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RESEARCH PAPERS

Oak decline in forest and urban ecosystems: impacts, diagnoses and management strategies

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Summary. Oak decline, in acute and chronic forms, is an emerging challenge in the forest and urban environments of Europe and the Mediterranean basin. Oak trees have central ecological and cultural roles: they support diverse organism communities, are involved in hydrological and biogeochemical cycles, and provide ecosystem services in natural and anthropised landscapes. Populations of *Quercus* species are increasingly threatened by combined effects of extreme weather events, soil degradation, hydrological imbalance, and increasing numbers of emerging pathogens. These factors interact in complex ways, often accelerating decline processes and complicating diagnoses and management. Advances in visual assessment, remote sensing, and molecular tools are improving early decline diagnoses, and accurate assessments of severity. Integrated management approaches, incorporating vegetation management, adaptive silviculture, and soil and water conservation, offer promising pathways to improve oak tree resilience. Attention is required in urban settings, where chronic abiotic stress and site constraints amplify tree vulnerability. Long-term monitoring networks and multidisciplinary approaches are essential for understanding disease progression, anticipating risks, and guiding effective interventions. This review synthesises current knowledge on oak decline dynamics, diagnostic approaches and management strategies, providing a framework to support sustainable, science-based strategies, to mitigate the disease and ensure long-term viability of oak-dominated landscapes.

Keywords. Acute and chronic decline, multitrophic disease complexes, vector–pathogen interactions, tree health monitoring.

INTRODUCTION

Trees are fundamental components of terrestrial ecosystems, providing essential ecological functions, supporting biodiversity, and delivering a range of ecosystem services (Rackham, 2008; Boyd *et al*., 2013). Among forest species, oaks (*Quercus* spp.) are keystone trees across Europe and the Mediterranean basin, sustaining wildlife, enhancing soil fertility, and contributing to carbon sequestration (Schroeder *et al*., 2021). Oak populations are increasingly threatened by a range of decline syndromes collectively referred to as "oak decline", which arise from complex interactions between biotic agents, such as insects and pathogens, and abiotic factors including drought, soil limitations, and climate change (Denman *et al*., 2018; Carluccio *et al*., 2025). These syndromes differ in their temporal dynamics, symptom severity, and underlying causal factors. Chronic Oak Decline (COD) is the most widespread and long-recognised form, characterised by slow and progressive deterioration of tree health over several years or decades, typically associated with repeated or prolonged abiotic stressors, such as drought, nutrient-poor soils, or site mismanagement, often followed by secondary biotic attacks (Denman and Webber 2009). In contrast, Acute Oak Decline (AOD) is a recently recognised and rapidly progressing syndrome, distinguished from COD by the sudden onset of severe symptoms and high rates of tree mortality (Carluccio *et al*., 2024b; Bene *et al*., 2025). AOD has been reported in the United Kingdom and across several European countries, including Poland, Italy, Latvia, Portugal, Spain, and Switzerland, and affects multiple oak species including *Quercus robur* L., *Q. petraea* Matt., and *Q. ilex* L. (Brady *et al*., 2010; Denman *et al*., 2012; Carluccio *et al*., 2024b).

While COD and AOD are both multifactorial, AOD is strongly associated with specific biotic agents, particularly the bacteria *Brenneria goodwinii* and *Gibbsiella quercinecans*, and their putative vector, the beetle *Agrilus biguttatus*, which affect trees already predisposed by abiotic stress (Jose *et al*., 2004; Carluccio *et al*., 2024b; Bene *et al*., 2025). Females of *A. biguttatus* are attracted by volatile organic chemicals (VOCs) emitted by declining oaks, and by bacterial VOCs, promoting a feedback mechanism that accelerates disease progression (Thomas *et al*., 2025). Chemicals produced by *A. biguttatus* also enhance bacterial growth and induce expression of pathogenicity-related genes, increasing bacterial virulence (Doonan *et al*., 2020; Cambon *et al*., 2026). Beyond *A. biguttatus*, other xylophagous and subcortical insects (e.g. *Cerambycidae* and *Scolytinae* spp.) colonise weakened trees and facilitate pathogen entry by creating wounds in bark and cambial tissues, particularly under water stress conditions (Macháčová *et al*., 2022). In contrast, in COD, insect activity is largely secondary, accelerating rather than initiating decline in already stressed trees (Denman *et al*., 2010). Thus, the complexity of the syndromes in these environments arises from interactions of multiple pests and pathogens, including the soil-borne oomycete of the genus *Phytophthora*, and compounding environmental stressors of drought, soil degradation, excessive nitrogen deposition, ground-level ozone, and surfactants in marine aerosols (Frisullo *et al*., 2018; Carluccio *et al*., 2024a; Carluccio *et al*., 2024b).

Human activities are important pathways for the spread and intensification of oak decline syndromes. Forestry operations can create tree wounds that facilitate bacterial infection in AOD, if tools are not adequately disinfected, while the movement of infected wood, bark, mulch or chips poses additional risks. In COD, human-mediated spread is especially important, as *Phytophthora* spp. are commonly introduced through infected nursery stock, contaminated machinery or soil attached to vehicles or footwear, risks that are amplified in urban environments (Cushman and Meentemeyer, 2006; Denman *et al*., 2010).

The rapid progression and the high mortality associated with oak decline make oversight of affected stands a priority. Understanding oak decline epidemiology, including distribution of pathogens and vectors, is crucial for implementation of effective control and mitigation strategies. This knowledge is essential for preserving tree health and biodiversity, and for informing reforestation and restoration practices in rural and urban environments (Denman *et al*., 2018; Carluccio *et al*., 2024b).

