systems of cork oak under different fertigation treatments. The circularity value ranges from 0 (irregular shapes) to 1 (a perfect circle). The goal was to understand how fertilization affects plant growth forms and their health (Kent et al. 2005).

2.7. Statistical analyses (Partial correlation)

Partial correlations were used to examine the relationship between tree size (represented by total tree volume) and the independent variables, while controlling for the effects of the treatments (rainfed or fertigation). Additionally, a reverse analysis was conducted to assess the correlation between treatments and the independent variables while controlling for the effects of tree size (total volume).

3. Results

3.1. Tree volume

The tree volume underscores the experimental design, where trees were grouped into pairs based on similar dimensions (Table 2). The smallest trees (pair 1) had volumes approximately half and one-third of the total volume of the trees in pair 2 and pair 3, respectively. Within the largest pair (pair 3), the tree with fertigation

Table 2. Bhe volume of the above-ground and below-ground parts of the tree, the total tree volume, and the root-to-shoot volume ratio.

Tree code (treatment) versus tree characteristics	Pair 1		Pair 2		Pair 3	
	Tree 1	Tree 2	Tree 3	Tree 4	Tree 5	Tree 6
	(control)	(fertigation)	(control)	(fertigation)	(fertigation)	(control)
Volume of aerial part (m^3)	0.0234	0.0224	0.0027	0.0074	0.0734	0.0389
Volume of roots (m^3)	0.0278	0.0217	0.0075	0.0012	0.0421	0.0375
Total tree volume (m^3)	0.010	0.008	0.052	0.044	0.076	0.115
Root to aerial part volume	54 : 46	49 : 51	74 : 26	14 : 86	36 : 64	51 : 49

had a volume one-third larger than its rainfed counterpart. The results of the root-to-crown ratio indicate that the treatment affected the distribution of volume between the above-ground and below-ground parts of the trees in the smallest pair. Under rainfed conditions, the smallest tree exhibited a significant dominance of the root system, which gradually decreased, resulting in a more balanced crown-to-root volume ratio. In contrast, trees with access to fertigation displayed the opposite trend.

3.2. Partial correlations

The parameters positively associated with tree size included all partial volumes, as well as crown surface area and length, and the area explored by the roots (see Table 3). Roots from orders 1 and 3 were negatively correlated with tree size, while roots from order 4 showed the opposite trend. There was no significant interference from the effects of the treatments.

Regarding the treatments, significant correlations were observed only when controlling for tree size. Fertirrigation trees had larger trunk volumes but exhibited a reduced average root diameter (Table 4).

3.3. Length of roots and branches

A graphical comparison of total root length to total branch length reveals a trend: the smallest trees (pair 1) exhibited a more balanced investment in root and crown length, the intermediate trees (pair 2) showed a greater investment in root length, and the largest trees (pair 3) demonstrated a greater allocation of resources towards branch growth (Fig. 4).

3.4. Weighted average diameter of root diameter

Rainfed trees consistently exhibited thicker roots than fertigation trees (Fig. 5). The greatest difference in root thickness was observed in Group 1, where rainfed trees had significantly thicker roots compared to their fertiga-

Table 3. Partial correlations of the tree total volume (representing tree size) with the trees' parameters, not controlling ("none" column) and controlling for the effect of treatment (rainfed: 0; fertirrigation: 1).

Controlling variable Parameters			None			Treatment (0.1)		
			Pearson correl.	Sig. (2-tailed)	Df	Pearson correl.	Sig. (2-tailed)	Df
Treatment			0.131	0.805	4			
	Total		1.000		0	1		
	Aerial part	Trunk	0.986	< 0.0001	4	0.998	<0.0001	3
		Branches	0,969	0.001	4	0.972	0.006	3
		Crown	0.984	< 0.0001	4	0.993	0.001	3
	Root system	Collar root	0.972	0.001	4	0.975	0.005	3
		Roots	0.939	0.005	4	0.974	0.005	3
		Total	0.958	0.003	4	0.983	0.003	3
	Root/shoot		–0.369	0.472	4	–0.378	0.530	3
Surface	Crown		0.978	0.001	4	0.98	0.003	3
	Root		0.733	0.098	4	0,747	0.147	3
Lenght	Crown		0.929	0.007	4	0.928	0.023	3
	Root		0.639	0.172	4	0.632	0.253	3
Average root diameter			0.509	0.302	4	0.848	0.070	3
Root orders	1		–0.884	0.019	4	–0.882	0.048	3
	2		–0.868	0.025	4	–0.942	0.017	3
	3		0.158	0.765	4	0.154	0.805	3
	4		0.872	0.023	4	0.952	0.012	3
Shape area	Root		0.829	0.041	4	0.891	0.042	3
	Crown		0.561	0.247	4	0.639	0.246	3
Circularity	Root		0.219	0.677	4	0.215	0.728	3
	Crown		0.637	0.174	4	0.655	0.230	3

