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Impacts of *Quercus suber* irrigation on improving floristic diversity and soil quality in 10-year-old stands

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Abstract We analyzed the dynamics of floristic diversity and soil characteristics in a 10-year-old fertirrigated cork oak (*Quercus suber*) stand, a species of high ecological, social, and economic importance in the Mediterranean region. Given the decline of cork oak in recent decades, long-term research on newly established stands using fertirrigation was initiated to accelerate tree growth until productive maturity. The study was conducted over a 6-ha area, subjected to various fertirrigation treatments. Across the study site, 4 × 8 m sample plots were established under three canopy cover classes. The aim of this study was to assess soil recovery and floristic composition in relation to canopy cover. Soil recovery was evaluated by comparing the current chemical composition with the initial soil status. For floristic composition, the Zürich-Montpellier School method was applied within each sample plot. Conservation status was assessed by the quality and quantity of plant bioindicators. Hierarchical Cluster Analysis and Principal Component Analysis were used to determine the degree of similarity between plant communities. The main results indicated an overall soil recovery that was not associated with canopy cover. In contrast, the diversity and quality of floristic composition differed significantly in areas with higher canopy cover compared to more open areas, though plant diversity was lower under dense canopies. These findings suggest that irrigating cork oaks accelerates ecological recovery, facilitating the establishment of new forest ecosystems in a shorter time frame. The most positive impacts were observed in the improvement of floristic composition and a reduced need for heliophilous shrub control.

Keywords Plant bioindicator · Mediterranean forest · Cork oak · Soil recovery · Cork oak irrigation · Ecological succession

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Introduction

The cork oak (*Quercus suber* L.) is a natural evergreen oak native to the western Mediterranean basin, known for its ability to regenerate its outer bark after extraction (cork). Cork stripping is allowed by law when the trunk perimeter at 1.30 m height reaches 70 cm. Afterwards, cork can be stripped every nine years, independently of the tree size (Article 13 of Decree-Law no. 169/2001).

Despite Portugal hosting the largest area of cork oak forests in the world, a widespread decline of these trees has been occurring in their range area (Ribeiro and Surovy 2008), combined with a reduced natural regeneration (Pons and Pausas 2006; Simões et al. 2016; Mechergui et al. 2023). Several factors have been linked to cork oak decline, most notably root disease caused by *Phytophthora cinnamomi* Rands, prolonged drought events, soil limitations on root development, and improper management practices (Ferreira et al. 1992; Moreira and Martins 2005; Ribeiro and Surový 2008; Dinis et al. 2015). Thus, beyond biotic and edaphoclimatic influences, anthropogenic factors manifested through management practices also contribute to tree decline. Examples include soil disturbance for pasture sowing and/or shrub control, as well as maintaining high cattle densities on plots, which hinder natural regeneration and compromise tree vitality, as has been demonstrated in previous studies (Dinis et al. 2015; Godinho et al. 2016; Listopad et al. 2018; Camilo-Alves et al. 2020). To improve the success of establishment and accelerate cork oaks growth, fertirrigation has been tested in long-term scientific experimental plots (Camilo-Alves et al. 2020, 2022). The research aims to find efficient fertirrigation to reduce the time until cork stripping while advancing the fundamental understanding of how water availability influences the structural and physiological responses of trees. This understanding is crucial, as fertirrigation will be discontinued once productivity is achieved, requiring cork oaks to adapt to the subsequent rainfed conditions. In addition to research conducted at the tree level, ecological processes at the stand level should also be assessed. The anticipated acceleration of cork oak growth due to fertirrigation may enhance the forests' ecosystem functions and, consequently, the services they provide. This rapid development of forest environments, characterized by dense canopies, is expected to facilitate the recovery of both biotic and abiotic soil properties, promote ecological succession within the understory, and contribute to carbon sequestration. Aspects of the ecological importance of the rainfed cork oak system have already been assessed in several studies (e.g., Dubbert et al. 2014; Rives et al. 2012). In general, Mediterranean forests are characterized by high floristic diversity at both shrub and herbaceous levels (Cowling et al. 1996; Quinto-Canas et al. 2021), where plants can be used as bioindicators to assess conservation status and the dynamics of ecological succession (Raposo et al. 2020). For example, lianas are indicators of good conservation status in Mediterranean forests and provide insights into bioclimatic zones and soil qualities (Pinto-Gomes and Paiva-Ferreira 2005; Rivas-Martínez 2005). Therefore, monitoring the ecological status of forest stands using practical tools, such as plant bioindicators, is becoming increasingly important for interpreting environmental properties (Burger 2006; Parmar et al. 2016; Cano-Ortiz et al. 2021; Terwayet Bayouli et al. 2021; Mishra and Farooq 2022). The presence of plants that signal specific climatic, soil, or geographic characteristics allows for the evaluation of an area's ecological state, providing insights into its conservation status and successional dynamics. This tool is effective due to the strong ecological fidelity of plants (Wang et al. 2023). As a result, the higher the degree of endemism, the greater the plant's value as a bioindicator.

