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Review

Prospects for Oak Cultivation in Europe Under Changing Environmental Conditions and Increasing Pressure from Harmful Organisms

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Abstract: It is assumed that climate change (global warming) worsens the living conditions for conifers and at the same time favours the cultivation of deciduous trees, including oaks. In fact, in Poland, for example, many more oaks are now being planted as forest-forming tree species than in the 1980s and 1990s. However, the monitoring of the health status of European forests (according to the International Co-operation Project) does not confirm these optimistic assumptions, and oak has been cited as one of the most damaged tree species in terms of defoliation in recent decades. The prospects for oak cultivation in European forestry are therefore a combination of abiotic conditions and biotic damage factors. This review article focuses in particular on the new threats posed by pathogenic organisms causing emerging diseases. These include newly identified bacteria responsible for the so-called Acute Oak Decline (AOD), oomycetes (especially those specialised in damaging fine roots, such as *Phytophthora quercina* T.Jung) and semi-parasites of the genus *Loranthus*. At the same time, the pressure from commonly observed insects and fungi described in connection with the complex syndrome of oak decline, which is divided into predisposing, inciting, and contributing factors (according to Manion's disease spiral), has not abated. Therefore, international, interdisciplinary research (such as that proposed in Oakland) is needed, using modern technologies (RS remote sensing) based on the comparison of satellite images (from different years), not only to inventory the most valuable oak stands in Europe (microrefugia) but also to identify trends in changes in their condition and biodiversity. As RS has its limitations (e.g., resolution), aerial monitoring should be complemented by quantitative and qualitative inventory from the ground, e.g., monitoring of the presence of soil microorganisms using effective molecular biological methods (e.g., Next-Generation Sequencing NGS).

Keywords: remote sensing; Oakland; NGS; AOD; oomycetes; primary insects; secondary pests; *Loranthus*

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Citation: Lyubenova, A.; Baranowska, M.; Menkis, A.; Davydenko, K.; Nowakowska, J.; Borowik, P.; Oszako, T. Prospects for Oak Cultivation in Europe Under Changing Environmental Conditions and Increasing Pressure from Harmful Organisms. *Forests* **2024**, *15*, 2164. https://doi.org/10.3390/f15122164

Academic Editor: Tiziana Panzavolta

Received: 14 November 2024
Revised: 1 December 2024
Accepted: 5 December 2024
Published: 8 December 2024

1. Introduction

Healthy forests are essential for humanity. Although native forests are adapted to a certain level of disturbance, all forests face the challenge of coping with new pressures such as climate change, air pollution, and invasive pests [1]. The oak decline syndrome is a worldwide phenomenon that affects the entire distribution of oaks and has always been a cause of great concern. The general discussion about oak decline was part of the broader problem of forest decline [2].

Recently, the Polish Academy of Sciences developed a model of species distribution based on climate change scenarios [3]. They quantified the changes in predicted distribution ranges and threat levels until 2061–2080 for 12 European forest tree species under three climate change scenarios. They combined tree distribution data from the Global Biodiversity Information Facility, EUFORGEN, and forest inventories and developed species distribution models using MaxEnt and 19 bioclimatic variables. The models were developed for three climate change scenarios—optimistic, moderate and pessimistic—using three general circulation models for 2061–2080. The study revealed different responses of tree species to projected climate change. Species were categorised into three groups: "winners"—mainly late-growing species, namely *Abies alba* Mill., *Fagus sylvatica* L., *Fraxinus excelsior* L., *Quercus robur* L. and *Quercus petraea* (Matt.) Liebl.; "losers"—mainly pioneer species, namely *Betula pendula* Roth, *Larix decidua* Mill., *Picea abies* (L.) H.Karst. and *Pinus sylvestris* L.; and alien species—*Pseudotsuga menziesii* (Mirb.) Franco, *Quercus rubra* L. and *Robinia pseudoacacia* L.—which could also be considered "winners". Assuming restricted migration, most of the species analysed would face a significant reduction in the area of suitable habitat. The extent of the threat was greatest for the species that currently have the northernmost centres of distribution. The ecological consequences of the predicted reduction in range would be severe for both forestry and nature conservation. However, the above model does not take into account the harmful biotic factors that could change the prospects in the case of the so-called "winners". Ash trees are dying in Europe due to the pathogenic fungus *Hymenoscypus fraxineus* (T. Kowalski) Baral, Queloz & Hosoya, introduced from Asia [4], and European oaks are among the most defoliated tree species of the last decade according to the European health monitoring programme (ICP) [5,6].

Without considering insect pests and pathogens, especially those causing emerging diseases, it is therefore difficult to assess the future of silviculture in Europe. The decline of forests usually takes place over decades and is caused by a combination of biotic and abiotic stress factors that often interact at several trophic levels [7,8]. Climate change and other disturbances, such as human impact, have the potential to introduce new combinations of stressors that make predicting the effects of multiple stressors extremely difficult [8]. In addition, recent reports of population declines also mention emerging insects and pathogens, many of which are native species. This further complicates the nature of the changing patterns of forest decline in response to changing environmental conditions [7].

In this paper, we provide an overview of the phenomenon of oak decline in the light of recent findings on the role of various anthropogenic, ecological, and genetic factors, with a focus on emerging pathogens (alien invasive species). The recent alarming phenomenon of Acute Oak Decline (AOD) in Europe will be discussed, as well as perspectives on oak silviculture.

2. Oaks in Europe

Oaks are key players in the vegetation of the northern hemisphere and are considered the most diverse genus of temperate trees in the northern hemisphere [9]. In the Old Continent, the genus *Quercus* is widespread, despite a lower species richness of up to 30 species in Europe versus approximately 435 species in America and Asia. The most widely distributed in Europe are pedunculate (*Q. robur*) and sessile oaks (*Q. petraea*). They co-occur sympatrically, as a main component of temperate deciduous mixed forests, and share common characteristics. In addition to their undoubted economic and ecological importance, oak trees have a profound cultural significance throughout Europe [10]. Türkiye oak (*Quercus cerris* L.) is common in southern Europe, mainly in the Balkan and Italian peninsulas. The species has a good adaptability to a variety of different site conditions and has satisfactory tolerance to drought, although its wood is inferior [11]. *Q. robur*, *Q. petraea*, and *Q. cerris* represent an economically important basis of forestry in certain parts of Europe [2]. Other important oak species are the light-demanding Hungarian oak (*Quercus* *frainetto* Ten.), the evergreen holm oak (*Quercus ilex* L.), the cork oak (*Quercus suber* L.), and the pubescent oak (*Quercus pubescens* Willd.) [12]. In the eighteenth century, originating from North America, the Northern red oak, *Q. rubra*, has been introduced into Europe. Initially established in botanical gardens, via planted forests, *Q. rubra* is now widely used in operational forestry across the continent [13]. The current distribution of oak forests is expected to change significantly in the future. Climate change, agricultural intensification and land abandonment are recognised as the key drivers for the variations in oak species biogeography. Model predictions for *Quercus ilex*, *Q. suber*, *Q. robur* and *Q. petraea* in Europe project the change in suitable habitats in geographic space for these species. The general patterns through time show a shift to the northeast for *Q. robur*, as well as for *Q. petrea*, albeit less pronounced. *Q. ilex* will disappear in the southwestern regions of Spain and will adapt to new suitable habitats in western France, consistent with the current observations of its spread from plantations in that area [14].