Table 4. Partial correlations of the treatment (control: 0; fertirrigation: 1) with the trees' parameters, not controlling ("none" column) and controlling for the effect of tree total volume (representing tree size).

Controlling variable Parameters			None			Treatment (0.1)		
			Pearson correl.	Sig. (2-tailed)	Df	Pearson correl.	Sig. (2-tailed)	Df
Treatment			1		0	1		0
	Total		0.131	0.805	4			
	Aerial part	Trunk	0.285	0.584	4	0.934	0.020	3
		Branches	0.221	0.674	4	0.385	0.523	3
		Crown	0.264	0.613	4	0.762	0.134	3
	Root system	Collar root	0.049	0.927	4	–0.337	0.580	3
		Roots	–0.134	0.800	4	–0.754	0.141	3
		Total	–0.09	0.865	4	–0.762	0.134	3
	Root/shoot		–0.656	0.157	4	–0.66	0.226	3
Surface	Crown		0.203	0.700	4	0.357	0.555	3
	Root		–0.054	0.919	4	–0.223	0.719	3
Lenght	Crown		0.126	0.812	4	0.013	0.984	3
	Root		0.158	0.764	4	0.098	0.876	3
Average root diameter			–0.699	0.122	4	–0.898	0.039	3
Root orders	1		–0.12	0.821	4	–0.008	0.989	3
	2		–0.515	0.296	4	–0.815	0.093	3
	3		0.04	0.940	4	0.02	0.975	3
	4		0.525	0.285	4	0.847	0.070	3
Shape area	Root		–0.231	0.659	4	–0.614	0.271	3
	Crown		–0.312	0.547	4	–0.47	0.425	3
Circularity	Root		0.043	0.935	4	0.015	0.981	3
	Crown		–0.083	0.876	4	–0.217	0.726	3

tion counterparts. In Group 2, the difference was smaller but still significant, with rainfed trees having thicker roots than fertigation trees. The smallest difference in root thickness was observed in Group 3, where the roots of rainfed and fertigation trees were more similar in size. It is noteworthy that rainfed trees maintain a consistent average root diameter regardless of their size. In contrast, the average root diameter of fertigation trees increases with size, reaching values comparable to those of rainfed trees only in the largest tree.

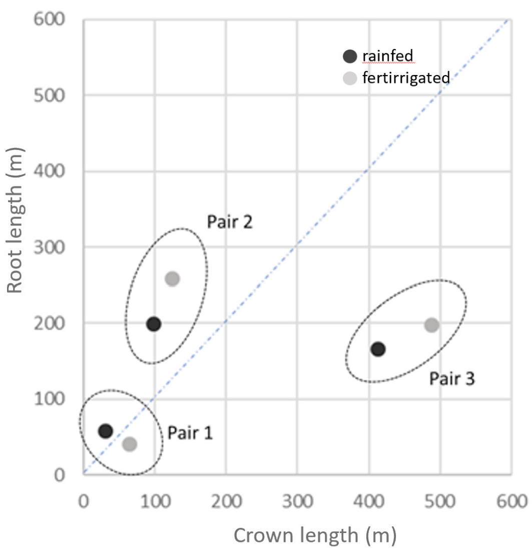

Fig. 4. Root length by crown length of the rainfed and fertigation excavated cork oak trees.

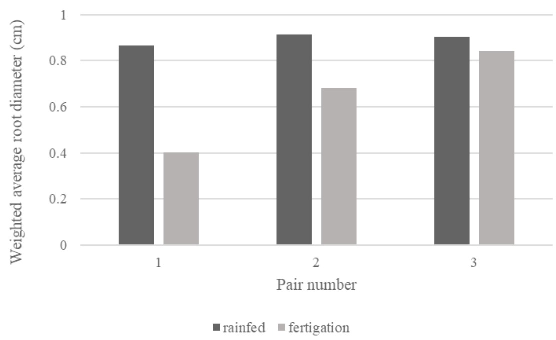

Fig. 5. Average root diameter of rainfed and fertigation roots in cork oak.