Therefore, the main objectives of this study are to identify the influence of cork oak canopy coverage on the soil recovery and understory floristic diversity in a fertirrigated stand. Additionally, the study aims to identify key plant bioindicators associated with advanced conservation states and the dynamics of ecological succession. In this way, we seek to understand the real impacts of the enhancement in cork oak growth by means of fertirrigation on ecological improvement and stand quality during the early establishment phase. This information is particularly relevant for the recovery of degraded areas with low ecological resilience, also contributing to enhanced carbon sequestration.

Methodology

Study area

The study area is located in the parish of Santana do Mato, in the municipality of Coruche, within the

Ribatejo region (Portugal), which is traditionally known for cork production. The substrate is predominantly sandy soils, with sandstone layers occasionally found at depth, dating back to the Miopliocene geological period (Rodríguez Fernández et al. 2019). These soils are highly permeable sedimentary sands, tend to have an acidic pH, and contain a low percentage of organic matter. According to the most recent climate normal (1981–2010), the average annual precipitation was 600.7 mm, and the average annual temperature was 16.2 °C. (I.P.M.A. 2023). Bioclimatically, the area is classified as oceanic, thermomediterranean, sub-humid, and semi-hyperoceanic (Rivas-Martínez et al. 2017).

The potential natural vegetation consists of climatophilous and edafoxerophilous cork oak series (*Aro neglecti-Querco suberis Sigmetum*) (Costa et al. 2012). However, human activities over the years have created clearings, transforming the pristine forests into areas for hunting (heaths) and pastoralism (montado), often accompanied by secondary forests of stone pine (*Pinus pinea* L.). Today, heliophilous shrubs and degraded soils dominate the successional stages, including species such as *Ulex australis* subsp. *welwitschianus*, *Stauracanthus genistoides*, and sargasais with *Halimium halimifolium* (L.) Willk., *H. calycinum* (L.) K.Koch, *Cistus salviifolius* L., and *Lavandula sampaioana* subsp. *lusitanica* (Chatyor) Rivas Mart., T.E. Díaz and Fern. Gonz., among others. In areas with some soil improvement, heathers like *Erica scoparia* L. and *Erica lusitanica* Rudolphi can be found, bordering willow stands such as *Frangulo baeticae-Salicetum atrocinereae* (Raposo et al. 2016).

Historically, land use in the study area was focused on annual crops such as tomatoes, forage, and corn, which were eventually abandoned. The Regasuber experimental plot was established in 2014, covering an area of approximately 6 hectares on a slope with a gradient of approximately 5%, facing north (Fig. 1). As part of the preparatory work, the land was plowed and scarified to remove competing flora. Cork oak seedlings were planted in a perfect square spacing of 4×4 m. The Regasuber plot has been regularly irrigated since planting to promote tree establishment and growth. A detailed characterization of the experimental plot is available in Camilo-Alves et al. (2020). In short, the subsurface drip fertirrigation system consists of irrigation tubes equipped with 1.6 L/h drippers spaced 1 m apart, buried at a depth of 40 cm, and positioned 60 cm east of the planting lines. Each year, the fertirrigation period takes place during the summer drought. Several irrigation volumes have been tested over time, but fertilization has been kept constant throughout the irrigation treatments. Herbaceous and shrub control was carried out annually

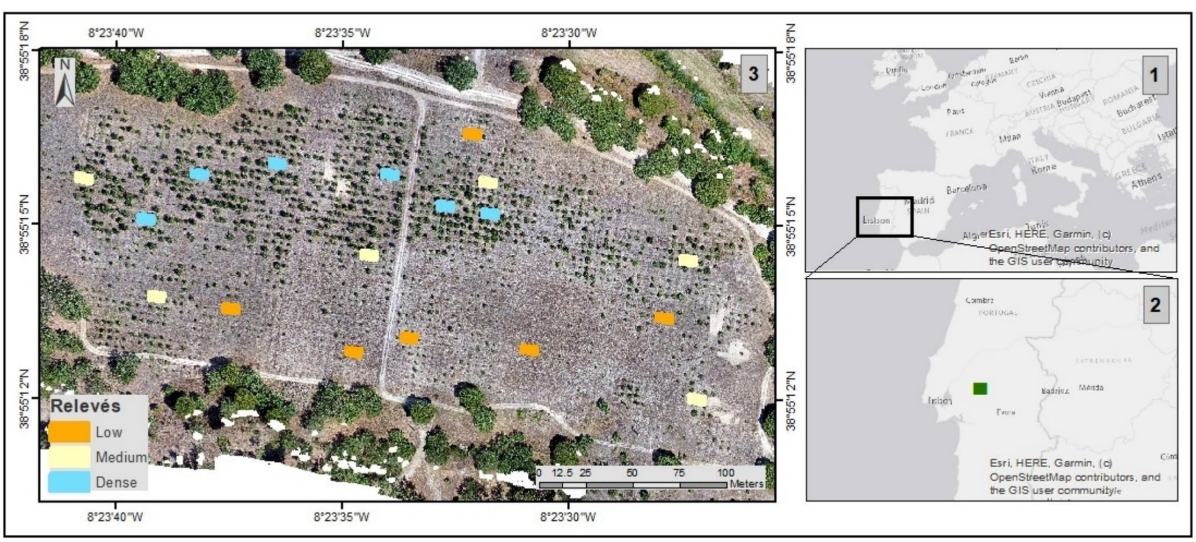

Fig. 1 Location of the study area and respective sampling points. 1- Southwest Europe; 2—Center of Portugal; 3—Study area (original images collected by drone)

during the first years after planting. It has not been performed for the past five years prior to this study.