The present review summarises current understanding of the effects of Oak Decline in natural and urban ecosystems, and the current options for managing the disease, including preventive measures, monitoring, diagnostic techniques, and silvicultural/phytosanitary interventions. Management practices currently in use are also summarized, and the main shortcomings that hinder disease control are identified.

METHODS

To gather information for address the main questions in this "rapid review" (as defined by Chigbu *et al*., 2023), the authors searched literature for relevant peer-reviewed papers or economic reports categorised in three main subjects: 1) Role of *Quercus* species in natural and urban environments, and implication of their decline; 2) Tools to detect oak decline; and 3) Management strategies for declining oaks where subjects 2) and 3) are centred on acute decline rather than general decline. The literature search was conducted across the scientific databases Scopus and Web of Science. All articles that were found applying the search criteria (outlined below) were initially retained, regardless of language, publication status or date.

The literature search was primarily conducted within Scopus, with designated queries for each subject and further refined if necessary. The literature research on 1) (above) was conducted using the keywords "Quercus" OR "Oak*" AND "ecosystem*" AND "urban*" OR "natural*" AND "decline", and resulted in 220 articles. For topic 2), the principal keywords used were "Oak decline" OR "Acute Oak Decline" AND "diagnostic" OR "tool*" OR "health" resulting in 330 articles. For topic 3) the keywords used were "Oak decline" OR "Acute Oak Decline" AND "management strategy", which resulted in 136 articles.

All pre-print articles that had not been peer-reviewed were excluded. Articles were screened for relevance to the topic and for redundancy, with information already obtained from other sources. In case of redundancy, they were prioritised as papers either published in high impact journals, or deemed central for the aims of this review, and as the most recently published. For each category, highly relevant articles were identified, and hand searches of their respective citations were conducted to include additional relevant articles. An additional Internet search using the search engine Google, was conducted to identify economic reports on *Quercus* spp. non-wood products (e.g., cork, and hardwood). The final number of scientific articles and commercial documents used for this review was 143.

IMPACTS OF OAK DECLINE

Consequences of oak decline in ecosystems

The genus *Quercus*, which is widely distributed across the world (San-Miguel-Ayanz *et al*., 2016; Oswalt *et al*., 2019; Gildenhuys *et al*., 2024), includes the two subgenera: subg. *Quercus* and subg. *Cerris* (Denk *et al*., 2017). Oaks are able to live in habitats differing in humidity, acidity, and/or soil texture (Olarieta *et al*., 2017; Nicolescu *et al*., 2018). Apart from their intrinsic value in supporting a high number of species (Tallamy and Shropshire, 2009; Bargali *et al*., 2015; Mitchell *et al*., 2019), one of the main characteristics of *Quercus* trees is that they influence their habitat dynamics, due their evolved mast seeding capabilities (Sork, 1993, McShea *et al*. 2007). In some environments, oak trees can act as foundation species (Dayton, 1972), capable of influencing population and community dynamics, with severe consequences where oak trees disappear (Ellison *et al*., 2005). Also, when oak trees occur outside forest areas, they to play prominent roles in maintaining biodiversity and connectivity between habitats (FAO, 2018). Each of the *Quercus* subgenera includes deciduous and evergreen species, that often thrive in the same environments, aiding environmental heterogeneity. This can influence species living alongside oaks (Blondel *et al*., 1992), in pure oak forests and in mixed species forests (del Rìo *et al*., 2018; Wehnert *et al*., 2021).

Oak forests are increasingly threatened in several regions. In some localities of the United Kingdom, almost 80% of the oak trees showed symptoms of decline with increased tree mortality (Denman and Webber, 2009). Native oaks (*Q. petraea* and *Q. robur*) occur in a large part of England (Farjon, 2022), and are with more than 2,000 species, including 326 obligate associates (Mitchell *et al*., 2019). Therefore, oak decline probably alters ecological biodynamics in the United Kingdom, by disrupting habitat availability for dependent fungi, invertebrates, birds, and mammals, reducing nutrient cycling, and altering soil composition. In the Forest habitat disruption is exacerbated in the United Kingdom by the simultaneous occurrence of ash dieback affecting *Fraxinus excelsior* L. (Baral *et al*., 2014), a combination of disturbances that can severely impact biodiversity in this region (Mitchel *et al.,* 2019).

There is evidence of the particularly beneficial role played by oak trees in mixed stands with other tree species (Pretzsch *et al*., 2013). This positive impact may be due to the combined effects of specific ectomycorrhizae (ECM) communities interacting with each other (Tyler, 1992) and the ability to exert hydraulic lift by the *Quercus* trees (Caldwell *et al*., 1998). These interactions may increase the capability of mixed forests composed of oaks (*Q. petraea, Q. robur*) and European beech (*Fagus sylvatica* L.) to extract and mobilise nutrients and water from different land patches. Loss of oaks in these sites may reduce productivity, considering that pure non-oak forests were shown to produce on average 30% less biomass than mixed stands with oaks, especially in poor-condition sites (Pretzsch *et al*., 2013). The presence of trees affected by AOD alone does not alter their ECM communities (Barsoum *et al*., 2021). Thus, effects on soil and water mobilization are probably direct consequences of the loss of oak trees, rather than the presence of AOD at a site. Less information is available on the effect of COD on ECM, water and soil mobilization. However, indirect evidence suggests that these balances may be disrupted, given that several species of *Phytophthora* may tree root lengths up to 65% (Seddaiu *et al*., 2020).