3. Early and Contemporary Forest Decline Etiology Concepts

The most prominent concepts of early forest decline etiology, which analyse the complex interactions between host, site, climate and one or more pathogens, have been put forward by [15]. Examining the forest decline as a class of disease, the authors highlight three approaches: the "host, stress, pathogen" concept, the "predisposing, inciting and contributing factors" concept and the "poorly understood aetiology" concept. The role of climatic perturbations as a universal inciting factor for decline has been specified. It is suggested that in boreal and temperate forests, decline is initiated by a winter thaw/freeze event. It was found that this was common to a variety of decline events in America and Europe [15].

Manion [16] developed these early concepts further by proposing a framework for considering the concept of "healthy levels of disease" based on the Phoenix Helix metaphor and the basic procedures for assessing mortality. Forests sustain life through the process of decay, but they also sustain the ecosystem by suffering incremental losses over time. A remarkable perspective on emerging pests and the mechanisms of mortality during decline is presented by [7]. The authors consider the pathogens responsible for forest decline in the recent past that have not been previously reported or discovered in the role of major causal agents, many of which are native insects and diseases.

Using literature from across European oak ecosystems, and based on Manion's decline model, the abiotic and biotic factors associated with oak declines in *Q. robur* and *Q. petraea* have been discussed recently by [17]. The role of soil condition, mycorrhiza and pollution as predisposing factors in oak decline are considered alongside the genetic predisposition. The main indicated inciting factors are drought, other climatic factors, and defoliating insects, while pathogens and wood- and bark-boring insects were identified as the main contributing factors. The authors conclude that more research is needed to understand the role of extreme frost, waterlogging, soil properties, land management, nitrogen and heavy metal pollution, genetic predisposition, and mycorrhizal changes [17].

The death of oaks occurs at regular intervals, hence the hypothesis that when the trees are growing in optimal conditions, there is enough water with mineral salts for all of them. However, if the conditions suddenly deteriorate, e.g., due to drought, the strong competition between the oaks leads to a lack of nutrients for all the oaks, and the process of dieback begins. This situation occurred in Poland in the 1980s. In 1981, there was a lot of precipitation, followed by a severe drought (1982–1984). Trees with shallow roots (0.5–1.0 m) died first. This in turn led to a decrease in competition between the trees, and the trees remaining in the stand revived for many years until the next unfavourable period in 2000–2006. Then, additional weakened trees were killed by insects of the genus *Agrillus* (mainly *Agrilus biguttatus* (Fabricius, 1776)), whose population increased dramatically.

Sessile oaks have deeper roots and a higher root biomass than English oaks, which makes them more resistant to severe drought. In addition, their leaves contain more bitter tannins, which discourages primary insects from eating them. Therefore, mixing both oak species in a stand has a good chance of reducing the risk of dieback and achieving the breeding objective (maintaining the forest until harvest age).

Another survival strategy of oaks is to extend the period of leaf production in spring (early and late flushing) [18]. As a rule, early varieties (*praecox*) are more damaged than late varieties (*tardive*) by the development of the insect population, which generally also adapts to the development of the trees. From this point of view, silviculture in stands with both oak species and their different varieties (*praecox* and *tardive*) spreads the risk of massive tree mortality and supports not only the main silvicultural goal of foresters, namely the preservation of the forest until felling age but also the biodiversity of the forest ecosystem.

4. Analysis of Oak Decline: Symptoms and Occurrence in Europe

Oak decline has occurred regularly in European forests in recent decades [15,19,20]. The symptoms described in the literature in connection with oak decline are complex and complicated. The syndrome has been observed in all age groups [2]. The different symptoms may not occur synchronously and vary in severity. Individual trees or groups of trees, parts of stands, or, in rare cases, entire stands may be affected [21]. According to many authors, oak disease can be chronic or acute. In the chronic form, there is a weakening of the crown in the upper part and a yellow-green discolouration of the leaves [22], due to abnormally increased branch shedding and the death of buds and branches in the upper canopy, accompanied by gradual leaf fall [21]. This process can take 3–4 or even 10 years [22]. In some cases, when environmental conditions improve, the loss of branches can be compensated by the production of new branches in the following growing seasons and the crown can fully recover. However, the symptoms and causative factors are not the same in all regions [21]. The acute condition begins with the wilting of leaves on individual shoots or on the entire crown, starting at the top of the tree in a very short time. The dry leaves remain on the shoots for a while. The crown gradually becomes bare as individual shoots die off. Adventitious buds can often develop on dying trees, covering a large part of the boot from base to tip. In the final stage, the roots also begin to die off [22]. Other reported symptoms include dark slimy exudates flowing from small cracks in the bark, especially on the trunk of *Q. cerris*. They are usually associated with numerous fungi and bacteria and internal xylem discolouration. The dark stoma formation typical of *Hypoxylon mediterraneum* (De Not.) Ces. & De Not. can be observed under the bark of severely decaying plants [23].

Episodes of oak mortality occurred several times in northwest Germany between 1910 and 1940 and after 1987 and 1997. Cycles of rapid mortality in local but widespread centres were observed, followed by decreasing and slower mortality. It was found that these cycles can last up to 10 years and are sometimes preceded by a reduced growth phase [21]. Thomas and colleagues propose a conceptual model of the interplay of abiotic and biotic factors responsible for the onset of oak mortality. This model applies to Central European oak stands on rather acidic sites (soil pH (H_2O) $\leq$ 4.2). According to their hypothesis, heavy insect infestation in at least two consecutive years in combination with climatic extremes (summer drought or winter/spring frost or both) is the most important factor complex for the onset of oak mortality. Important additional stress factors are the hydromorphic site conditions and possibly an excess of nitrogen.