3.5. Comparison of the area explored by the root and crown systems

The difference between rainfed roots and fertigation roots was most pronounced in pair 2 (Fig. 6). The most significant difference in crown area between fertigation and rainfed trees was observed in pair 3, the largest pair. For the remaining two pairs, the difference in canopy area between fertigation and rainfed trees was minimal. The shape of the area for each tree is shown in Supplementary material.

The right graph displays the root area (m^3) for the same three pairs of samples. Both graphs illustrate the effect of fertilization on vegetative growth. Comparison of the order of branches and roots in cork oak.

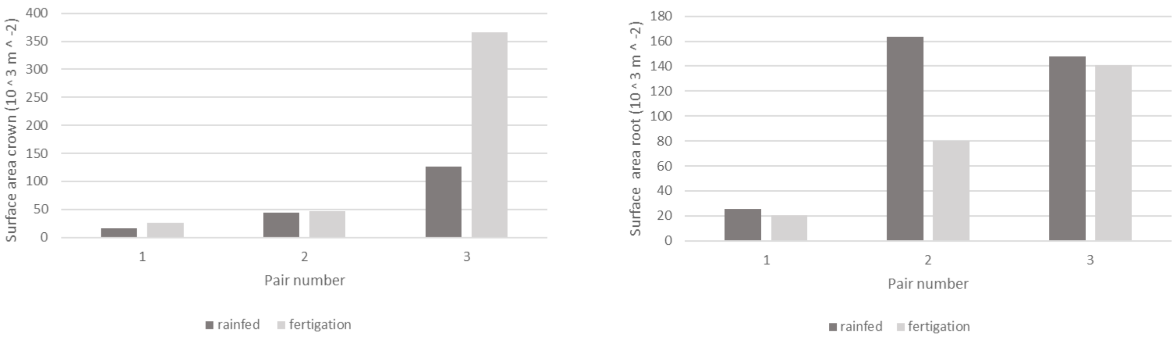

Fig. 6. The left graph shows the crown area (m²) for three pairs of samples (1, 2, 3), with the data divided into unfertilized (dark gray) and fertilized (light gray) samples.

While branches were categorized into up to three orders, root orders extended up to the ninth order. First-order roots were predominant in the smallest trees (pair 1) and in the control tree from pair 2. The largest tree exhibited a co-dominance of third- and fourth-order roots, while third-order roots were dominant in the remaining two trees (Fig. 7).

3.6. Circularity of crown and root

The roots are typically less circular in shape compared to tree crowns. There are no significant differences in crown circularity among all the trees. However, the largest trees (pair 3) exhibited greater root circularity than the other pairs (Fig. 8). The most pronounced difference in circularity is observed between pairs 1 and 2, where the discrepancy between roots and crowns is greatest. In contrast, pair 3 shows less difference in circularity. Therefore, the pair with the highest root circularity is pair 3.

4. Discussion

4.1. Fastrak Polhemus system – experience and prospect

The findings of this study underscore the significant role of water availability in Mediterranean ecosystems, were seasonal droughts limit tree growth and regeneration. Young cork oak trees in our experimental plot showed increased radial growth in response to summer fertigation, aligning with previous research (Dinis et al. 2015a). In contrast, the control tree, which did not receive fertigation, invested more in root development relative to crown growth, demonstrating a typical drought-avoidance strategy, as documented by Otieno et al. (2006) and Nardini et al. (1999). This finding also agrees with Chirino et al. (2008) and Tsakaldimi et al. (2005), who emphasized that young cork oak saplings prioritize deep root development to survive in water-scarce environments.