Co-existence of deciduous and evergreen oaks may also affect maintenance of diverse niche partitioning and heterogeneous distribution of nutrients in soil in natural environments. A Spanish study of mixed oak forest of evergreen cork oak (*Q. suber* L.) and deciduous Algerian oak (*Q. canariensis* Wild) highlighted how these species may influence their environments, through biogeochemical niche repartition and tree-soil positive feedback, contributing maintenance of heterogenous soil nutrient distribution and structural diversity in a Mediterranean forest (Aponte *et al*., 2011). This eco-evolutionary feedback, as summarised by Post and Palkovacs (2009), is a common process that can influence several trophic levels (Aponte *et al*., 2013), and affect species recruitment (Brandt *et al*., 2013) and tree population dynamics (Burns and Brandt, 2014).

It is not yet clear how each of the evergreen and deciduous oak species is susceptible to each syndrome, AOD and COD. Although bacteria associated with AOD have been isolated from symptomatic plants of evergreen and deciduous species (Ragazzi *et al*., 1995; González and Ciordia, 2020; Fernandes *et al*., 2022; Carluccio *et al*., 2025), susceptibility of individual species has not been established, so the causal factors remain unclear.

In some cases, non-native oaks have been found to be healthier than native oaks (Laux *et al*., 2022), mostly due to fewer negative interactions with native pathogens or other stress factors leading to reduced susceptibility to decline syndromes (Gosling *et al*., 2024). From disease management perspectives, reduced susceptibility to AOD and COD in non-native compared with native oak species may confer competitive advantages to non-native trees, by increasing their survival and reproductive success in declining stands. Such disease-mediated advantages can facilitate shifts in forest composition and replacement of native species, with consequences for biodiversity and ecosystem functioning (Mitchell *et al*. 2003; Lovett *et al*. 2006).

Consequences of oak decline in urban areas, and on human health

In urban environments, trees contribute to regulation of local climates, by reducing surface and air temperatures through shading and evapotranspiration, by lowering building cooling requirements, and influencing urban weather patterns and atmospheric processes (Avissar, 1996). Oak proportions are variable in urban trees, but are generally high since oaks can grow on poor quality soil and tolerate drought and heat (Bocsi *et al*., 2021; Andreas *et al*., 2023). While urban trees provide important ecosystem services, occurrence of oak decline can increase risks associated with their presence in cities. Declining trees are prone to branch failure and mortality, posing hazards to public safety and infrastructure (Sæbø *et al*., 2000; Kirkpatrick *et al*., 2013). Loss or deterioration of tree canopies can also affect urban air quality and local atmospheric processes through changes in VOCs (isoprene, α-Pinene, limonene), emissions and airflow regulation (Escobedo *et al*., 2011; Vos *et al*., 2013; Churkina *et al*., 2015).

Oak forests play key roles in ecosystem functioning, and their decline can result in substantial ecological costs. Beyond their ecological importance, oaks are also valuable components of human-dominated landscapes, providing economic, cultural, and environmental benefits in many countries (FAO, 2018; Rautela *et al*., 2025). Oak dominated forests and urban green spaces also contribute to human well-being by supporting physical and mental health, improving environmental quality, and providing recreational opportunities (Bowler *et al*., 2010; Johansson *et al*., 2014). Historical records show how humans influenced development and distribution of oak forests in the previous centuries (Abrams, 1992). Any decline, whether due to AOD or COD, will affect many aspects of human life and health in cities (FAO, 2018). Natural oak forests, as well as other trees, provide non-material benefits to human populations, benefits that are often referred to as cultural services (Reid et al., 2005; FAO, 2018), and these are perceived as a cultural heritage for landscapes (Plieninger *et al*., 2004; Garrido *et al*., 2017; O'Brien *et al*., 2024). Bowler *et al*. (2010) found that people perceive green areas, especially in urban areas, as positive and beneficial. However, not all environments are perceived equally: a biotope with an intermediate level of canopy openness and understory vegetation elicited the most positive emotional response, compared with either a dense and unmanaged stand or a monocultural forest characterised by low structural complexity and sparse understory vegetation (Johansson *et al*., 2014).

As forests may contribute to improving psycho-physical health, their disappearance may also affect it negatively. Wagner and Miederhoff (2025) surveyed the psychological impacts of forest losses due to bark beetle infestation, and they reported serious emotional shock experienced by forest owners, dominated mainly by frustration. Forest owner emotions have non-negligible roles in forest management decisions (Lähdesmäki and Matilainen, 2014), and must be considered when planning management strategies. There are no studies assessing linkage of the presence of AOD or COD to human health-related responses, but it is likely that oak decline may threaten human well-being. Dieback of oak trees due to AOD and COD in cities (Carluccio *et al*., 2024; Tkaczyk *et al*., 2025), causing increased quantities of dead wood requiring disposal, and a general state of decay and unkemptness, could increase public dissatisfaction (Krischke *et al*., 2025).

Consequences for economies

If oaks have expanded the areas they occupy, especially in the last few centuries due to human activity (Abrams, 1992; FAO, 2018), humans also exploited oak productivity for production of non-wood forest products including cork (FAO, 2018), for which the European market is expected to grow, and of oak hardwood production to increase (Johannesson and Ek, 2005). Demand has been especially high in the European parquet sector, where oak dominated, accounting for the 82% of total production in 2020 (Oliver, 2022). In many regions, local communities rely heavily on oak forests for forest products, ecosystem services, and economic sustenance (Rautela *et al*., 2025), while in other communities, oaks are valued, especially by landowners, for their usefulness as animal grazing areas and a timber sources (Plieninger *et al*., 2004; Garrido *et al*., 2017; O'Brien *et al*., 2024). Oak area pastures are widely used for livestock grazing, and their maintenance is often driven by the needs of local pastoral farming systems. Loss of these environments may occur from over-exploitation of these habitats, driven by short-term horizons among landowners (Pinto-Correia and Azeda, 2017), or from land abandonment and livestock removal (Johannesson and Ek, 2005). The Mediterranean basin is characterised by geographical distinction of causes of anthropic losses of oak forests: in many regions of northern Africa, where active rural populations are increasing, the main cause is overexploitation of oak forests, while in Mediterranean Europe, opposite rural population trends occur, and land abandonment is more common (Bugalho *et al*., 2011).