Data collection and analysis

Due to mortality events caused by animals or differences in plant growth, resulting from endogenous factors or local variations in resource availability, variations in canopy cover were observed throughout the plot. Based on this heterogeneity, three categories of tree canopy coverage were randomly inventoried with six replicates for each one (Table 1). Tree canopy coverage was obtained throught UAV aerial images of the plot and measured using ArcGIS. Sample areas with 4×8 m were selected after categorizing the canopy cover. Irrigation volume from 2014 to 2023 ranged from 7459 to 32,358 L across the sample areas. The 12-6-6 NPK fertilization corresponded to a total of 1.76 kg of nitrogen by sample area, with no variation across the treatments. A floristic survey was performed within each sample area.

Before planting, soil profile evaluation was carried out in 2014 at eight random locations, down to 2 m. In 2024, a composite sample was obtained in each sample area within the soil's first 3–30 cm, after removing the litter. The 18 composite soil samples were analyzed by the official laboratory of the University of Évora, AmbiTerra, to determine pH, organic matter content, nitrogen, potassium, phosphorus, magnesium, and carbon levels. Since the soil sample collection points differed between 2014 and 2024, the results were compared by taking into account the average values of the 2014 soil samples. Univariate analysis of variance was performed to infer soil chemical differences across the three canopy cover classes, with total irrigation by sample area as a co-variable.

To identify the flora, the main reference floras from Portugal, Spain, and the Iberian Peninsula were used (Coutinho 1939; Franco 1971, 1984; Castroviejo 1986; Valdés et al. 1987; Franco and Rocha-Afonso 1994; Blanca et al. 2009). The syntaxonomic nomenclature followed the work of Costa et al. (2012) and was complemented by Rivas-Martínez et al. (2002), Rivas-Martínez (2011). Data collection in the field was conducted using the Zürich-Montpellier School method proposed by Braun-Blanquet and Pavillard (1928), followed by Tüxen (1937), Géhu and Rivas-Martínez (1981), Rivas-Martínez (2005), and updated by Biondi (2011).

Results were subjected to hierarchical cluster analysis using Ward's method with Euclidean distance to measure dissimilarity, performed using SPSS software (Rodríguez-Guitián et al. 2007). The transformation of coverage-abundance values followed Van der Maarel (1979). Principal Component Analysis (PCA) was performed for dimensionality reduction. The analysis was based on the correlation matrix, using the Kaiser criterion for component retention. Components explaining more than 10% of the total variance were extracted.

Table 1 Classes of *Q. suber* canopy cover used in the sample areas in the Regasuber experimental plots

Densitie	Coverage intervals (%)	Avarege coverage (%)
Low	0–10	3.40
Intermediate	11–39	20.85
Dense	40–65	49.88

Results and discussion

Evolution of soil characteristics

Soil was characterized as unstructured with sandy texture, loose tenacity and friability, non-stickiness, no plasticity and minimal compaction. More than 75% of the particles were classified 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 was reached (C horizon). Within the sandy soil of the plot, the wet bulb extends to a diameter of only 60 cm.

Analyses conducted on the soil in 2024 revealed significant increases, particularly in nitrogen and magnesium content, but also in organic matter (Fig. 2). No differences were observed across varying classes of canopy cover, nor in relation to variations in irrigation volumes. It should be stressed that fertilization was similar in all the sample areas. In the initial phase, the soil was observed to be poorer in nutrients, with a slightly acidic pH. Potassium was the only element to show elevated values in some samples; though it exhibited considerable variability