Reports of oak decline from all over the world have been found in the scientific literature since the early 1900s [24]. Oak decline was first mentioned in Germany in 1739, followed by Switzerland and Hungary (1850 and 1877, respectively). In the 20th century, it was reported from all other European countries, with Spain being the last country to be added [25].

In Eastern Europe, in the European part of the former Soviet Union, the largest outbreaks of oak decline have been observed at regular intervals since 1901–1906, 1927–1930, 1941–1944, and 1964–1980. Most researchers working on this problem at the time linked the observed oak decline during this period to unfavourable climatic factors or even pointed out that they were the main cause of the weakening of the stands [22].

In Poland, abnormal oak mortality was first observed in the early 1980s. The catastrophic oak mortality, which began in 1981, was associated with the exceptional summer drought of 1982 [26]. In 1984–1985, oak mortality spread very rapidly across the country [27]. Mortality events in cork and holm oaks have occurred in the Mediterranean region since the beginning of the 20th century, but the severity of the decline increased in the 1980s. These accidents have been linked to the combined effect of the invasive pathogen *Phytophthora cinnamomi* Rands and drought events [28].

Since around 1983, more and more cases of oak decline have been reported in Italy, especially in the southern regions. Several oak species (*Q. cerris*, *Q. frainetto*, *Q. pubescens*, and *Quercus trojana* Webb) were affected. The subsequent study in the oak forests of Southern Italy shows that various factors play a role. The conclusion suggests that low rainfall combined with inappropriate silvicultural practices are the cause of the general weakening of the trees, predisposing the plants to attack by weak and/or opportunistic fungal pathogens [23].

In Bulgaria, large parts of the oak forests are located in densely populated areas or in areas with intensive recreational activities. For anthropogenic reasons, the most important occurrences of *Q. robur*, the most valuable oak species, have been destroyed. Since 1950, extensive research has been carried out in Bulgaria in the field of silviculture, and it was found that the outbreaks of tree mortality coincide with the period of the previous prolonged droughts (e.g., 1945–1950). It was found that tree dieback usually starts from the top, and in this case, *Cerambyx cerdo* Linnaeus, 1758 is always found. Sometimes, however, the process begins with the appearance of canker wounds that gradually affect the whole tree. It has been shown that flat, south-facing soils are more favourable for the occurrence of oak decline. The Türkiye oak proves to be more resistant to the syndrome than the Hungarian oak. Oak dieback affects trees of all ages, but pure oak plantations are affected to a much greater extent than mixed plantations. In the years before the outbreak of decline, growth is weak in spring, which is due to the mass development of herbivorous insects and mildew. Grazing by domestic animals also favours the occurrence of oak decline [29].

5. The Role of Interactions Between Abiotic and Biotic Factors in Oak Decline

Forests are increasingly threatened by climate-related stress factors such as droughts, heat waves and intense precipitation, which challenge the adaptive capacity of long-lived tree species such as oak [30]. This increased stress leads to increased susceptibility to pathogens and herbivorous insects and carries the risk of biodiversity loss and ecosystem degradation for important tree species such as oak decline [31,32]. Oaks, for example, are associated with various fungal species such as *Fistulina hepatica* (Schaeff.) With., which are themselves endangered. Many of these fungi, including those that live in the soil and form mycorrhizal networks, remain unrecognised locally. Meanwhile, invasive alien fungal species are causing new diseases that threaten the diversity of oak ecosystems. Oak forests are crucial for biodiversity conservation as they harbour more than 2300 species, including fungi, invertebrates, lichens, birds and mammals, many of which are strongly or obligatorily associated with oaks [33].

In most studies, the decline of oaks is attributed to a complex interaction of several biotic and abiotic factors [21]. Most episodes of oak decline are associated with repeated and prolonged climatic stresses such as drought, waterlogging, frost or unusually high temperatures [34].

There is a broad consensus that temperatures in large parts of the world will be warmer in the future. If climatic conditions are favourable and the environmental requirements of pathogens are met, there may be an outbreak of disease or epidemics. The changes in climatic conditions over the last 60 years, i.e., the increase in mean winter temperatures, the shift in seasonal precipitation from summer to winter and the tendency towards heavy rainfall, favour infection by several *Phytophthora* species in Central Europe. Floods and droughts are generally accepted as triggers of oak decline [7,26,27,34–38].

6. Biotic Factors and Invasive Species

In the past, the dieback of oak has been attributed to pathogens like the causative agent of oak mildew *Erysiphe alphitoides* (Griffon & Maublanc) Braun & Takamatsu (*Microsphaera quercina* (SchW.) Burrill—old) and the root-system-inhibiting fungus *Armillaria mellea* (Vahl) Kummer. The opinions about the role of *A. mellea* have been at both extremes—from considering it as one of the most dangerous factors to the understanding that its principal role was to kill off trees that were already "irretrievably damaged". Subsequently, at least seven species with different ecological and pathological characteristics within *the A. mellea* sensu lato complex were identified [39].

The oak powdery mildew has been recorded since the beginning of the 20th century in Europe on *Q. robur* and *Q. petraea*. The most common species is *E. alphitoides*, followed by *Erysiphe hypophylla* (Nevod.) U. Braun & Cunningt. and *Erysiphe quercicola* U. Braun & Y.S. Paul. *E. alphitoides* was found to be spread throughout Europe and is regarded as having high invasive success. The species is characterised by tolerance to a wide range of environmental conditions, while *E. quercicola* and *E. hypophylla* display more restricted and mostly separate areas of distribution [40]. Invasive alien species (IAS) are a major component of human-induced global environmental change, and their negative impact on biodiversity is responsible for dramatic consequences and high economic costs. This points to a recent and rapid increase in the number and impact of IASs [41].

The invasive oak lace bug (OLB) (*Corythucha arcuata* (Say)) was first discovered in Europe in 2000 in northern Italy [42]. After only a decade, an explosive spread was observed, and by 2019, it had been detected in 20 countries. The host range includes almost all Eurasian deciduous oak species and many other woody plants (*Rubus*, *Corylus*, *Acer*, etc.), which means that the lack of suitable hosts will not limit its further spread. The oak bug is a typical "hitchhiker"—it can "jump" great distances in a short time via road and rail transport. The rapid spread and significant population growth in consecutive years in some recently invaded European countries indicate a considerable risk potential. The newly introduced pest that can severely affect the physiology of oak trees will lead to worsening prospects for oak forests, particularly if damage persists. An additional risk is the possibility that OLB could transmit leaf pathogens [43].