Although there have been no studies on prediction of economic consequences of AOD or COD, some have predicted the effects of oak decline from other causes, and have estimated significant economic impacts for private and public sectors (Anderson and Cordell, 1988; Kovacs *et al*., 2011; Dhungel and Ochuodho, 2024). Urban tree management entails substantial costs, including pruning, removal of hazardous branches, and felling of severely diseased trees. However, these expenditures are generally outweighed by the ecological, social, and economic benefits provided by urban trees, particularly when public safety and human well-being are considered (McPherson *et al*., 1999). In some cases, estimated costs are particularly high. For example, the potential costs for tree loss and replacement of oaks in Canadian streets due to oak wilt (caused by *Bretziella fagacearum*) were estimated to be between 266 and 420 million Canadian dollars (Pedlar *et al*., 2020). *Phytophthora ramorum,* which causes Sudden Oak Death (SOD) in North America, was predicted to cause losses of $US 7.5 million for municipalities and $US 135 million for single-family homes (Kovacs *et al*., 2011). Loss or decline of oak trees may also reduce property values, because trees on private properties are widely recognised as contributing positively to real estate values (Morales *et al*., 1983; Anderson and Cordell, 1988).

To date, most of the literature describing oak decline has focused on disease caused by *Phytophthora*. In North America, particular attention has been devoted to SOD (Rizzo and Garbelotto, 2003; Kovacs *et al*., 2011; Pedlar *et al*., 2020). In contrast, oak decline in Mediterranean regions is generally regarded as a disease complex, involving interactions among environmental stressors, *Phytophthora* species, and other biotic agents, including bacterial pathogens (De Sampaio e Paiva Camilo-Alves *et al*., 2013). The systematic review of Marques *et al.* (2025) highlighted the main causal factors in Mediterranean climate regions in America (California) and across the Mediterranean basin. Bacteria associated with AOD, and symptomatic trees affected by COD were surveyed across Europe (Carluccio *et al*., 2024a; Tkaczyk *et al*., 2025), but there are no estimates available of their economic implications. However, conclusions can be inferred regarding the impacts of oak decline, dieback, or general unkemptness of urban forestry for human physical and psychological health (see, above, *Consequences of oak decline in urban areas and on human health*).

Oak Decline: early detection and monitoring tools

Field-based tools

Tools or techniques for specific recognition of symptoms of oak decline symptoms are not readily available. Complexity of Oak Decline, its various contributing factors, and the similarity of visible symptoms with other syndromes, make it difficult to obtain specificity and certainty for associating standard data with precise symptomatic stages. As Lausch *et al*. (2017) reported, quality and consistency of forest health assessments depend on the expertise of field teams, which can limit comparability between assessments. For this reason, early detection of oak decline relies on systematic visual inspections, which remain the most accessible and rapid method for identifying symptomatic trees. For example, AOD-affected trees exhibit distinctive weeping stem bleeds, which indicate areas of necroses and fluid-filled cavities in underlying inner bark (Denman *et al*., 2012; Denman *et al*., 2014). These symptoms are often accompanied by longitudinal fissures and necrotic bark lesions (Denman *et al*., 2012). Characteristic "D"-shaped exit holes of buprestid beetles (*A. biguttatus*) are also commonly observed on affected stems (Brown *et al*., 2018). In the case of COD, however, the symptoms lead to drastic reductions of host plant crown volume, severely impairing tree fitness and resulting in slow death within several years (Carluccio *et al*., 2024b).

The early appearance of symptoms, even in small numbers, provides critical opportunity for rapid assessment of oak health and timely interventions (Denman *et al*., 2010). Field surveys remain critical first steps in evaluating tree health and detecting oak decline, both in forests and in urban areas. While AOD manifests rapidly, causing noticeable symptoms that require prompt intervention, COD evolves slowly and requires long-term monitoring to assess disease progression. Quantitative approaches, such as the Phenotypic Decline Index and the Decline Acuteness Index, provide standardised measures of severity and rate of decline, enabling comparisons across trees and over time (Finch *et al*., 2021). Ground surveys can be complemented by remote sensing and GIS-based analyses, which integrate environmental and pedoclimatic data to support risk mapping and predictive modelling for natural and urban oak populations (Murfitt *et al*., 2016; Crocker *et al*., 2023). Their success, however, depends on careful, site-specific planning, long-term monitoring, and integrated consideration of ecological, structural, and soil-microbe-tree interactions. Urban oaks may experience additional stress, including from soil compaction, limited rooting volumes, and microclimate extremes, which can influence onset and progression of decline. Standardised field-based protocols are important for ensuring robustness and comparability in forest health assessments. Lausch *et al*. (2017) emphasised that many *in situ* indicators rely substantially on expert judgement, introducing observer bias and limiting data harmonization across teams and regions (Figure 1). Ground surveys are also spatially constrained, and are often conducted at multi-year intervals, reducing their capacity to detect rapid or transient tree declines.