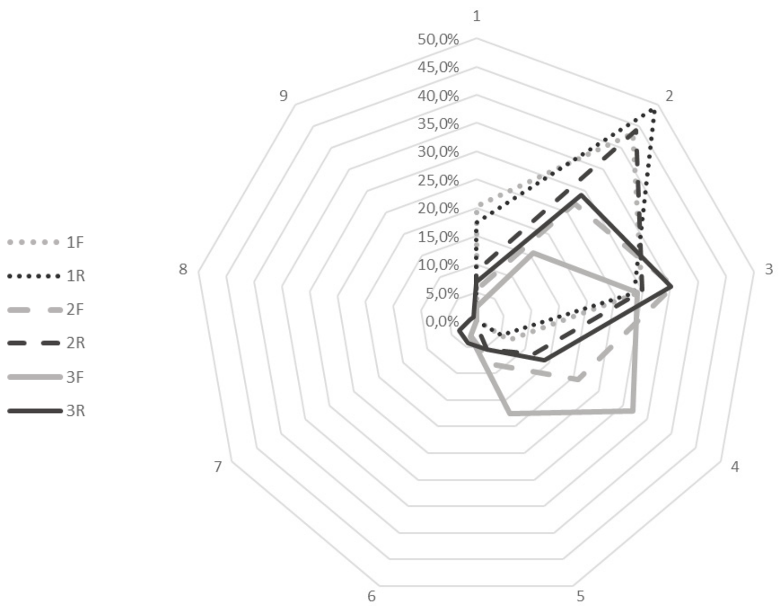

Fig. 7. Relative proportion of root orders by tree. F: Fertigation; R: Rainfed per tree in cork oaks.

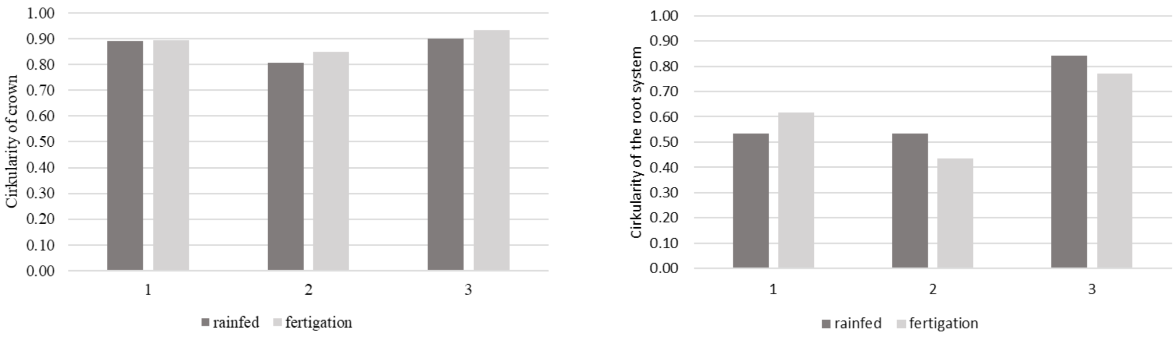

Fig. 8. Both graphs demonstrate the effect of fertilization on the circularity of both crowns and root systems in cork oak. The right graph displays the circularity of the root system for the same three pairs of samples. The left graph illustrates the circularity of the crown for three pairs of samples.

Moreover, our results suggest that water availability has a pronounced impact on the structure of trees during early developmental stages. The smallest control tree, subjected to drought conditions, exhibited a disproportionate investment in its root system. This is consistent with research by Zhou et al. (2019) and Lozano et al. (2020), who noted that drought often leads to thicker root systems to improve water absorption. Conversely, the fertigation tree in the same pair showed a larger crown relative to its root system, indicating that fertigation can alleviate water stress, allowing trees to allocate more resources to crown growth.

In contrast to our results, Morillas et al. (2023) found that seedlings exposed to high water availability developed thicker roots, correlating with improved drought survival. This suggests that various factors, such as tree age or environmental conditions, may influence root development. As for the larger trees (pairs 2 and 3), their root systems were more proportional to their crowns, implying that over time, the structural differences observed in younger trees may diminish as they grow.

The crown-to-root ratios observed in our study, along with the overall explored root area, support the notion that early investment in the root system is essential for long-term tree development. As trees mature, this initial investment in roots is balanced by further crown expansion, as indicated in Figures 4 and 6.

4.2. Fertigation effect on cork oak

The diachronic analysis reveals that climate change is contributing to increased cork oak mortality rates. Without incorporating a synchronic analysis, it would be challenging to fully understand these mortality patterns and adapt management strategies accordingly. Our findings of higher mortality in agrarian-road-pastoral systems suggest that improper land-use practices could be exacerbating the impact of environmental stressors. To mitigate this, a minimum tree cover of 35–40% is recommended to enhance ecosystem resilience (Ribeiro et al. 2024).