Co-infections with multiple *Phytophthora* species are often associated with dying trees. Phosphite, applied as a trunk injection, foliar spray, or soil drench, can inhibit the growth and sporulation of *Phytophthora* species. It has been used for preventing or slowing the spread of *Phytophthora* in significant stands. For instance, in Spain, the crown conditions of *Phytophthora*-infected *Quercus ilex* were improved after phosphite application through foliar and trunk spray. These methods were widely used in natural ecosystems in Western Australia against *P. cinnamomi* for the protection of vulnerable plants. A reduction was demonstrated in the *Phytophthora* inoculum load in the soil around phosphite-treated plants [44].

The basis for the development of a cost-effective agent for the control of *Phytophthora* spp. on oaks was proposed by [45]. In field trials conducted over several years, the efficacy of potassium phosphite applied as a foliar or trunk spray was investigated. The health of *Q. robur* trees was shown to improve, and no negative effects on growth, the endophyte community or the soil microbiota were observed.

The investigation of the impact and role of the charcoal disease *Biscogniauxia mediterranea* (de Notaris) Kuntze in the decline of oaks in a relict forest in Italy revealed a close correlation between oaks with a pronounced decline in vigour and the occurrence of *B. mediterranea*. The study was triggered by the dramatic increase in the infestation of oaks in this forest with the fungus, which is probably linked to the hot temperatures and recurring droughts that chronically weaken the trees [46].

Acute Oak Decline (AOD) is destroying thousands of native oaks, *Quercus robur* and *Q. petraea*, in continental Europe and the UK. The syndrome is caused by the decomposition of the inner bark tissue caused by the development of several species of bacteria. Despite the close association between the two spotted oak buprestids *Agrilus biguttatus* and AOD, its role remains unclear. Using novel dendrochronological modelling, researchers have shown that decades of reduced stem growth predispose the trees to acute oak dieback. In the study, novel statistical techniques were developed to analyse dendrochronological data, enabling a simplified analysis of stem growth and facilitating its use as a tool to determine the health status of tree stands [47]. The bacterial species *Brenneria goodwinii* Denman, Brady, Kirk, Cleenwerck, Venter, Coutinho & de Vos and *Gibbsiella quercinecans* Brady et al., the causative agents of AOD, were detected for the first time in Poland in 2021 in weakened *Quercus robur* stands. The presence of the bacteria was confirmed by real-time PCR in the exudates in bark cracks of oaks with observed AOD decline symptoms [48,49].

Another study used a metagenomic approach to determine whether four AOD-associated bacteria previously identified in stem sap exudates were present in symptomatic, asymptomatic and "in remission" native oaks with Acute Oak Decline. The aim was to determine if there were differences between the geographical locations and between the health groups sampled at each site. It was concluded that AOD-associated bacteria may be members of the normal oak microbiome, whose presence on a tree is not sufficient to cause AOD symptoms [50].

6.1. The Menace of Oaks by Loranthus europaeus

Loranthus europaeus Jacquin 1762 is a hemiparasitic, dioecious shrub from the order *Santalales* and the family *Loranthaceae* [51]. It most frequently attacks oaks (*Quercus* sp.), which is why it is also called oak mistletoe [52] and yellow mistletoe because of the colour of its fruits. In places where *L. europaeus* grows into the host, an overgrowth of the host plant tissue occurs [53]. This area resembles a tumour that can reach a diameter of over 30 cm [54,55]. Host plants for *L. europaeus* include *Q. brantii* Lindl. (*Q. persica* Jaub. & Spach; [56,57], *Q. cerris* L. [53,58,59], *Q. dalechampii* Ten. [60], *Q. frainetto* Ten. [58,60,61], *Q. libani* G. Olivier., *Q. infectoria* G.Olivier [62], *Q. palustris* Muenchh [60,63], *Q. pedunculiflora* K. Koch [64], *Q. petraea* (Mattus.) Liebl. [53,58,65–67], *Q. pubescens* Willd. [60,63,68], *Q. robur* L. [58,60,63,65], *Q. virginiana* Mill. [60], and *Q. rubra* L. [60,63]. The natural range of *L. europaeus* overlaps with the distribution area of oaks (Figure 1). It is predicted that global warming will favour the expansion of the range of *L. europaeus* [69].

Figure 1. Current range of *L. europaeus* (map generated in Google My Maps based on data from the literature cited above and selected verified coordinates from the GBIF portal) GBFI.org (2024) [70].

Loranthus europaeus is particularly dangerous for oaks that are exposed to a water deficit caused by drought. Drought and global warming make host trees more susceptible to infection by *L. europaeus* [36]. Forest fragmentation is considered to be a factor that promotes the spread of *L. europaeus* [71]. The better the condition of the oaks, the less effective the infection by *L. europaeus*. With sufficient moisture and nutrients, the host tree grows well and can even shade the mistletoe, but in dry and barren areas, the oak grows more slowly and thus provides good conditions for the mistletoe to thrive, ultimately leading to severe disease consequences. The spatial distribution of mistletoe is influenced by the distribution of hosts [72–74]. As for the abundance of *L. europaeus* in *Q. petraea* stands, it has been shown to be higher in trees with larger diameters [67]. *Loranthus europaeus* is a factor that accelerates the ageing of the crowns of infected trees, and the passage of time plays an important role in determining the distribution of mistletoe in the stand [67]. Idžojtić et al. [75] showed that the older the trees, the lower the height, and the sparser the stands, the more trees are *L. europaeus*. Ogris et al. [54], Millaku et al. [61] confirmed that the older the stand, the greater the susceptibility to infection by *L. europaeus*. Another factor that influences the susceptibility of trees to infection is their genotypic characteristics. The individual susceptibility of oak to infection with *L. europaeus* may pose a potential threat to an increasing number of genotypes of this tree species that are susceptible to mistletoe infection [76]. Eliáš [77] showed that *L. europaeus* occurred in hornbeam forests only on oaks (*Q. cerris* and *Q. petraea*). It did not infect hornbeam (*Carpinus* sp.), although it was most common in these habitats [77].