Remote sensing tools

Integration of field observations with remote-sensing data, operationalised through the unified frameworks of spectral traits (ST) and spectral trait variations (STV), has been proposed for standardization of disease assessments, while increasing temporal resolution and spatial coverage (Lausch *et al*., 2017). Integrating soil moisture sensors and climate indices with spectral metrics and LiDAR-derived structural data enables early detection of physiological stress and spatial risk mapping of forest stands vulnerable to decline (Torresan *et al*., 2021). Evidence from recent applications reinforces this perspective. Using dense satellite time series, Guzmán *et al*. (2023) demonstrated the capacity of remote sensing to detect early, disease-related phenological shifts in oaks within short temporal windows. This rapid diagnostic capability is critical for managing decline syndromes, as it enables timely interventions and facilitates spatially explicit risk assessments.

Despite these advances, significant challenges remain for operational deployment of remote sensing. Firstly, remote sensing is most suitable for monitoring COD, allowing the slow evolution of the syndrome to be tracked on large spatial scales, while for AOD, the rapid onset of symptoms requires close integration with visual field surveys. Many remote-sensing products also lack standardised quantification of uncertainty and robust validation frameworks, limiting their usability for decision-making (Fassnacht *et al*. 2024).

Long-term monitoring networks combining permanent ground plots with remote sensing and climate data have been proposed as a key strategy for detecting trends in tree mortality and dieback at a global scale (International Tree Mortality Network, 2025). By integrating these multi-source long-term datasets, machine learning approaches can be applied to predict areas at elevated risk of decline, enabling proactive disease management before visual symptoms emerge (Estrada *et al*., 2023), although application to AOD remains limited. Furthermore, ground-based measurements remain indispensable for calibration, and advanced terrestrial methods such as terrestrial laser scanning (TLS) also present problems due to occlusion, difficult field logistics, and variability in acquisition protocols.

Biological indicators remain as central components for forest-health monitoring. Abas (2023) identified three major biomonitoring categories, i.e. morphological, physiological, and behavioural approaches, each showing methodological advances over the past decade. That review also highlighted persistent limitations, including absence of globally standardised protocols, and substantial methodological heterogeneity across studies, mirroring consistency issues observed in visual field assessments.

Although most monitoring systems have been developed in forest ecosystems, similar protocols are increasingly being applied to urban oak populations, due to their high exposure to chronic abiotic stress. Urban trees are typically subject to high temperatures, soil compaction, limited root space, and irregular water availability, conditions that can exacerbate decline symptoms and make early visual diagnoses feasible (Mullaney *et al*., 2015; Pretzsch *et al*., 2015). Because urban trees are usually individually accessible, repeated canopy assessments and bark inspections can be performed with finer temporal resolution than in forests. Urban monitoring could also benefit from high-resolution proximal sensing technologies, such as UAV multispectral imaging and terrestrial laser scanning, which have been shown to be effective for mapping fine-scale canopy decline and stem anomalies in heterogeneous forest environments (Ecke *et al*., 2022). Integrating urban data with forest monitoring improves detection of spatial clusters of decline, and refines risk models across landscape gradients (Figure 1).

Molecular diagnostic tools

Accurate diagnoses of oak decline require laboratory confirmations, as visible symptoms alone are often insufficient due to overlap between different biotic and abiotic disorders, including those caused by bacterial infections, insect damage, or root pathogens (Denman *et al*., 2010). This diagnostic uncertainty applies to acute and chronic decline syndromes, which may share external symptoms despite differing in causative agents and rates of progression. Molecular diagnostics increasingly complement field surveys and monitoring programmes, enabling early diagnoses of pathogens associated with decline, confirmation of visually suspected cases, and support for management decisions such as sanitation, selective removal, or containment.

Diagnostic tools for oak decline symptoms have expanded considerably in recent years, and now include conventional PCR, quantitative PCR (qPCR), high-resolution melting (HRM) analysis, and sequencing-based approaches, which are particularly useful for detecting bacterial taxa associated with rapidly progressing decline processes (Langer *et al*., 2025). Conventional PCR is widely used for detection of known pathogens, but provides only qualitative results, and is generally less sensitive than quantitative methods. In contrast, qPCR enables both detection and quantification of target DNA, making it possible to identify low pathogen amounts and infections at early stages (Mackay, 2004). High-resolution melting analyses allow discrimination of closely related taxa based on sequence variation, and have been successfully applied for plant pathogen diagnostics. However, HRM requires prior knowledge of target genomic regions (Reed *et al.,* 2007). Sequencing-based approaches, such as DNA metabarcoding and shotgun metagenomics, enable simultaneous detection of multiple microbial taxa without prior assumptions regarding the causal agents, making them particularly suitable for investigations of complex disease systems (Quince *et al*., 2017).

These methods are especially relevant for oak decline, where increasing evidence indicates that disease expression may result from complex multi-taxa interactions, rather than single-pathogen infections. In addition to targeted detection, microbiome- and metagenome-based studies have highlighted the frequent coexistence of multiple microbial taxa in symptomatic oak tissues, supporting the hypothesis that some forms of oak decline involve complex, multi-agent interactions rather than infections by individual pathogens (Denman *et al*., 2018). This view is consistent with evidence from plant microbiome studies, which highlight that plant diseases often involve complex interactions among multiple microbial taxa, rather than individual pathogens (Bulgarelli *et al*., 2013). Molecular diagnostics have also improved understanding of host ranges and geographic distributions of pathogens associated with decline, showing their occurrence across different oak species and environments, including in forest and urban settings. (Bene *et al*., 2025; Tkaczyk *et al*., 2025).