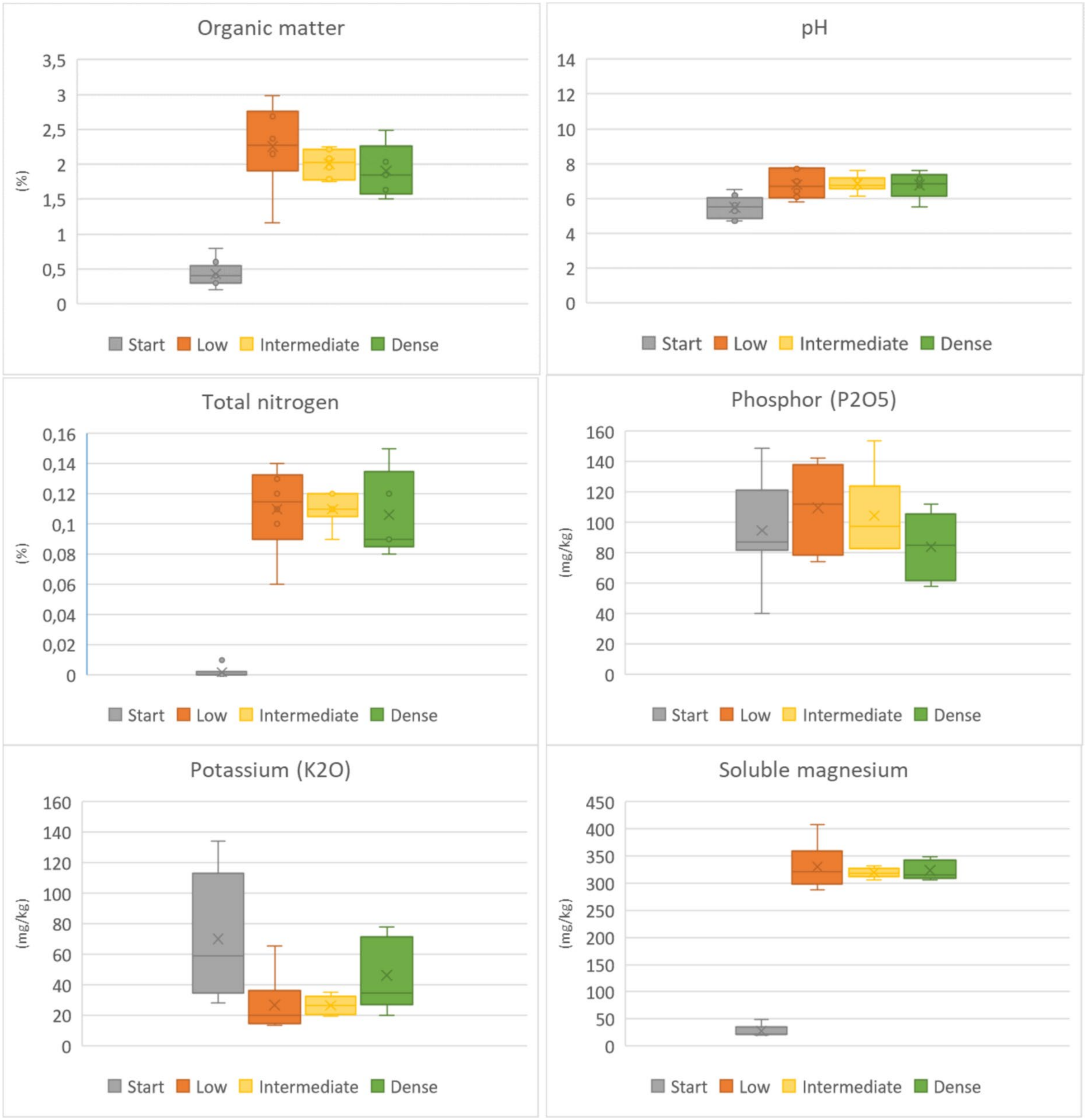

Fig. 2 Results of soil analyzes for pH, organic matter, nitrogen, potassium, phosphorus and magnesium. Start (year 2014); by canopy coverage classes (year 2024)

across the profiles. Over the past 10 years, there has been a general improvement in the soil's chemical composition, which is favourable to more demanding species in the course of ecological succession. This improvement is likely related to reduced soil disturbance (Karlen et al. 1994). This should be considered an investment in assessing environmental quality and supporting ecosystem services (Rodrigues et al. 2023).

It is also important to note that soil conservation fosters greater intraspecific relationships, allowing symbiotic, mutualistic, and commensal organisms to enhance forest development. An example of this is mycorrhizal fungi, which improve the resilience of species to disturbances such as water stress (Gosling et al. 2006; Bonfante and Anca 2009; Willis et al. 2012).

Analysis of identified taxa

Vegetation cover was nonexistent in the first year due to land preparation. Ten years after the establishment of the *Q. suber* population, 95 floristic taxa were identified in the 18 sampling areas, covering a total of 576 m^2. The most represented biological type was therophytes, indicating an early stage of ecological succession across all canopy coverage (Fig. 3). However, in areas with greater canopy cover, a notable increase in hemicryptophytes and phanerophytes was observed, likely due to the protection provided by the tree canopy and the resulting higher humidity beneath it, which facilitated the establishment of more ecologically demanding plants.

Botanically, there is a notable presence of plants from the *Asteraceae*, *Fabaceae*, and *Poaceae* families, which account for approximately 56% of the total number of species inventoried (Fig. 4).

The best-represented phytosociological class was *Stellarietea mediae*, followed by *Tuberarietea guttatae*, totaling 52 species (Fig. 5). Both classes consist of therophytes that occur in pioneering ecological situations. However, the Stellarietea mediae class comprises nitrophilic or semi-nitrophilic vegetation found on substrates rich in nitrogenous matter, often occupying disturbed soils in urban and agricultural areas, including path edges and roadsides. The high number of species in this class in areas with greater coverage is associated with greater vegetation growth, which promotes the accumulation of nitrates on the soil surface (plant detritus, comprising leaves, twigs, and other organic matter). The *Tuberarietea guttatae* class is composed of pioneer plants that grow in spring and early summer, exhibiting xerophytic characteristics, small size, and indifference to the chemical composition of the substrate. Typically, these communities occupy biotopes poor in non-humified organic matter (Rivas-Martínez et al. 2002; Costa et al. 2012). Overall, an ecological improvement in the system was identified with the increase in cork