According to Kubíček et al. [78], in protecting stands from *L. europaeus*, it is important to focus on proper management, primarily protecting young trees from drought (introducing drought-resistant species and increasing species diversity). Ogris et al. [54] suggest that in a stand infected by *L. europaeus*, the proportion of trees should be reduced in the long term and replaced with species adapted to dry and warm habitats. Removing infected trees, especially those with the largest diameters, should limit the spread of *L. europaeus* [78]. Bratanova-Dancheva et al. [79] emphasise the need to focus on the individual protection of infected trees. One proposed method for combating *L. europaeus* is the use of herbicide sprays based on glyphosate salts [78]. The use of dark foils to limit *L. europaeus*' access to light has also been tested, but unfortunately, this does not prevent its regrowth [80]. Inventory plays a significant role in the context of protecting trees from *L. europaeus* [65,81].

Loranthus europaeus should be considered as an indicator of habitat health or, in the case of heavy infestation, as a signal of landscape disturbance [82]. The frequent occurrence of *L. europaeus* indicates a poor state of the population [83]. Trees infested by *L. europaeus* show reduced growth, and heavy infestation leads to their decline [59,65,84]. Heavy infestation by *L. europaeus* leads to a loss of wood quality [53]. Naseri et al. [85] reported that the mortality rate of oaks infected with *L. europaeus* was higher than that of uninfected oaks. Oaks colonised by *L. europaeus* show reduced growth and physiological efficiency [86].

Trees colonised by *L. europaeus* are more susceptible to secondary abiotic and biotic factors (insects, fungi such as *Armillaria* sp., *Ophiostoma* sp., etc.; [55]. Ogris et al. [54] report that trees damaged by *L. europaeus* are weakened and more easily infected by dead or broken branches. They are attacked by various types of fungi that cause wood rot, such as fungi of the genus *Phellinus*. The following fungi have been isolated from the branches of mistletoe-infested oaks: *Colpoma quercinum* (Pers.) Wallr., *Caudospora* sp., *Coryneum elevatum* (Riess) B. Sutton, *Valsa intermedia* Nitschke, and *Stereum* sp. These fungi become pathogenic for oaks when exposed to stress factors [54].

6.2. Genetic Factors Influencing Oak Decline in Europe

The decline of oaks (*Quercus* sp.) in Europe is associated with various genetic factors in addition to environmental stressors. Many studies show that the decline of oaks is multifaceted and affects the genetic diversity of the trees, the ability of oak stands to adapt to climate change and infections by pathogens, and the ability to develop symbiotic relationships with soil microorganisms.

The genetic variation of the species studied should be described in order to understand the relationship between genetic variation and resilience or adaptation processes. First, nuclear and organelle-based diversity in *Quercus robur* and *Q. petraea* studies in Europe showed significant differentiation between oak populations centred on polymorphic regions in the chloroplast DNA [87]. Indeed, based on the maternal inheritance model, chloroplast markers (cpDNA) helped to describe the phylogenetic lineages of oaks in Europe and showed a higher degree of variability within populations compared to the degree of variability based on nuclear DNA markers [87]. Later, detailed studies on the distribution of chloroplast DNA (cpDNA) haplotypes were described, e.g., for Great Britain [88], Denmark [89], France [90], Spain [91], the Baltic countries [92], and 2600 populations from Europe [90], and Poland [93]. These studies confirmed that the geographical diversity of cpDNA is related to the geographical location of the populations studied, which originate from the three main southern European refugia, namely the Iberian Peninsula, the Apennines, and the Balkans [90]. Based on analyses of the chloroplast DNA of oaks from all over Europe, it was found that the population groups of types "A", "D" and "E" originate from the Balkan Peninsula refugium, group "B" from the Iberian Peninsula, and group "C" from the Apennine Peninsula [90,94]. Along with the migration of the oak from south to north, a decrease in genetic variability based on cpDNA was observed. The oak populations in the Iberian Peninsula showed the highest coefficient of variation—HT = 0.804—compared to the French populations—HT = 0.734, the British HT = 0.629 and the Irish HT = 0.374 [88,90,91]. This is partly due to the loss of alleles during species migration and partly due to the gradual adaptation of populations to changing climatic conditions with latitude. Interestingly, Polish populations of *Q. robur*, especially from the Krotoszyn Plateau (the central part of the country), showed a higher overall level of genetic variability (HT = 0.809) than other regions of Poland [93] (Nowakowska observations), which is probably due to the fact that at least three post-glacial refugia, namely the Balkan, Apennine, and Iberian Peninsulas, are connected.

It can be assumed that a more diverse gene pool of a species promotes the probability of the occurrence of a favourable allele combination and thus ensures the survival and adaptation of the population to changing environmental conditions [95–97]. The likely reason for the higher resilience of genetically more diverse populations is their greater ability to adapt to abiotic [98] and biotic stresses [99]. Some research using advanced sequencing and transcriptome analysis techniques is shedding light on the putative genetic mechanisms that enable oaks to respond to drought, frost and other environmental stresses, which is fundamental to understanding the phenomenon of oak dieback [100–103]. In the study of oak decline, the role of mycorrhizal fungi also appears to be related to the genetic makeup of oaks and may have an indirect effect on tree health and/or decline [50].

Summing up, the genetic variability of oak populations has a major impact on the processes of adaptation and survival of a stand prone to decline. Advanced studies at the genomic sequencing level indicate a better adaptation of oak stands that harbour higher genetic diversity to both abiotic and biotic external factors, favouring the weakening of the trees. Despite many unknowns in the relationship between genetic structure and plant response to the decline phenomenon, further research in these areas is essential for developing effective conservation and management strategies for oak forests.

7. Other Factors Involved in Oak Damage and Dieback Processes

In the 1980s, Ophiostomatales fungi (*Ophiostoma* or *Ceratocystis* spp.) were blamed for oak dieback and labelled as a vascular disease of oaks in Poland [104]. However, the artificial inoculation of young oaks with isolated tree vascular fungi (xylem fungi) did not confirm that they were responsible for the dieback. They only caused wood discolouration and were otherwise found in the living tree tissue, so it was assumed that their endotrophic way of life was their strategy to be the first to invade the tissue, namely the water-bearing vessels after the tree died (where they were most frequently found). Thus, they not only did not cause tree decay, as suspected, but perhaps also prevented the colonisation of the tissue by the pathogenic fungus *Ceratocystis fagacearum* (Bretz) J. Hunt (now *Bretziella* (Bretz) Z.W. de Beer, Marincowitz, T.A. Duong & M.J. Wingfield), as endophytes do on the American continent [105].

At the same time, other hypotheses assumed that air pollution, eutrophication, and nutrient imbalances leading to chemical stress in the soil were the causes of forest dieback (including oak stands). It was also assumed that forest dieback was a result of acid rain. However, in the 1990s, it turned out that European forests were growing remarkably well (doubling their annual growth), presumably due to N or S deposition [106]. This theory has therefore collapsed, apart from proven localised leaf burning near industrial plants.