DNA-based methods are still essential for the differential diagnoses of oak decline syndromes. These include species-specific PCR assays, quantitative qPCR for pathogen quantification, HRM analyses for genotype discrimination, and sequencing-based approaches (e.g. metabarcoding and shotgun metagenomics). Thes tools are valuable for distinguishing pathogens that produce similar symptoms, but differ in biology, epidemiology, and host interactions. In Mediterranean oak ecosystems, root-infecting *Phytophthora* species have been identified as major contributors to chronic decline, often producing symptoms that overlap with other decline processes (Frisullo *et al*., 2018).

Despite their advantages, molecular diagnostics have limitations. DNA-based methods may detect genetic material from non-viable organisms, which can lead to false-positive interpretations of active infections (Nielsen *et al*., 2007). These limitations highlight the importance of integrating molecular diagnostics with field observations, ecological context, and physiological assessments, to ensure reliable disease interpretations (Martinelli *et al*., 2015). Integration of early molecular detection, differential diagnoses, and community-level analyses provides a robust framework for understanding oak decline. When combined with traditional field-based approaches, these tools enable accurate interpretation of acute and chronic syndromes, and support the development of effective disease management strategies (Figure 1).

Forest and urban management interventions for oak decline

Management of oak decline generally involves monitoring for infected trees and restricting access to affected areas, while tree felling is recommended only when a limited number of trees are affected, to reduce pathogen spread without unnecessary removal of healthy oaks

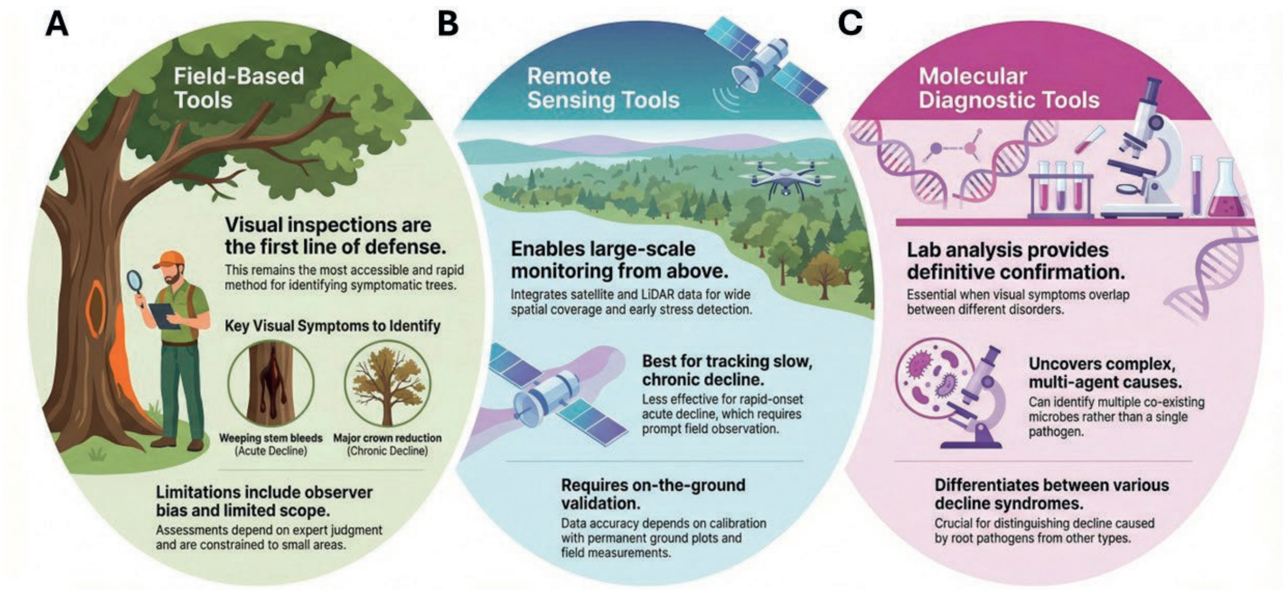

Figure 1. Monitoring oak decline: a three-pronged approach. A. Field-based tools; B. Remote sensing tools; C. Molecular diagnostic tools. Image generated by Google NotebookLM (2026).

(Denman *et al*., 2010). Given that forms of oak decline are frequently associated with stress factors (drought, resource competition, soil degradation), integration of silvicultural thinning, selective removal and soil and water management offers a comprehensive, ecosystem-based, management framework (Martinelli *et al*., 2015; Brown *et al*., 2018). Monitoring and recording symptomatic trees, including their location, distribution, and severity, are essential for effective and active forest management, enhancing the resilience of oak stands (Denman *et al*., 2010).

For monitoring, there are significant differences between forestry and urban settings. In forestry, oak management occurs at landscape scales, prioritizing ecosystem-level processes, and pathogen containment, considering distribution and severity of symptoms (Konijnendijk *et al*., 2005). In urban settings, monitoring is aimed towards risk management and public safety. Assessments are based on tree stability and potential danger to infrastructure and people, combined with rigorous hygiene and sanitation protocols (Jim and Zhang, 2013). Given these differences, managing urban oaks requires context-specific preventive and intervention strategies. These include adequate irrigation, avoiding overwatering that causes root rot, mulching around individual trees to ensure strong, healthy growth, and pruning to remove dead and damaged branches (Scharenbroch, 2009).

