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Challenges and Management Strategies for Mediterranean Cork Oak Forests: Impacts of Climate Change, Human Activities, and Invasive Species – A Review

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Abstract

The Mediterranean cork oak (Quercus suber) forests, crucial for maintaining biodiversity and supporting local economies, are experiencing severe and multifaceted declines driven by an array of environmental and anthropogenic factors. These unique ecosystems are increasingly threatened by climate change, which is manifesting through more frequent and severe droughts, elevated temperatures, and unpredictable precipitation patterns. Such climatic shifts are not only affecting cork production but are also compromising the overall health and resilience of these forests. Concurrently, human activities, including extensive deforestation, overharvesting, and the conversion of forested lands into agricultural or urban areas, have intensified habitat fragmentation and disrupted natural processes essential for forest regeneration. The spread of invasive species, particularly Aleppo pine (Pinus halepensis), exacerbates these challenges by encroaching on traditional cork oak habitats. This intrusion alters forest composition, reduces biodiversity, and affects ecosystem functionality. Furthermore, diseases such as Phytophthora

cinnamomi are playing a critical role in forest decline by attacking cork oak roots, impairing water and nutrient uptake, and contributing to soil degradation. The combined effects of these pressures result in a diminished capacity for natural regeneration and increased vulnerability of these forests to further disturbances. To counteract these threats, adaptive forest management practices are imperative. Selective thinning operations can enhance forest resilience by reducing competition for resources and improving water and carbon use efficiency. Reforestation efforts should focus on planting drought-resistant native species to better align with future climate conditions. Additionally, effective grazing management is essential to prevent soil degradation and maintain vegetative cover. Long-term monitoring and proactive management strategies are crucial for early detection and control of invasive species and diseases, which will help mitigate their impacts and support forest health. Sustainable land use practices, including the promotion of diverse tree species and the integration of indigenous plants, can bolster ecosystem resilience and support a robust soil trophic network. Engaging stakeholders and local communities in conservation efforts and raising awareness about sustainable forestry practices are vital for the successful implementation of these strategies. By adopting a comprehensive and coordinated approach, we can better safeguard the ecological integrity and economic value of Mediterranean cork oak forests, ensuring their sustainability for future generations.

Keywords: Cork Oak Forests, Climate Change, Invasive Species, Forest Management, Biodiversity

Introduction

Forests in the Mediterranean Basin are noted for their remarkable plant and animal diversity, significantly contributing to global terrestrial biomass (Myers *et al.*, 2020). These ecosystems, characterized by wide environmental gradients, face various pressures from both natural and anthropogenic factors (Keenan *et al.*, 2019). In Europe, both coniferous and broadleaved forests

have seen significant declines since the late 20th century due to broader ecological stresses (Bucur *et al.*, 2021; Linderholm *et al.*, 2022). The dynamics of these ecosystems are influenced by a combination of biotic and abiotic factors (Fernández-Martínez *et al.*, 2020).

The Mediterranean region faces significant risks due to global climate change, making it particularly vulnerable to various environmental impacts (Giorgi & Lionello, 2008). *Quercus* species (Fagaceae) have historically played a crucial role in agroforestry systems managed by humans and livestock for millennia (Kremer *et al.*, 2021). However, climate change is expected to drive significant shifts in these ecosystems (Gómez-Aparicio *et al.*, 2022). *Quercus suber* (cork oak) forests, economically and ecologically valuable, are already experiencing notable declines (Gentilesca *et al.*, 2017; Matías *et al.*, 2019). Reduced precipitation and prolonged droughts are adversely affecting cork oak regeneration, growth, and distribution (Hernández-Serrano *et al.*, 2022). Moreira *et al.* (2023) have identified factors such as climatic variability, historical land management, and livestock pressure as crucial determinants of cork oak population dynamics, influencing mortality rates, forest density, and regeneration.

Drought continues to be a major constraint on forest productivity globally (Liu *et al.*, 2022) and significantly impacts agriculture (Ciais *et al.*, 2019). Mediterranean forests, including those dominated by *Quercus* species, have faced increased mortality and dieback due to recurring droughts (Moreira *et al.*, 2023). Emerging threats such as *Phytophthora cinnamomi*, a soil-borne oomycete causing root rot and tree mortality, further endanger cork oak ecosystems (Burgess *et al.*, 2020). Human overexploitation and livestock pressures exacerbate these issues, hindering natural regeneration (Rodriguez-Sánchez *et al.*, 2021). Mediterranean ecosystems are

increasingly affected by the complex interplay of climate change, resource overuse, human-induced fires, deforestation, improper land use, and pollution (Peñuelas *et al.*, 2021).