Until recently, little was known about the role of *Phytophthora* species in oak forests and their importance for tree mortality. In the 2000s and with the development of molecular biological methods, many new species of *Phytophthora* were identified, including a species specialised in damaging the fine roots of oak *Phytophthora quercina* T.Jung [107,108]. Many of them can be transmitted via soil and watercourses. Some have many potential hosts. Recently, the pathogen *P. cinnamomi* was detected in the most valuable oak stands in the forest area of Krotoszyn (western Poland) (data not yet published).

There has been much talk recently about the acute decline of oak trees in Britain and the buprestid beetle, *Agrilus biguttatus*. However, from the 1980s until today, the mass mortality of oak stands in Europe, including Poland, has been observed [109] as a multifactorial process [110]. In North America, the phenomenon of oak decline is also treated as a complex process [98,111]. To date, a number of harmful biotic and abiotic factors have been described [21,98,112,113]. Prolonged exposure to such factors causes physiological stress and triggers immune processes in the trees [114]. In situations where soil water is scarce, plant defence mechanisms against pests are limited. The first natural defence process is the moistening of the wood (wet wood), which probably leads to a reduction in oxygen content and hinders colonisation by secondary pests (e.g., *Agrilus*) [115]. When the damage to the foliage (defoliation) occurs for the first time, the damage is much greater (and even leads to the death of the tree) than when it occurs repeatedly (the tree then develops defence mechanisms) [111]. So when the damaging factor disappears, the trees remain in a state of heightened alertness (priming) and can pass this information on to their offspring [116]. Oaks, which are frequently damaged by primary pests (leaf pests), retain an increased phenolic acid content in their leaves, which discourages insects from eating them. For this reason, primary leaf insects tend to feed on pedunculate oaks, which contain less bitter tannins than sessile oaks.

Global warming and the international trade in plant material promote the spread and occupation of new ecological niches by new invasive pathogens and insect pests [117]. This phenomenon is exacerbated by the opening of borders in Europe, which favours the spread of pathogens that were previously only found in southern European countries, such as *Phytophthora cinnamomi, Phytophthora ramorum* Werres, De Cock & Man in't Veld and *Phytophthora kernoviae* Brasier, Beales & S.A. Kirk [118]. More recently, oomycetes of the genus *Phytophthora*, especially the specialised species *P. quercina* [119–121], have been implicated as causing damage to even 90% of fine roots [122]. There is also a recurring concept of bacterial damage to tree taxa described in the 1980s as *Pseudomonas* spp. and *Xanthomonas* sp., mainly because the aforementioned species *B. goodwinii* has recently been identified from exudates occurring on oak bark in spring and autumn [99,123]. However, there is no information on the dispersal mechanisms and mode of entry of *B. goodwinii* into oak tissue, although artificial inoculations of 3-year-old pedunculate oak seedlings have confirmed the pathogenicity of these organisms [124]. It is also likely that endophytic bacteria populate the sap seeping under the bark in winter and only become visible during spring warming (Oszako personal information). At that time, their massive growth and gaseous metabolites exert mechanical pressure on the bark, which cracks and secretes sap, from which the aforementioned bacteria can be easily isolated. However, the cause of such sap-filled pockets under the cortex could be water disorders caused by root-damaging organisms, e.g., *Phytophthora* or *Armillaria*, or physiological disorders, e.g., embolism. This hypothesis requires further research.

8. Need for Further Research

There is an urgent need to conserve European oak forests (*Quercus robur* and *Q. petraea*), which are crucial for the protection of biodiversity, provide important ecosystem services and represent a cultural heritage. The effects of climate change, including rising temperatures, changing precipitation patterns and extreme climate events, are threatening these ecosystems through increasing stress factors such as pests and pathogens. This situation jeopardises both the oak species and the rich biodiversity they support. This includes over 2300 species associated with oak ecosystems [33].

Five countries (Bulgaria, Lithuania, Poland, Romania and Sweden) have formed a consortium and developed project proposals as part of the European Biodiversa programme OAKLAND (Figure 2). The overall aim of the OAKLAND project is to develop a comprehensive, science-based framework for maintaining the resilience of oak forests and their biodiversity under the pressures of climate change. The specific objectives focus on

- Creating a high-resolution, integrated map of European oak forests that prioritises ecosystem conservation based on ecosystem health, species richness and climate resilience in the project partners' countries.
- Establishing a network of oak microrefugia ("oak islands") that provide climatically buffered habitats to support biodiversity and genetic diversity under changing environmental conditions.
- Developing a system to assess the resilience of oak forests based on the co-migration potential of oaks and species dependent on them (e.g., fungi, lichens, insects).
- The identification of priority protected areas within the oak distribution range in the partner countries, especially in the high-risk zones in southern Europe, and the development of policy recommendations that take into account ecological, social and economic factors.

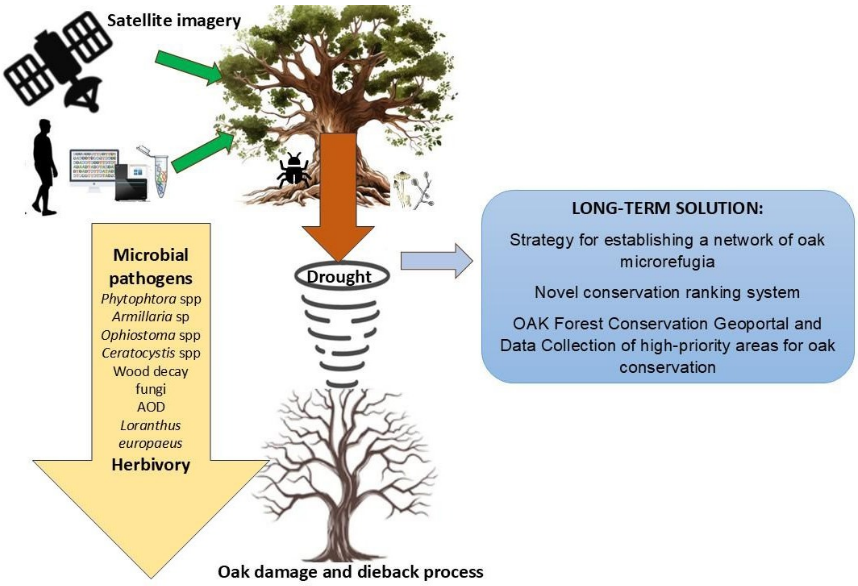

Figure 2. Conceptual scheme of the OAKLAND project.