In addition to preventive measures, it is equally important to establish appropriate protocols for managing infected trees, to limit pathogen or disease spread, and ensure safety in urban areas. These can include removal and safe disposal of dead or severely diseased branches, avoiding pruning in wet conditions, and disinfecting all tools and equipment when moving from one tree to another. Infected trees are generally left in place unless urgent safety concerns arise, with efforts to minimise disease transmission. Where oaks must be felled, it is important to avoid wet conditions so as not to increase pathogen spread. Pruning is often discouraged in active decline sites as it can exacerbate tree stress and provide entry points for opportunistic pathogens (Pautasso *et al*., 2015). Where felling or pruning is necessary, destroying infected material on-site or through controlled disposal is essential to mitigate risk of long-distance pathogen transmission (Denman *et al*., 2010).

Thinning and removal of severely symptomatic trees

One of the main silvicultural interventions for oak decline management is controlled thinning of over dense stands. By reducing stand density, thinning relieves competition among trees for essential resources (light, water, nutrients), thereby improving vigour of residual trees. Silvicultural thinning can effectively buffer trees against climate induced stress. In oak stands, thinning may enhance above-ground tree vigour and below-ground resilience, as it has been shown to modify microbial composition and increase soil bacterial biomass under drought (Moreau *et al*., 2022). Evidence from broad-leaf forests across North America and Europe shows that tree thinning consistently reduces drought vulnerability, and enhances physiological resilience in mature forest stands (D'Amato *et al.,* 2013; George *et al*., 2022). In the context of oak decline, where stressors of drought and resource limitation are recognised as predisposing factors, increased vigour that can result from thinning may help to reduce vulnerability to opportunistic pathogens and secondary pests.

Selective removal of severely affected or heavily infested trees may further contribute to disease mitigation. Removing trees with advanced symptoms can lower local pathogen inoculum levels. Forest landscape modelling suggests that harvesting alternatives (thinning, group selection, clearcutting) can reduce potential for oak decline in high-risk sites during future decades, even though effectiveness varies among approaches (Wang *et al*., 2013). Management of infected wood involves avoiding felling in wet conditions, quickly removing and destroying bark and sapwood on site, disinfecting shredders and not using parts of infected trees for mulch or compost. Use of wood requires caution, with high-temperature treatments (>60 °C) being preferred to reduce the risk of bacterium survival (Denman *et al*., 2010). In managed stands with careful retention of structural biomass, group selection harvests were identified as particularly effective for limiting oak decline, while preserving ecosystem function (D'Amato *et al*., 2011).

Soil and water management

Improving site environmental conditions is important, because soil compaction, nutrient depletion, and water limitation are common stressors in oak woodlands. When these factors combine with frequent droughts, they can trigger or worsen decline phenomena (Gentilesca *et al*., 2017; García-Angulo *et al*., 2020). Improving soil structure, for example, by reducing compaction, increasing organic matter, and enhancing aeration and infiltration through mulching or maintaining understory vegetation, can improve root health and water availability. Appropriate soil management, including maintenance of organic topsoil layers, avoidance of compaction, and preservation of vegetation cover, improves soil structure and porosity, enhances water infiltration and retention, and thereby sustains forest hydrological functions, stabilises water yield, and reduces erosion and sediment load (Li, 2025; Gu *et al*. 2025).

Leaf litter and ground vegetation influence soil water retention, and availability during drought, emphasizing the importance of maintaining vegetation cover, minimizing soil compaction, and preserving organic matter (Schnabel *et al*., 2013). These factors can improve infiltration and water retention, whereas tree removal can increase drought and flood risk. Increasing organic carbon inputs around stressed or declining oaks can improve tree resilience. These practices can elevate soil pH and promote abundance of ammonia oxidizing bacteria, which play important roles in soil nitrification. Microbial conversion of ammonium to nitrate increases nitrogen availability a form that is readily taken up by trees (Denman *et al.,* 2010). High grazing pressure can reduce soil cover and disperse litter, making livestock control important in drought-prone oak woodlands (Johannesson and Ek, 2005; Schnabel *et al*., 2013).

Water management measures, such as preserving microtopography, reducing runoff, and increasing soil water retention, can buffer trees against seasonal water deficits, especially under climate pressures. In a Mediterranean oak forest, it has been shown that tree thinning may alter soil microbial communities and increase microbial biomass and enzyme activity during dry periods. This indicates that thinning may improve nutrient cycling and root nutrition under stress (Bastida *et al*., 2019). Silvicultural thinning can hence support above-ground tree vigour and below-ground functionality, by sustaining microbial processes that are critical for root performance. Experiments with clonal oak saplings (Quiroga-González *et al*., 2025) showed that while severe drought reduced soil bacterial richness and diversity, fungal communities were had increased resilience, and could increase their richness in favourable soil water-holding conditions. This evidence emphasizes how that microbial responses to drought are complex and species-specific, and that management must consider these dynamics. Interventions like thinning or selective removal, however, must be balanced with biodiversity conservation and long-term structural stability, since dead wood and complex forest structure are important for soil carbon storage, habitat, and soil-microbe interactions (Onoszko *et al*., 2025).

Water management is a strategy for mitigating effects of drought, heat waves, and combined stress on mature and young trees. This may involve maintaining or restoring local hydrological regimes, implementing measures to reduce runoff, or enhancing water retention through mulching or understory management. Water management strategies in forests should also consider landscape features. Lowland areas benefit from increased infiltration due to gentle slopes, whereas upland sites with steep slopes and shallow soils are more prone to runoff and to impacts of extreme rainfall (FAO, 2025). In addition, deep-rooted oaks may contribute to water redistribution through hydraulic lift, releasing water from deep soil layers into dry upper layers, thereby improving soil moisture availability and supporting tree and understory plant growth during dry periods (Caldwell *et al*., 1998; Jose *et al*., 2004). Long-term monitoring of precipitation, water tables, and streamflow helps guide management decisions, balancing water yield goals with biodiversity and slope stability considerations. Soil and water management combined with adaptive silviculture are a promising, though context-dependent, strategy to enhance oak resilience. Furthermore, afforestation and reforestation can enhance soil water buffering capacity, reducing short-term fluctuations in soil moisture, and contributing to stable water availability for trees and understory vegetation (Molenaar *et al*., 2024).