Research has examined various factors contributing to cork oak forest degradation. For instance, Aleppo pine (*Pinus halepensis*) demonstrates greater physiological plasticity under resource scarcity compared to holm oak (*Quercus ilex*), which has a broader regeneration niche (Gómez-Aparicio *et al.*, 2022). This study seeks to: (i) examine the effects of climate change, with a specific focus on drought, on cork oak forests; (ii) examine species-specific responses to climate change, with a focus on drought; (iii) assess the effects of resource overexploitation on cork oak decline and dieback; and (iv) analyze the role of diseases in cork oak forest degradation. The study will also propose recommendations for enhancing the resilience of cork oak forests to ongoing and anticipated climate change impacts.

Materials and Methods

This study utilized a comprehensive review of literature published from 2000 to 2024, with data sourced from prominent academic databases, including Clarivate Web of Science® (http://apps.webofknowledge.com/), Scopus®, and ScienceDirect®. The literature search employed specific keywords such as “Cork Oak Forests,” “Climate Change,” “Invasive Species,” “Forest Management,” and “Biodiversity” to ensure a targeted approach. This methodology aimed to capture a wide range of studies relevant to the ecological and management aspects of *Quercus suber* forests.

In addition to peer-reviewed articles, grey literature was also considered to enrich the research. Unpublished doctoral theses and other relevant documents provided insights that may not be

available in conventional academic publications. This inclusion helped to broaden the understanding of the subject matter and incorporate diverse perspectives, thereby enhancing the robustness of the findings.

The initial search produced a large volume of results, which were refined based on the relevance of titles and abstracts. This careful selection process yielded a final database of 56 references. Each selected study was required to meet specific criteria: it had to be published in English and focus on *Quercus suber* forests, specifically addressing the effects of climate change, the impact of invasive species, and effective management practices. This structured approach ensured that the review presented is both comprehensive and pertinent to current challenges in *Quercus suber* forest management.