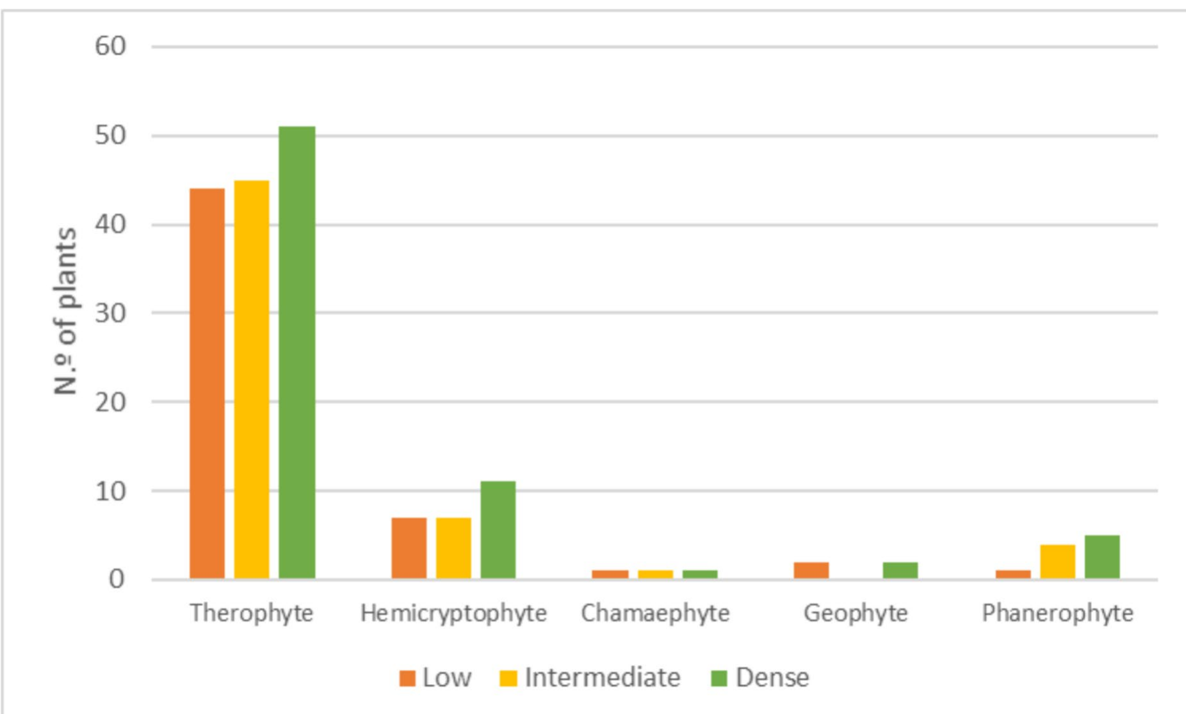

Fig. 3 Biological types for each tree canopy coverage class in the Regasuper experimental plot, Coruche, Portugal

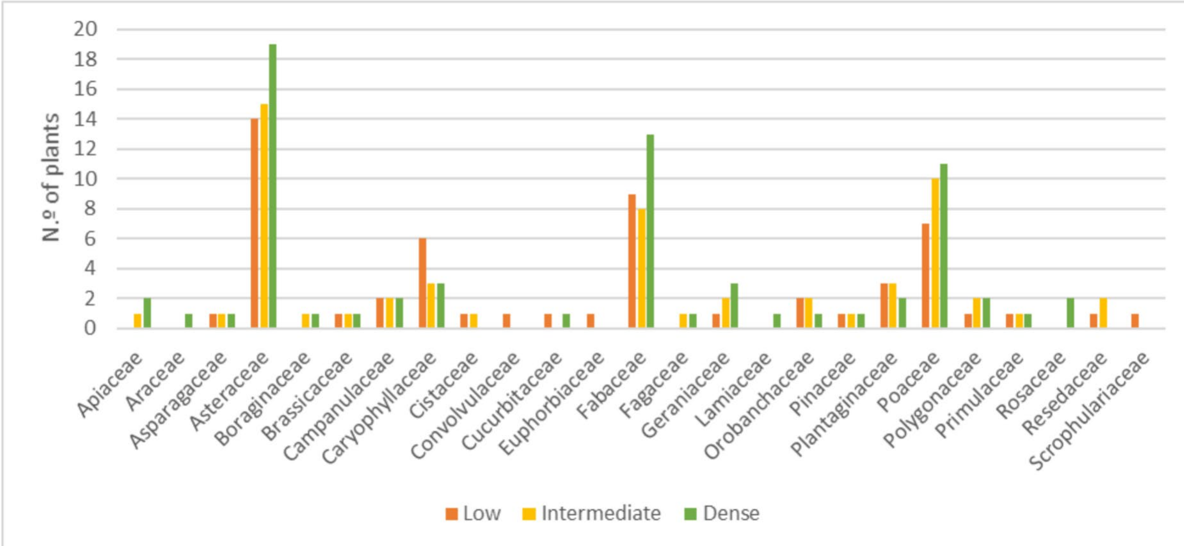

Fig. 4 Species diversity at family level by type of tree canopy coverage class in the Regasuper experimental plot, Coruche, Portugal