Water availability remains a key factor for cork oak survival, as shown by the species' reliance on groundwater during summer droughts (Otieno et al. 2006; David et al. 2007; Dinis 2014). Deep root systems are an essential drought-avoidance strategy for cork oak saplings (Chirino et al. 2008), a pattern clearly observed in our smallest control tree. This behavior aligns with previous research that highlights the critical role of early root development in ensuring survival under limited water conditions (Tsakaldimi et al. 2005).

The factor most closely correlated with our treatments was average root diameter. Under drought conditions, previous studies on herbaceous species have reported increased root diameters to reduce hydraulic failure risk and improve nutrient uptake (Zhou et al. 2018; Lozano et al. 2020). Our findings support these observations, as control trees showed greater root thickness compared to their fertigation counterparts. Interestingly, Morillas et al. (2023) observed that high water availability led to larger root diameters, which may suggest that thicker roots are not exclusively a drought response but also a sign of overall root system health.

Trunk volume was the only component directly correlated with the treatments. While crown and root development follow seasonal patterns, radial growth depends more heavily on meteorological conditions, with fertigation producing significant increases in growth (Camilo-Alves et al. 2022). Our results also indicate that the root area explored is linked to tree size, with larger trees accessing more soil and water. The long roots observed in the control tree from pair 2 are likely a response to the need to search for water in deeper soil layers. Despite this tree having a shorter total root length compared to its fertigation counterpart, its root architecture supports these results (Supplementary material). Root circularity was not significantly affected by the treatments, consistent with previous studies conducted on the same experimental plot (Dinis et al. 2018).

Root circularity nearly achieved in larger trees suggests that as roots mature, they expand in all directions. However, no clear trend indicated fertigation reduced root circularity, reinforcing the idea that cork oaks can adapt to their environment without dependence on localized water sources like those created by irrigation drips.

Lastly, soil density also plays a critical role in shaping root architecture. As observed in Portuguese cork oak studies, soil compaction negatively affects tap root length (Dinis et al. 2015b). In our study, compacted soil likely contributed to the observed root expansion in control trees, where limited access to water and nutrients forced the plants to prioritize root growth.

5. Conclusions

Rainfed trees exhibited a dominance of the root system, especially in the smallest trees. However, this effect was less pronounced in fertigation trees, resulting in a more balanced crown-to-root volume ratio. In terms of root and branch length, the smallest trees focused more on root system development, while larger trees allocated more resources to branch growth. This pattern appears to be more correlated with tree size than with treatments. Irrigation had a stronger influence on trunk volume, whereas control trees displayed larger root diameters.

The structural development of trees was more closely correlated with tree size than with fertigation treatments. Irrigation seems to influence tree structure primarily in smaller trees, suggesting that as trees grow larger – assuming tree size serves as a proxy for age – they may develop root systems that are less dependent on external water sources. This indicates that fertigation systems could potentially be phased out once trees reach a certain size without negatively impacting their vitality. This observation aligns with the findings of Camilo-Alves et al. (2022), which showed that the cessation of fertigation in 15-year-old irrigated cork oak did not lead to a reduction in tree vitality. This study represents an initial step toward understanding the long-term effects of water availability on the development of cork oak under natural conditions, with important implications for their management and use in forestry.

The method used for data collection in this study is unique in its ability to measure very small and overlapping parts. It has proven to be particularly effective for root measurements, mainly due to its capability to measure even when roots and soil have similar colors. The Polhemus Fastrak magnetic digitizer provides high-quality 3D models that can be used in further research.

Due to the labor-intensive process of excavating the root system, only six trees were analyzed in this study. Further research is recommended to explore the relationships between irrigation type, soil compaction, and root structure in different tree sizes. Such research could provide valuable insights for optimizing irrigation strategies and better understanding tree growth in various environments.

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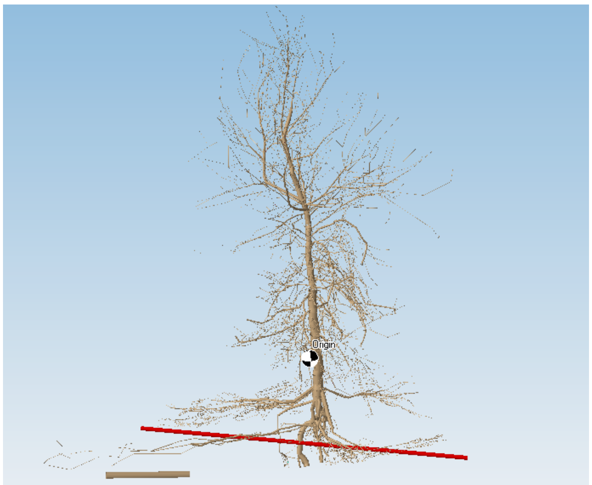
Supplementary material