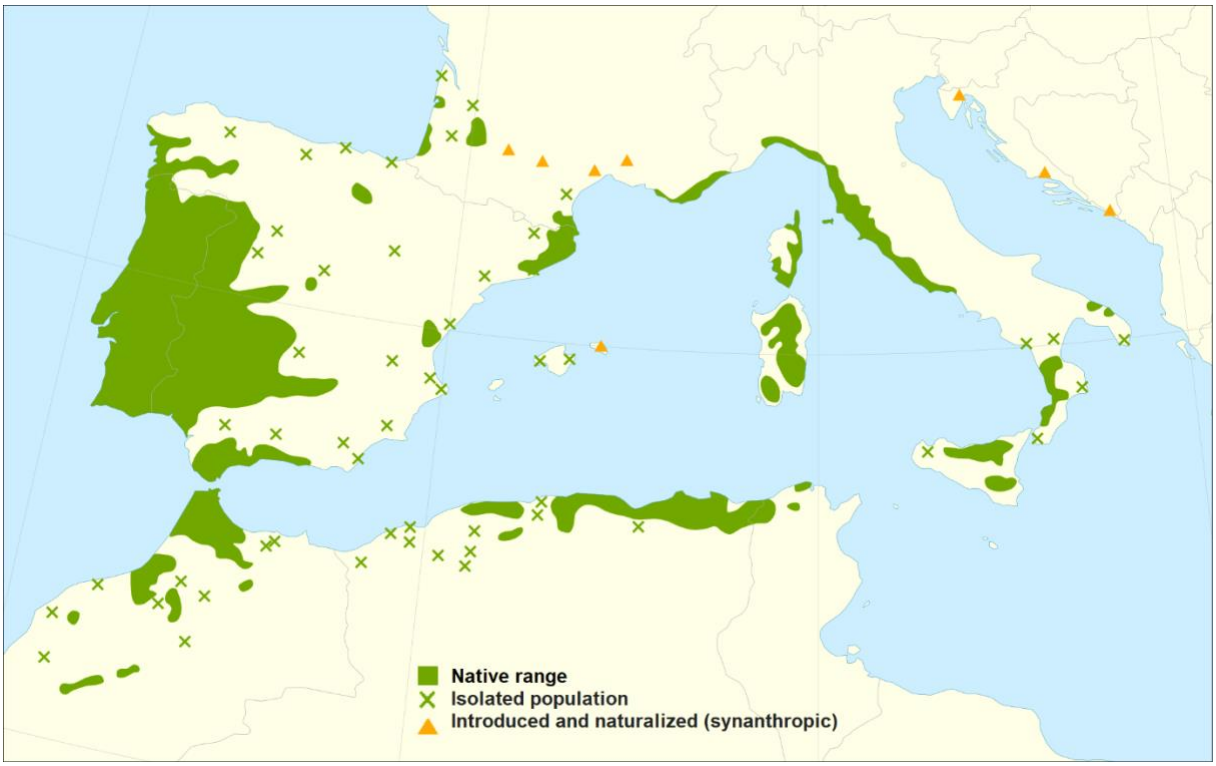

Figure 1: Geographical distribution of the cork oak (Caudullo *et al*., 2017)

The Decline of Quercus Forests Due to Climate Change and Drought

The rise in global temperatures has increasingly made drought a significant barrier to forest productivity and tree growth (Babst *et al.*, 2019). The intensification of arid conditions severely impacts forest health (Allen *et al.*, 2015). The Mediterranean region, already highly vulnerable, is projected to experience more frequent and severe drought events, negatively affecting forest productivity and product quality (Oliveira *et al.*, 2016). In the arid western Mediterranean Basin, drought conditions impede tree growth and elevate mortality rates due to slowed growth (Valeriano *et al.*, 2021).

Recent studies highlight the crucial role of water in supporting primary production in cork oak agroforestry systems, especially during summer droughts (Linares *et al.*, 2020; Martínez-Vilalta *et al.*, 2021). Pérez-Girón *et al.* (2022) found that summer water constraints significantly impact Net Primary Production (NPP) models, with more pronounced effects in open ecosystems with sparse canopy cover compared to those with denser canopies. This underscores the critical role of summer water availability for cork oak systems, irrespective of canopy density. Pérez-Girón *et al.* (2022) also noted the importance of both soil and atmospheric moisture in driving climate-related primary production, while the oceanic atmosphere can help moderate extreme drought years. A negative correlation between coastal distance and summer relative humidity indicates that summer humidity limits cork oak systems, closely related to stomatal closure (David-Schwartz *et al.*, 2019).

Recent research by Martínez *et al.* (2023) identified extreme climatic events, such as severe temperatures for evergreen oak forests and rainfall deficits for deciduous oak forests, as key

factors driving observed changes. Peñuelas & Sardans (2021) observed that increased aridity from more frequent and prolonged droughts has pushed Mediterranean forest communities to their limits, driving migration to wetter areas and exacerbating pest outbreaks and wildfires. Studies show a strong correlation between annual growth and seed production in Mediterranean forests and the severity of droughts (Galiano *et al.*, 2022; López *et al.*, 2022). The decline of Mediterranean oaks (*Quercus* spp.) and pines (*Pinus* spp.) in southern Europe, marked by dieback, defoliation, and reduced growth, is largely attributed to frequent drought events, often exacerbated by higher temperatures and pathogens (Tsiaras *et al.*, 2022; Fernández *et al.*, 2023). These factors disrupt nutrient cycling rates, soil trophic structures, and soil fertility (Hernández *et al.*, 2023; Rodríguez *et al.*, 2022), leading to increased tree dieback and mortality.

Tree radial growth is influenced by climatic factors such as precipitation during the growing season and preceding winter, as well as soil water retention (Moreno-Gutiérrez *et al.*, 2023; Ríos *et al.*, 2023). Besson *et al.* (2014) demonstrated that cork oaks exhibit considerable resilience to annual precipitation fluctuations but are sensitive to the timing and quantity of late spring rainfall. Oliveira *et al.* (2016) noted that adverse weather conditions significantly affect cork growth, influencing economic dynamics. Research consistently shows a positive relationship between cork ring width and precipitation, while temperature generally has a negative effect (Mendoza *et al.*, 2022; Vargas *et al.*, 2023). Rainfall in November and December enhances cork growth in the following season, highlighting the importance of soil water retention (Oliveira *et al.*, 2016).