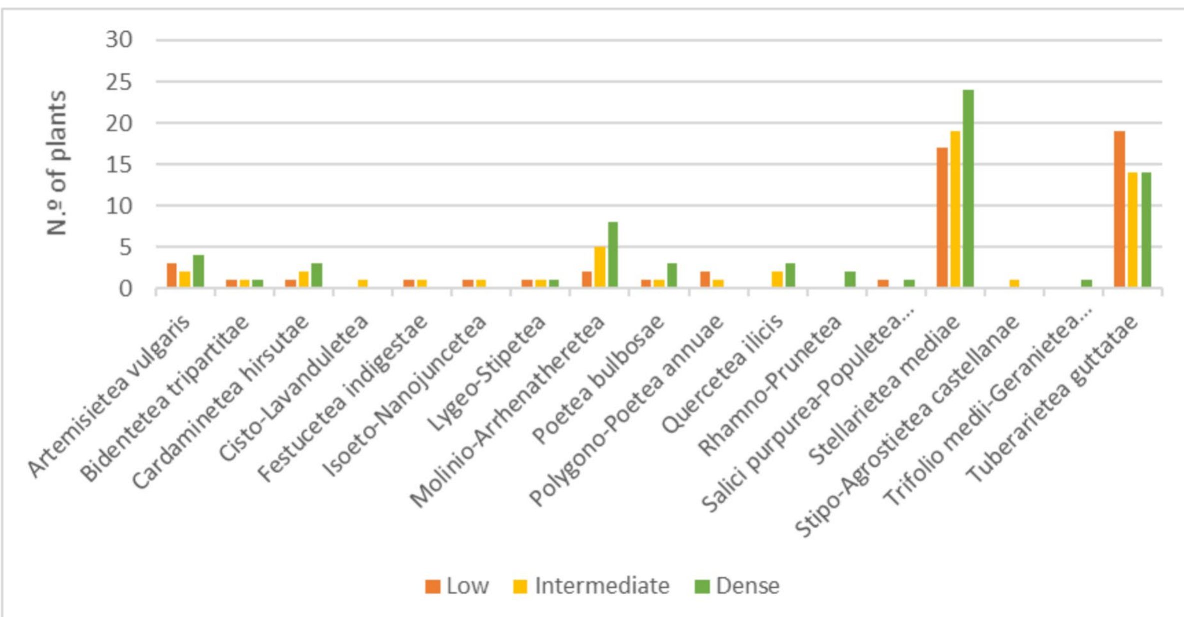

Fig. 5 Distribution of species at the level of phytosociological class and by type of tree canopy coverage class in the Regasuper experimental plot, Coruche, Portugal

oak canopy coverage, which resulted in a reduction of pioneer and annual plants and an increase in perennial herbaceous species. Classes such as *Molinio-Arrhenatheretea, Poetea bulbosae, Rhamno-Prunetea,* and *Quercetea ilicis* showed an increase in the number of species, suggesting an improvement in soil characteristics.

Statistical analysis of plant communities

The similarity analysis clearly distinguished the inventories conducted in areas with greater shade from those carried out under intermediate and lower-density canopies (Fig. 6). The inventories performed in areas with low and intermediate tree cover exhibited some floristic proximity, as they are both in ecological progression and share the common factor of solar radiation, although this is less pronounced in areas with intermediate canopy. Therefore, factors such as tree canopy growth appear to be decisive in altering the floristic composition beneath cork oak cover. It is important to note that, since soil parameters did not vary across sample areas, variations in floristic composition are mainly due to the tree canopy coverage. Additionally, the similarity analysis did not differentiate the