3D model of 3F



3D model of 3R

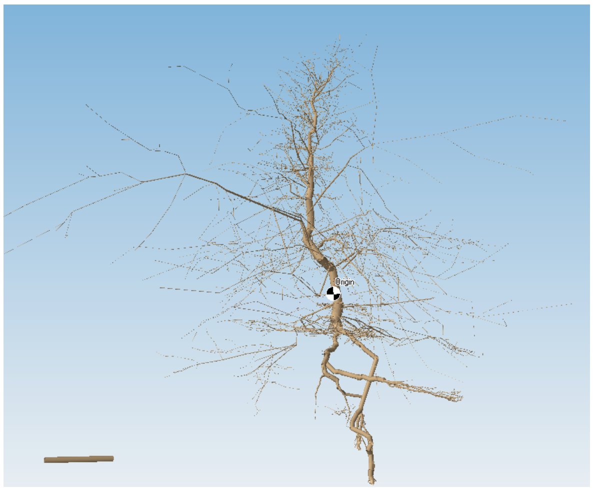
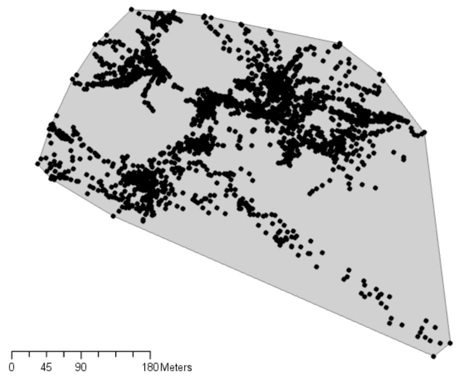


Fig. S1. A 3D model of the largest examined pair. The red line represents the tube. The brown line represents a scale of 1 m.

Roots of 3F



Roots of 3R

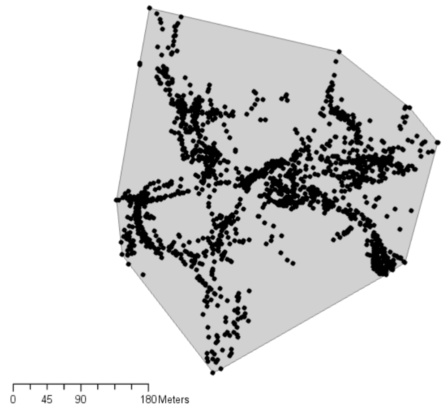
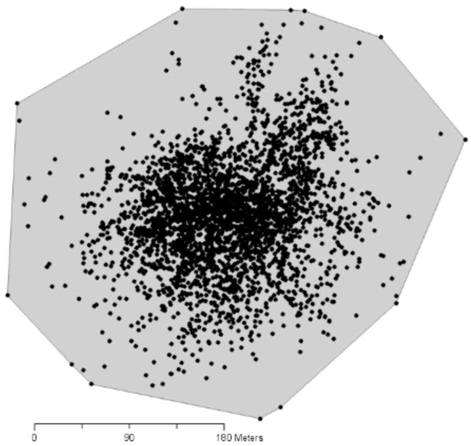


Fig. S2. The area occupied by the root system of cork oak under fertilization and rainfed. The black dots represent the coordinates of the measured points, while the gray area illustrates the covered space.

Crown of 3F



Crown of 3R

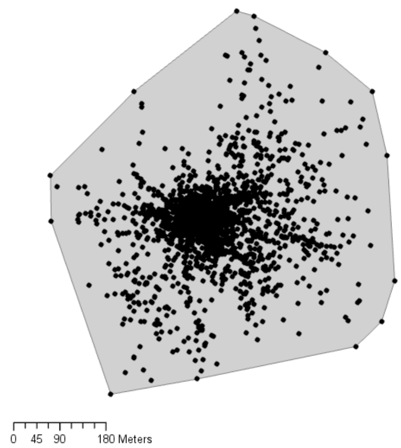


Fig. S3. The area occupied by the crown of cork oak under fertilization and rainfed. The black dots represent the coordinates of the measured points, while the gray area illustrates the covered space.