Soil type also impacts cork growth patterns by influencing deep root development and groundwater access (Costa *et al.*, 2023). Oliveira *et al.* (2016) emphasized the critical role of

precipitation in cork growth, particularly in Spain's Coruche region, where temperature initially supports growth but later can have negative effects. Short-term droughts, especially in spring, significantly impact cork growth, although cork trees can recover quickly from extreme drought years like 1995, 1999, and 2005.

Reductions in *Quercus suber* forest areas and cork production have been documented across the Mediterranean basin, including Portugal, Spain (Gómez *et al.*, 2022), France (Lemoine *et al.*, 2023), Italy (Morandi *et al.*, 2022), and Maghreb countries like Algeria, Morocco, and Tunisia (Touhami *et al.*, 2020). In Tunisia, severe declines in *Quercus suber* forests were reported between 1988 and 1995 due to prolonged droughts, resulting in approximately 63,622 dead trees (Ben Jamaâ & Hasnaoui, 1996). Hasnaoui (1998) documented a 40,000-hectare reduction over 40 years, averaging 1,000 hectares annually. In Algeria, drought cycles, lack of silvicultural management, and reforestation with Aleppo pine have contributed to cork oak dieback (Dehane *et al.*, 2011).

Resilience and Adaptation of Cork Oaks to Climate Change

Research by Oliveira *et al.* (2016) highlighted that cork oaks exhibit significant resilience, as evidenced by increased cork growth following the alleviation of drought conditions. These trees are particularly responsive to late spring precipitation, with cork growth improving as water availability increases. However, short-term droughts lasting between 2 and 11 months can severely hinder cork growth, potentially impacting the availability of raw materials crucial for industrial applications and affecting economic viability.

Recent studies emphasize that climate change will impose complex pressures on cork oak forest ecosystems, particularly under severe drought scenarios. Touhami *et al.* (2023) project that rising temperatures and prolonged drought conditions are already impacting these ecosystems and are expected to intensify. The limited adaptability of cork oaks to these changes makes them highly vulnerable to ongoing and future climate variations (Lindner *et al.*, 2023; Richter *et al.*, 2022). Effective adaptation strategies are essential, requiring continuous monitoring and proactive management to address the increasingly harsh conditions that forests will face for decades, if not centuries (Keenan, 2023; Dale *et al.*, 2020).

The transition of evergreen oak forests to shrublands, driven by elevated temperatures and increased wildfire frequency, represents a significant concern (Acácio *et al.*, 2017). Addressing these challenges necessitates the implementation of targeted management strategies and planning practices to preserve forest ecosystems and enhance drought resistance (Maguire-Rajpaul *et al.*, 2020; Wilson & Cagalanan, 2019; Mezgebu & Workineh, 2021). Reforestation efforts should prioritize indigenous species to better adapt to climate change impacts (Potter *et al.*, 2019; Serra-Varela *et al.*, 2020). Wahbi *et al.* (2019) recommend focusing forestry practices in the Mediterranean region on new strategies to bolster resilience and adaptability to climate change.

The Impact of Resource Overexploitation on Cork Oak Forest Decline

The Mediterranean Basin, known for its rich diversity of woody species, including approximately 290 species, faces significant environmental challenges due to historical and ongoing human activities (Gauquelin *et al.*, 2018). The region's unique characteristics, such as historical human impacts and diverse biodiversity, make it particularly vulnerable to current

environmental changes (Gauquelin, 2021). Ecosystem dynamics vary between the northern and southern Mediterranean coasts. For instance, in the northern Mediterranean, coastal urbanization and the abandonment of agricultural lands have led to increased forest cover. Between 1980 and 2011, forest cover in the French Mediterranean region grew by 0.5% to 2% annually, equivalent to approximately 16,000 hectares per year (IF, 2014; FAO, 2021). In contrast, the southern Mediterranean has experienced ongoing degradation, leading to habitat fragmentation and loss. Algeria, for example, saw its forest area decrease by 0.5% annually from 1990 to 2010 (FAO, 2021).