The project is organised into four interlinked work packages, each targeting specific aspects of conservation and delivering actionable results. The OAKLAND project is based on the theoretical framework of ecological resilience and adaptive forest management as an important response to the impacts of climate change on forest ecosystems. In particular, oak-dominated forests harbour unique communities of high conservation value, especially in Fennoscandia, where over 700 oak-associated species are listed as protected or endangered [125,126]. Effective conservation requires not only protected areas but also targeted measures in managed forests, such as the preservation of living and dead trees and the conservation of important habitats [127,128]. The OAKLAND approach involves the identification of microrefugia—small, climatically buffered sites that protect biodiversity by providing stable habitats in the midst of a changing climate [129]. This concept is in line with the realisation that such refugia can harbour unique genetic diversity, which is crucial for the adaptability of species to environmental change [130]. To counteract potential losses, especially of mature oaks that serve as habitats for species such as the hermit beetle or the stag beetle, OAKLAND's data-driven approach includes remote sensing technologies for small-scale monitoring. This method improves the understanding of biodiversity patterns and adaptation strategies across a wide range of oak distribution, which ultimately supports large-scale conservation planning [131]. By integrating ecological, social and economic aspects, OAKLAND will contribute to the goals of sustainable forest management, which are in line with the objectives of the EU Biodiversity and Forests Strategy to 2030. Achieving these goals requires continuous monitoring and adaptive interventions to maintain oak ecosystems as important providers of ecological and socio-cultural benefits across Europe.

The research questions of the project, which are being addressed by various working groups, are as follows:

- How can we effectively integrate satellite-based RS and ground survey data into a comprehensive geoportal for real-time monitoring and management of oak-dominated forest ecosystems?
- What criteria should be used to identify and prioritise microrefugia suitable for the conservation of oak-dominated forest ecosystems, and how can we evaluate their effectiveness in promoting biodiversity?
- How can we prioritise protected areas by assessing the co-migration dynamics between oak and its dependent species to create a conservation ranking system that quantifies forest resilience?
- What are the key socio-ecological factors that influence the vulnerability of oak forests and how can we incorporate social value into conservation planning? What are the key elements and possible strategies of biodiversity-focussed forest management in combination with viable forestry?

We established the following research hypotheses.

- The integration of RS data with ground-based biodiversity assessments in the OAKLAND forest conservation geoportal will enable the accurate monitoring of oak-dominated forests and improve the precision of conservation prioritisation. In particular, the combination of these data sources will identify priority conservation areas based on key indicators such as species richness, oak health, and climate resilience.
- Micro refugia selected based on specific climatic and ecological criteria (e.g., soil characteristics, shading, temperature and humidity) will have a greater capacity to conserve species and greater resilience to climatic stressors compared to areas that are not refugia. These microrefugia will more effectively support oak-associated biodiversity by buffering environmental extremes and providing habitat for endangered species, thereby maintaining genetic diversity.
- A conservation status classification system that takes into account the co-migration dynamics between the oak and its dependent species (e.g., certain fungi, lichens and insects) will increase the accuracy of resilience assessments and conservation status prioritisation. In particular, sites with a high conservation status will show better survival and health of the oak and its dependent species, supporting an ecosystem that is more resilient to the effects of climate change.
- By modelling climate risk in combination with social and ecological factors, high-risk oak sites (especially in southern Europe) can be accurately identified, enabling targeted policy measures that ensure a balance between biodiversity conservation and sustainable forest management. The strategies developed based on this knowledge will lead to more robust conservation frameworks that enable the adaptive management of

oak ecosystems and support both ecological and social objectives under the pressures of climate change.

The proposed work directly contributes to the EU Biodiversity Strategy for 2030 by bridging the gaps between science, policy and practice. By focusing on nature-based solutions such as the creation of a network of oak microrefugia and tree species adaptation strategies and the development of the OAKLAND Forest Conservation Geoportal, the project aims to provide evidence-based strategies that ensure biodiversity conservation and ecosystem resilience in oak forests. The project outputs will inform policy makers and stakeholders, addressing the societal challenges of biodiversity loss and climate adaptation. The results of the project will provide policy makers and stakeholders with key data across Europe while addressing societal challenges in terms of the quality of socio-cultural services provided by oak-dominated forest ecosystems in relation to biodiversity loss and adaptation to climate change.

The OAKLAND project represents a significant advance in the study and management of oak-dominated ecosystems in the context of climate change. On the other hand, we are aware of the limitations of the remote sensing method. Although it is successfully used to monitor forests and biodiversity, it has significant limitations, especially for high-resolution data (it is very difficult to achieve high accuracy due to resolution, reflectance values, scale, etc.). We also recognise that the proposed satellite technologies and remote sensing technologies alone may not be sufficient to inventory oaks and detect changes in biodiversity, especially changes in species diversity. Therefore, we would like to emphasise the need to support terrestrial land surveys, terrestrial photogrammetric measurements and biological measurements. Nevertheless, the current problem-solving approach has many advantages, as previous research initiatives have mainly focussed on static species distribution models and traditional conservation approaches. OAKLAND is exploring innovative strategies for forest-assisted migration (FAM) (or adaptation strategies for tree species) and assisted the development through the identification of oak microrefugia. This dual approach provides a dynamic understanding of how oak-associated species can adapt to rapidly changing climatic conditions, bridging the gap between current ecological knowledge and practical conservation efforts. One of the novel aspects of OAKLAND is the integration of advanced RS technologies with high-throughput sequencing results to identify potential sites for oak microrefugia and to effectively assess and monitor biodiversity in oak-dominated ecosystems. By utilising these tools, the project will provide high-resolution data that can capture the intricate relationships between oaks, their associated species and environmental conditions. This methodological advance will provide a deeper understanding of biodiversity patterns and ecosystem functions than conventional mapping techniques, which are often limited by coarse spatial resolution. In addition, the project proposes the establishment of a Forest Protection Geoportal, a unique digital platform designed to facilitate open data sharing and collaborative decision-making among stakeholders. This innovative approach not only improves access to important data but also promotes the inclusion of local knowledge and perspectives in biodiversity conservation strategies. Given the urgent need for effective climate change adaptation strategies, OAKLAND is exploring original concepts related to the identification of a network of microrefugia—critical habitats that protect biodiversity from extreme climate events. By identifying microrefugia and developing a strategy to create a network of oak "islands" (microrefugia) to protect biodiversity, the project advances the scope of the call to promote transformative change in forest management in line with the EU Biodiversity Strategy for 2030. OAKLAND also proposes the introduction of a novel conservation ranking system that assesses the success of co-migration of oaks and associated threatened species. By focusing on the interactions between oaks and the species that depend on them, this approach enables a more holistic understanding of ecosystem dynamics and supports the identification of priority areas for conservation action. In addition, the project will address the urgent need to prioritise conservation needs in high-risk areas (e.g., at the trailing edges of oak distribution) where trees are particularly vulnerable to climate change. By incorporating social and ecological aspects into the assessment process, OAKLAND will ensure that conservation strategies are not only scientifically sound but also socially acceptable and feasible. This comprehensive approach is in line with the EU Biodiversity Strategy for 2030, which promotes transformative changes in forest management. OAKLAND will also use modern sociological research methods to incorporate the needs and expectations of local communities and the public into decision-making in order to find more effective ways to halt biodiversity loss and climate change.