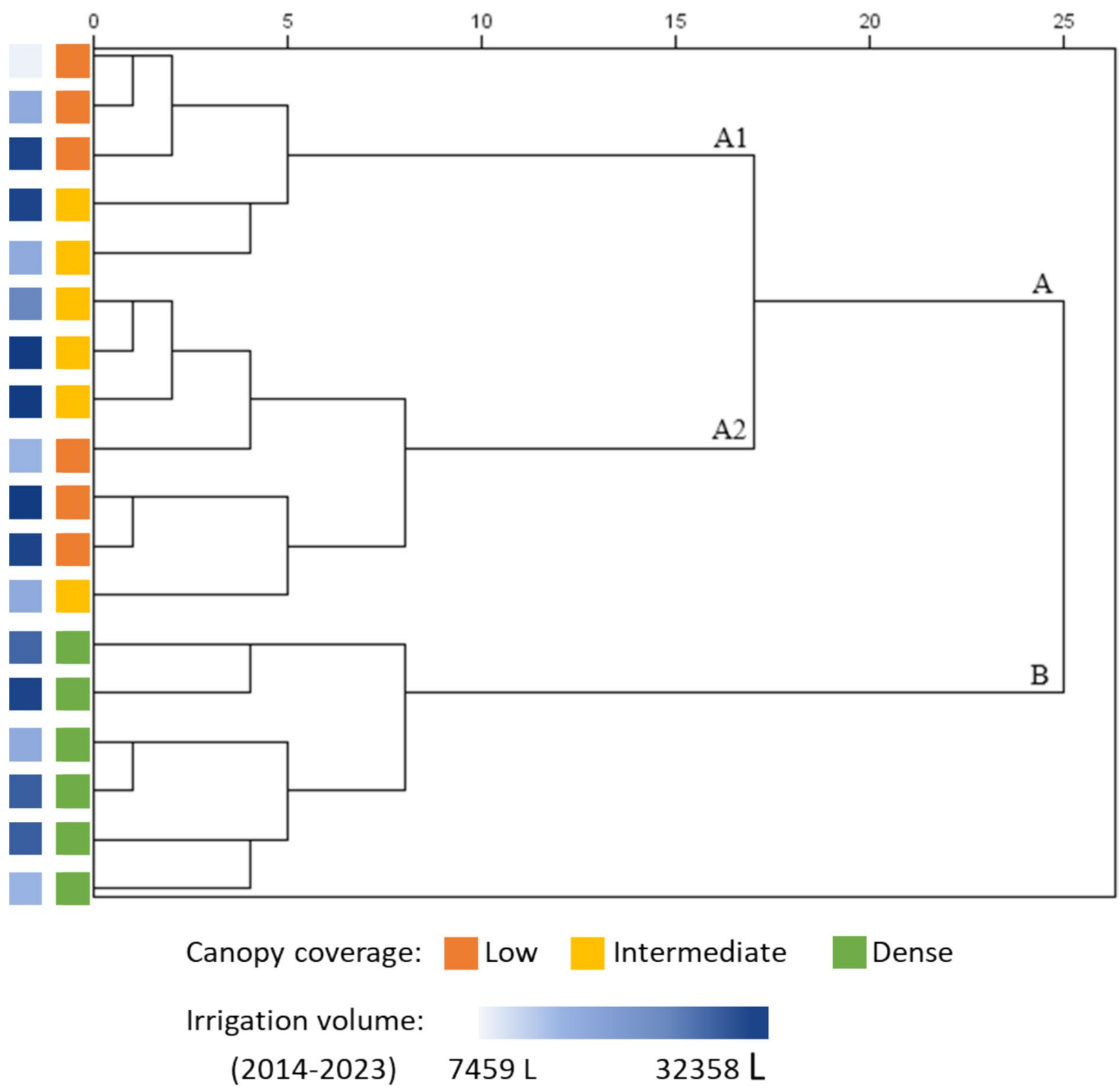

Fig. 6 Dendrogram of plant communities. Group A: 12 sample areas with Low and intermediate canopy coverage classes; Group B: the 6 sample areas with High canopy coverage classes

inventories based on irrigation volumes (Fig. 6). The water available to plants is not solely determined by irrigation volume but also by the soil's water-holding capacity, which plays a critical role. Consequently, cork oak growth across the Regasuber plot exhibits considerable variability, even under identical irrigation treatments (Camilo-Alves et al. 2020).

It is noteworthy that the subsurface irrigation system, applied in sandy soil conditions, generates wet bulbs situated below 40 cm and limited to a width of 60 cm. As a result, water is only accessible to plants with roots positioned above 40 cm and located within the vicinity of the irrigation lines. This restricted water availability accounts for the presence of species commonly associated with riparian zones, such as the class *Molinio-Arrhenatheretea*. However, these plant communities were observed exclusively along the irrigation lines, impacting only 15% of each sampled area.

Accordingly, the principal component analysis revealed a clear separation between the inventories conducted in areas with dense canopies and those in areas with less developed canopies (Fig. 7). In areas with dense canopies, plants at a more advanced stage of ecological succession were identified, as evidenced by the presence of species such as *Asparagus aphyllus, Arum neglectum, Crataegus monogyna* and *Rubus ulmifolius* (group A). The presence of these species reflects the closure of the tree canopy and the creation of a well-developed forest environment, albeit still with a low percentage of coverage. In areas with less developed canopies, species with greater pioneering and heliophilous characteristics were identified (group B), including *Plantago coronopus, Spergularia purpurea, Cerastium brachypetalum, Evax carpetana, Loefelingia baetica* and *Tuberaria guttata*, which were absent in areas with dense canopies. Therefore, the presence of the aforementioned species can help identify