Mediterranean forests, shaped by a long history of agro-sylvo-pastoral management and local interactions, have been extensively impacted by human activities (Blondel, 2017; Aubert, 2020). Scientific studies consistently highlight the negative effects of human activities on forest biodiversity, such as deforestation, degradation, and desertification (Gauquelin *et al.*, 2018). In France, the pressure on forest ecosystems is relatively low, particularly in areas like the Eastern Pyrenees, while Spain faces moderate pressure. Conversely, Morocco, Algeria, and Lebanon, where forests are crucial for rural livelihoods, experience high levels of pressure. Acácio *et al.* (2017) found that rising human pressure, combined with anticipated climate changes, will likely lead to further declines in evergreen oak forests and a gradual replacement of deciduous oak forests with xeric-adapted species. Gauquelin *et al.* (2018) also observed significant erosion impacts on Mediterranean forests, exacerbated by limited soil cover, intensive human activity, low soil organic matter, and disrupted ecological processes such as litter decomposition due to drought.

Extreme climatic events, including prolonged droughts, increased wildfire occurrences, and pest outbreaks, are expected to disrupt Mediterranean forest functionality (Moriondo *et al.*, 2022; Lindner *et al.*, 2023). Long-term observations from Acácio *et al.* (2017) revealed that cork oak forests exhibited the highest resilience (62%), with a notable shift towards pine and eucalyptus plantations. Holm oak forests demonstrated lower resilience (53.2%), transitioning mainly to agricultural lands, while deciduous oak forests showed the least resilience (45.7%), often converting to scrubland. These transformations were significantly influenced by anthropogenic factors such as forest fires, population density, and land accessibility.

The removal of large trees for wood likely diminished seed sources, hampering the regeneration of hardwood oak forests (Carvalho, 2020). Acácio *et al.* (2017) also observed that overexploited deciduous oak forests are transitioning into shrublands, with shrubs increasingly dominating the landscape. Mixed forests, featuring a variety of species including pine and hardwood, are anticipated to have lower pest susceptibility and greater resilience to disturbances, promoting higher biodiversity and adaptability to environmental changes (Jactel *et al.*, 2022; Jactel & Brockerhoff, 2023; Yachi & Loreau, 2000).

These findings emphasize that overexploitation remains a significant threat to cork oak and Aleppo pine forests in the Mediterranean region. Recent anthropogenic pressures, such as deforestation and tree felling, combined with natural factors like precipitation deficits and prolonged drought, have contributed to the decline of cork oak forests and hindered their natural regeneration (Hasnaoui, 2021). In Northwest Tunisia, increased local population pressure has

exacerbated forest damage, with an estimated 695,234 trees felled between 1996 and 2005 (DGF, 2005).

Figure 2: Cork oak stands in in north-west of Tunisia

Decline of Quercus Forests Due to Expansion of Hardwood Species

Globally, forests generally experience lower impacts from invasive species (Chytrý *et al.*, 2008). In Europe and the Mediterranean Basin, invasion pressure remains relatively modest (FAO, 2018; Clotet *et al.*, 2016). However, peri-urban forests are particularly susceptible to invasions due to human activities that facilitate the spread of invasive species (Pino *et al.*, 2013). Human-induced disturbances in open ecological areas create conditions that allow new species to establish themselves by providing ample resources (Erskine-Ogden *et al.*, 2016). Increased aridity and nitrogen deposition are known to enhance the growth of invasive Mediterranean woody species more than native species (Erskine-Ogden *et al.*, 2016). This suggests that

anticipated increases in aridity could further promote the spread of invasive species in the Mediterranean Basin, potentially altering forest dynamics in unpredictable ways (Fernández-Manjarrés *et al.*, 2018).

Recent research documents the expansion of eucalyptus and pine plantations into cork oak habitats, driven by afforestation policies (Pinto-Correia & Godinho, 2020; Costa *et al.*, 2021). These plantations often replace cork oak stands in already degraded areas (Acácio *et al.*, 2017). Research aims to investigate the impact of Aleppo pine expansion in cork oak habitats within the Mediterranean region, focusing on how these shifts influence local forest ecosystems and biodiversity. Preliminary findings suggest that the encroachment of non-native species such as eucalyptus and Aleppo pine not only alters forest structure but also affects local biodiversity by outcompeting native flora and modifying habitat conditions (Pinto-Correia *et al.*, 2022; Costa *et al.*, 2023).