Insects and vector control

The main role of the putative vector of AOD bacteria, *A. biguttatus,* is yet to be defined (Gosling *et al*., 2024). This insect is known to be a secondary pest of already damaged trees, and its activity probably increases during warm and dry periods (Thomas *et al*., 2002). As climate models indicate increased duration of drought periods, particularly in the southern Mediterranean regions (Lionello and Scarascia, 2020), the impacts of these insects on worsening the AOD syndrome may pose further threats to survival of oak tree stands. While some trapping methods, such as multi-funnel and prism traps, either baited with kairomones or unbaited, can be used to assess and control beetle pest populations, research has shown that these strategies may affect non-target species, thus threatening the local biodiversity (Tiberi *et al*., 2016; Kuhn *et al.,* 2024; Gosling *et al.,* 2024). Therefore, while sanitary oak tree felling and removal of dead or damaged trees may reduce these vector populations (Thomas *et al.,* 2002, Tiberi *et al.,* 2016), the use of trapping methods should be assessed on a case-by-case basis.

Another option may include the use of biological control agents, such as parasites of Buprestidae (*Oobius agrili*, *Tetrastichus planipennisi*, *Spathius galinae*), but this must be carefully considered, as parasitism of non-target species may occur. For example, some parasitoids used against Emerald Ash Borer can also attack larvae of other *Agrilus* species, posing a risk to native beetles (Reed *et al*., 2025). In addition, recent modelling studies confirm that vehicles and forestry machinery can be effective anthropogenic vectors, accelerating spread of forest pests and pathogens through transport of contaminated soil and plant material. Spores and infected soil particles could be transported over long distances on heavy machinery (Meurisse *et al*., 2019). Consequently, management strategies should prioritise biosecurity measures, such as vehicle cleaning, tool disinfection, restricted access to infected sites, control of soil movement, and prohibition of soil removal from sites affected by oak decline (Carlin *et al*., 2025).

Tree replanting

Another important strategy is replanting of trees. This should favour choice of locally sourced specimens that are adapted to particular site conditions, avoiding entire replacement of diseased trees with the same species, and favouring mixtures of broad-leaf trees with a maximum of 25% susceptible species (Denman *et al*., 2010). Care should be taken with nursery stock from infected sites, and the public should be informed about the presence of diseased trees through information signs (Denman *et al*., 2010). A current recommendation is to completely avoid the species that were previously present, when replanting a site affected by AOD or COD (Denman *et al*., 2010), and to avoid non-native species whenever possible (Tomlinson *et al*., 2015). Native tree species should also be favoured due to their contributions to biodiversity compared to non-native species (Laux *et al*., 2022). Monocultural plantations should be avoided as these can be severely damaged in individual outbreaks (Raupp *et al*., 2006). This favours tree mixtures when the proportions of susceptible species must also be considered (Denman *et al*., 2010).

In addition, promoting mixed species stands and maintaining understory vegetation can help stabilise microclimatic conditions, reduce evapotranspiration stress, and enhance ecosystem resilience. Tree planting techniques also offer other possibilities beyond simply replanting oak trees. An example is the *Dehesa*, a traditional Spanish agroforestry system that combines oak trees with other crops, including winter cereals (Moreno Marcos *et al*., 2007a). Competition between trees and crops is mitigated by facilitating effects such as improved microclimates, and soil water retention and fertility, which are reduced in mature agroforestry systems (Jose *et al*., 2004). Abandonment of cultivation in *Dehesas* in recent decades contrasts with the evidence supporting their reintroduction. The deep and extensive root systems of holm oaks reduce competition with crops, while their tolerance to poor soils makes them particularly suitable for long-term agroforestry (Moreno Marcos *et al*., 2007b).

Management strategies that promote persistence or expansion of oak populations must also consider potential unintended consequences. Increased oak abundance or distribution may simultaneously facilitate expansion of oak-associated pests, particularly under conditions of increasing water stress (Pedersen and Jørum, 2009). When combined with the increased vulnerability of water-stressed trees to insects and pathogens, this process may contribute to increased and systematic decline of oak trees on regional and international scales (Jactel *et al*., 2012).

CONCLUSIONS AND FUTURE PERSPECTIVES

Management of oak decline currently relies on a set of established approaches, including field-based tree health assessments, adaptive silviculture, soil and water management, and increased support from remote sensing and molecular diagnostics. However, important gaps remain that limit the effectiveness of current disease management practices. There is still limited coherence on how and when these tools should be applied across different oak species, decline syndromes, and environmental contexts. The contribution of soil microbial communities to management outcomes remains poorly understood, standardised protocols linking monitoring to management decisions are lacking, and robust long-term evaluations of management interventions are scarce, across a wide range of oak ecosystems. Addressing these gaps is essential to move toward consistent, predictive, and evidence-based management of oak tree decline.

AUTHORSHIP CONTRIBUTION STATEMENT

Alessandro Bene: Methodology, Investigation, Writing – original draft (oak disease section). Marzia Vergine: Writing – review and editing. Letizia Portaccio: Methodology, Investigation, Writing – original draft (forest management section). Guido Piraino: Methodology, Investigation, Writing – original draft (insect vectors section). Luigi De Bellis: Review and editing, Supervision. Andrea Luvisi: Writing – review and editing, Visualization, Validation, Supervision.

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