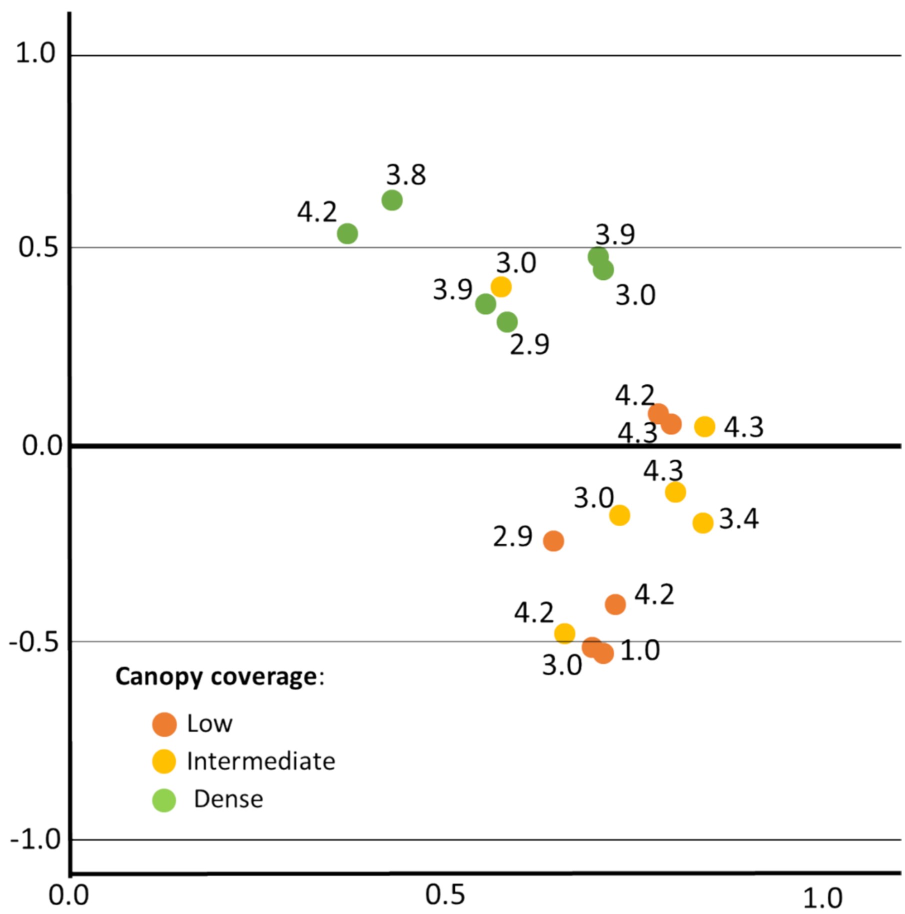

Fig. 7 Principal Component Analysis applied to floristic relevés of the sample plots, and the relationship with canopy coverage (color dots) and irrigation volume (numbering, in m3)

systems at an early stage of ecological succession or even those that are degraded. Inventories conducted in areas with intermediate tree cover showed greater variation in pioneer plants and forest environments, likely due to the penetration of sunlight through the tree canopy, which still allows some pioneer species to survive, resulting in a floristic composition similar to heliophilous situations with poorly developed crowns.

As water is a driving factor of life, but is scarce in many parts of the world, it must be used rationally to benefit system recovery without compromising future uses. The implementation of irrigation in Mediterranean forest stands is infrequent, primarily due to economic costs and water availability. However, at an early stage of establishment, irrigation not only enhances the success of plant installation but also contributes to the recovery and increase of forest biodiversity. Although studies on the impact of irrigation on the biodiversity of forest stands are limited, our results align with other research that addresses irrigation in forest ecosystems, which generally reports benefits for local biodiversity and greater ecosystem resilience (Friedman et al. 1995; Lindberg et al. 2002; Hartmann et al. 2017). From an ecological perspective, irrigation of cork oaks is justified during the initial establishment phase until the stand reaches maturity. Once the reproduction cork goes into production, irrigation can be gradually reduced, allowing the system to continue evolving independently while maintaining its natural functions.

Although rainfed *Q. suber* has been extensively studied in various fields—such as the physical characteristics of cork, the chemical composition of leaves, and stand management techniques—there is still a need to better understand the species' minimum ecological requirements for natural regeneration (Faria et al. 1996; Lopes-Fernandes et al. 2024; Morillas et al. 2023; Mishra and Farooq 2022). Research indicates that shade, provided by the presence of shrubs (Vizinho et al. 2023), or by canopy coverage (Ribeiro et al. 2024), influences the establishment of new cork oak plants. In the initial growth phase, cork oak exhibits semi-sciophilous behavior, partially benefiting from shade (Ribeiro et al. 2024; Ritsche et al. 2021). Thus, promoting a balanced and biodiverse system appears to enhance the establishment and productivity of *Q. suber*.

Conclusions

The establishment of new *Q. suber* stands with irrigation appears to accelerate the ecological recovery of degraded areas, particularly in terms of the quality and coverage of the floristic composition. The factor that contributed most to the emergence of plants at more advanced stages of ecological succession was the tree canopy, which creates a cooler environment with reduced evapotranspiration. At the soil level, while a significant increase in surface organic matter, magnesium, and nitrogen over time, no differences were observed in relation to canopy coverage. This highlights the importance of adopting soil conservation strategies, as recovery can take several years once the soil is degraded.

Over a ten-year period, there was a substantial increase in floristic species, with 95 different taxa recorded in 576 square meters inventoried. The recovery of the study area aligns with the standards of the Mediterranean Basin, the world's second-largest biodiversity hotspot.

Irrigation in cork oak forests is applied during the early developmental stages of the trees to shorten the period required before the first cork harvest. Additionally, the rapid recovery of tree cover presents management benefits, as it limits the development of heliophilous species, thereby reducing the need for interventions to control shrub cover and minimizing fire risk.

It is also noteworthy that irrigation, in addition to improving plant survival in the early phase, enhances long-term carbon sequestration, generating more carbon credits of international interest.

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Author contributions M.R.: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Writing– original draft; M.M.: Data Curation, Resources, Visualization, Writing– review & editing; C.P.G.: Data Curation, Supervision, Validation and Writing – review & editing; A.P.: Data Curation, Investigation, Resources, Writing - review & editing; J.R.: Data Curation, Visualization, Writing - review & editing; J.A.N.: Data Curation, Solftware, Writing - review & editing; N.A.R.: Formal analysis, Resources, Supervision, Validation and Writing– review & editing; C.C.A.: Conceptualization, Data Curation, Formal analysis, Writing – original draft.

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Data availability The data used in this work were collected by the authors.

Declarations

Conflict of interest The authors declare no competing interests.

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