Decline of Quercus Forests Due to Diseases

The increasing invasion of alien microorganisms has emerged as a significant cause of tree mortality in the Mediterranean region (Sala *et al.*, 2000). Notably, *Phytophthora cinnamomi*, an invasive oomycete, causes root necrosis in *Quercus suber*, impairing the trees' ability to absorb water and leading to decline symptoms similar to drought stress (Luque *et al.*, 2002; Sánchez *et al.*, 2002). The impact of *Phytophthora* on *Quercus* forests also correlates with reduced soil biological activity and nutrient availability (Marcais *et al.*, 2004), which significantly affects the soil's invertebrate community (Gomez-Aparicio *et al.*, 2012). The severity of *Phytophthora* impacts varies with site characteristics and tree species, with Mediterranean oak species being

more susceptible compared to *Pinus* species (Moralejo *et al.*, 2009). Among *Pinus*, the xeric species *Pinus halepensis* and *Pinus pinea* are more susceptible than more mesic species like *Pinus nigra*, *Pinus pinaster*, and *Pinus sylvestris* (Gea-Izquierdo *et al.*, 2014; Davi *et al.*, 2020).

Summer storms can exacerbate issues by causing water saturation and fluctuations between flooding and drought, which, combined with high temperatures, may enhance *Phytophthora* virulence (Pereira, 2007; González *et al.*, 2020). In some areas of Spain, the decline of *Pinus pinaster* is attributed more to drought and infestations of *Viscum album* rather than *Phytophthora* (Moreira *et al.*, 2018). Pathogenic fungi also pose significant threats to forests in North Africa, particularly affecting *Quercus ilex* and *Quercus suber* in the Algerian mountains (Ghaioule *et al.*, 2007). Emerging diseases and pests are increasingly impacting key tree species in agroforestry zones (Fernández-Manjarrés *et al.*, 2018). The decline of Holm and cork oaks in the Iberian Peninsula results from a complex interplay of biotic and abiotic factors (Ibáñez *et al.*, 2014).

Trees under drought stress are particularly vulnerable to attacks from fungi such as *Biscogniauxia* and *Diplodia*, the oomycete *Phytophthora cinnamomi*, and bark and wood borers like *Platypus cylindrus* (Branco *et al.*, 2014). *Phytophthora cinnamomi* is noted as a significant driver of global forest composition changes (Sena *et al.*, 2018). González *et al.* (2020) suggested that while drought alone is not a primary factor for *Phytophthora* disease onset, the combined effects of drought and *Phytophthora cinnamomi* infections likely contribute to the decline and mortality of oak trees.

Moricca *et al.* (2016) found that *Phytophthora cinnamomi* infects trees individually or in groups, targeting roots, collars, and trunks, leading to significant loss of both small and fine roots. Cork oak is potentially less affected by dieback than Holm oak due to its relative susceptibility to *Phytophthora cinnamomi* (Robin *et al.*, 2001; Rodríguez-Molina *et al.*, 2002). In Algeria, the severe decline of cork oaks on steep slopes has been linked to *Phytophthora cinnamomi* and the expansion of Aleppo pine, with cork oak wastage also associated with fires (Sánchez *et al.*, 2002; Moreira & Martins, 2005; Bouhraoua, 2010).

Recommendations for Adapting Cork Oak Forests to Climate Change

The Mediterranean region faces considerable challenges due to climate change, including shifts in species composition, increased invasion by non-native species, and changes in forest productivity (González *et al.*, 2022). Climate projections indicate rising average temperatures, increased frequency of extreme temperature fluctuations, and intensified precipitation events, particularly heavy rainfall in mountainous areas (Sánchez *et al.*, 2023). Western Europe is expected to experience more frequent droughts, heatwaves, and variability in precipitation patterns (IPCC, 2021).

Land Use and Agroforestry Practices: Fernández-Manjarrés *et al.* (2022) emphasize the importance of maintaining agroforestry and open husbandry practices to enhance forest resilience. Incorporating diverse species such as Holm oak (*Quercus ilex*), Downy oak (*Q. pubescens*), and Olive tree (*Olea europaea*), alongside shrubs like Mastic tree (*Pistacia lentiscus*) and Mock privet (*Phillyrea latifolia*), can improve ecosystem resilience to climate-induced changes, including altered fire regimes. Allowing land to revert to natural vegetation

while managing these species initially could further enhance ecosystem stability (Fernández-Manjarrés *et al.*, 2022).

Thinning and Silvicultural Interventions: Moderate to intensive thinning operations are beneficial for improving forest resilience to climate change. Wahbi *et al.* (2021) found that thinning enhances resistance to water scarcity and prolonged droughts. Extreme climatic events are accelerating changes in cork oak and deciduous oak forests; however, cork oak forests are not necessarily less resilient than other oak species (Acácio *et al.*, 2022). Thinning not only improves water and carbon use efficiency but also aids in forest regeneration, particularly after disturbances like fires (Helluy *et al.*, 2023; Aldea *et al.*, 2021; Calev *et al.*, 2020; Olivar *et al.*, 2019; Vilà-Cabrera *et al.*, 2022).

Disease and Pest Management: Effective management of pests and diseases is crucial. Combining thinning with the natural association of leguminous species can mitigate drought stress (Touhami *et al.*, 2024). Ennajah *et al.* (2021) found that associating cork oaks with native plants such as *Cytisus triflorus* can be a sustainable management strategy that reduces stress on cork oaks. Additionally, using *Pinus halepensis* as a rootstock for stone pine production can benefit arid regions (Mechergui *et al.*, 2022).

Sustainable Grazing Management: Overgrazing can degrade soil and hinder vegetation cover. Effective grazing management and maintaining forest patches between cultivated lands can stabilize cork oak ecosystems and enhance their resilience (Peñuelas *et al.*, 2022). González-Moreno *et al.* (2022) found that increased tree species diversity enhances soil trophic networks,

while proper grazing management reduces wildfire risks by promoting woody plants over flammable taxa (Ibáñez *et al.*, 2022).

Reforestation and Afforestation: Reforestation and afforestation are critical for soil conservation and carbon sequestration in degraded areas. Planting shade-providing species can facilitate subsequent oak replanting (Castro *et al.*, 2022). Periodic reduction of shrubs and grasses can enhance tree planting success (Ruiz-Peinado *et al.*, 2022). Thinning after fires can also promote forest regeneration (Garcia-Orenes *et al.*, 2022). Jurado Doña *et al.* (2023) suggest that sustainable forest management, including optimal thinning and reforestation with indigenous species, can reduce tree mortality and enhance cork oak regeneration under drier conditions.

Conclusions

This review highlights the numerous challenges facing Mediterranean cork oak forests, which are critical for both ecological balance and economic value. Key threats include increasing frequency and severity of droughts, disease spread, invasive species encroachment, and habitat conversion due to human activities.

Climate Change Impacts: Climate change has led to more frequent and severe droughts and temperature extremes, negatively affecting cork production and overall forest health. Extreme weather events, such as heat waves and intense rainfall, exacerbate these issues, placing additional stress on cork oak forests.

Human Activities and Overexploitation: Deforestation, land conversion, and excessive harvesting have fragmented habitats and degraded forest areas. These human activities, coupled with agricultural expansion and urbanization, have diminished the ecological integrity and biodiversity of cork oak forests, making natural regeneration processes more difficult.

Invasive Species and Diseases: The spread of invasive species like Aleppo pine, facilitated by climate change and human activities, further compounds the challenges facing cork oak forests. Pathogens such as *Phytophthora cinnamomi* are significant threats, causing root diseases that impair trees' ability to absorb water and nutrients, leading to forest decline and impacting soil health.

Management and Adaptation Strategies: Addressing these challenges requires a comprehensive approach. Adaptive forest management practices, such as selective thinning and reforestation with drought-resistant and native species, are crucial. Thinning operations can improve resilience by reducing competition for resources, while reforestation should prioritize native species suited to future climate scenarios. Effective management of invasive species and diseases involves proactive measures, including early detection and control strategies.

Sustainable Land Use and Public Engagement: Implementing sustainable land use practices, such as proper grazing management and rotational pasture use, is necessary to prevent soil degradation and maintain vegetation cover. Enhancing tree species diversity in reforestation projects can improve ecosystem resilience and support robust soil trophic networks. Educating

stakeholders and the public about sustainable forestry practices and forest conservation is vital for garnering support and ensuring effective management.

In conclusion, while Mediterranean cork oak forests face increasing threats from climate change, overexploitation, invasive species, and diseases, a coordinated and informed approach to forest management can enhance their resilience. By integrating adaptive management, proactive disease and pest control, sustainable land use practices, and public engagement, it is possible to preserve the ecological and economic value of these vital forests for future generations.

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