The OAKLAND project will involve a wide range of stakeholders, including the following.

- Forest managers and practitioners are responsible for implementing management practices and conservation strategies in oak forests.
- Conservation organisations and non-governmental organisations (NGOs) focus on biodiversity conservation and restoration, provide expertise, and advocate for policy change.
- Local communities and landowners have a direct influence on forest management practices and biodiversity conservation initiatives, ensuring that local knowledge and perspectives are incorporated and that the social importance of these areas is maintained.
- Policy makers and government authorities, at national and regional level, are responsible for the formulation and implementation of environmental policies related to forests and biodiversity, as well as socio-regional economic policies.
- Research institutions and academics contribute with scientific expertise, data analyses and innovative methods to improve the understanding of and strategies for the protection of oak forests.

We hope that the involvement of various communities will create perspectives and specialist knowledge for the preservation and breeding of oaks in dynamically changing environmental conditions resulting from climate change.

9. Factors Contributing to the Phenomenon of Oak Decline

The decline of oak forests in Europe is caused by a complex interplay of abiotic, biotic and anthropogenic factors [17] acting at multiple levels (Table 1). A structured understanding of these factors is crucial for identifying points of intervention and developing effective conservation strategies. Broadly speaking, these factors can be categorised into primary factors, which predispose trees to stress, and secondary factors, which exploit weakened individuals. Their interaction often exacerbates the overall decline.

Table 1. Summarised factors contributing to the phenomenon of oak decline.

Category	Factor	Impact	Examples
Primary factors	Abiotic stressors	Weaken physiological resilience, reduce growth, and predispose trees to biotic stress.	Drought, extreme temperatures, poor soils
	Anthropogenic pressures	Habitat loss, pollution, and mismanagement exacerbate environmental stress.	Urbanisation, deforestation, air pollution
	Genetic limitations	Low adaptability to stress due to limited genetic diversity.	Limited diversity in *Quercus robur*
Secondary factors	Pathogens	Exploit weakened trees, causing rapid decline in health and vitality.	*Phytophthora quercina*, *Brenneria goodwinii*
	Insects	Defoliate, bore into wood, or feed on sap, causing physical damage and stress.	*Agrilus biguttatus*, *Corythucha arcuata*
	Semi-parasitic plants	Drain nutrients and exacerbate stress in already weakened trees.	*Loranthus europaeus*
Interactions	Combined biotic and abiotic stress	Amplified impacts due to sequential or simultaneous stresses.	Drought and insect defoliation and pathogens

9.1. Primary Factors

Abiotic stress factors are among the most important primary factors contributing to oak decline. Climate change has increased the frequency and intensity of extreme weather events such as prolonged droughts, heat waves, and floods, which weaken the physiological resilience of oaks. Drought stress, for example, reduces water availability and disrupts the hydraulic function of trees, making them more susceptible to biotic pathogens such as root pathogens (e.g., *P. quercina*). Similarly, nutrient imbalances in degraded soils and shifts in seasonal precipitation patterns further impair oak health. Anthropogenic influences also play a crucial role in the decline of oak forests. Urbanisation, deforestation, pollution and improper forest management exacerbate environmental stress by reducing habitat quality and fragmenting ecosystems. The over-extraction of resources and inadequate reforestation programmes have exacerbated these pressures, leaving oak populations vulnerable to abiotic and biotic threats. Genetic constraints in oak populations exacerbate the effects of abiotic and anthropogenic stressors. Populations with low genetic diversity are less able to adapt to environmental changes and recover from disturbances. This is particularly evident in some European oak species, where habitat fragmentation in the past has reduced genetic diversity, limiting their resilience to stress.

9.2. Secondary Factors

Biotic factors are often secondary stress factors that take advantage of weakened trees and accelerate the decay process. Pathogens such as fungi and bacteria contribute significantly to this. *Phytophthora quercina*, a root pathogen, is responsible for severe oak dieback, particularly in Central Europe, where it damages fine roots in drought-stressed soils. Other fungal pathogens such as *Diplodia corticola* A.J.L. Phillips, A. Alves & J. Luque and *Armillaria* spp. cause cankers and decay, further weakening oak stands. Bacterial pathogens such as *Brenneria goodwinii* and *Gibbsiella quercinecans* are the main causes of AOD, a phenomenon that is being increasingly documented in Europe. Insect pests also contribute significantly to the decline of oaks. Defoliators such as *Tortrix viridana* (Linnaeus, 1758) and *Operophtera brumata* (Linnaeus) reduce photosynthetic capacity, while borers such as *Agrilus biguttatus* and sap-feeding insects such as *Corythucha arcuata* directly damage the vascular system and increase the susceptibility of trees to secondary pathogens. Semi-parasitic plants such as *Loranthus europaeus* exacerbate stress in already weakened oaks. These plants deprive their hosts of water and nutrients, reducing growth and vigour, especially in areas of prolonged drought.

9.3. Interactions Between Primary and Secondary Factors

The interaction between primary and secondary factors often amplifies their individual effects, creating a feedback loop that accelerates oak decline. For example, abiotic stress factors such as drought can predispose oaks to secondary infections by pathogens such as *Phytophthora* and defoliation by insects. Similarly, insect damage can create entry points for opportunistic fungal pathogens, while semi-parasitic plants exacerbate nutrient depletion. These combined effects emphasise the need for an integrated approach to oak health management.

10. Conclusions

The above consequences resulted in the interest among countries with large resources of oak stands to organise and create a joint research project called OAKLAND. The project addresses the critical societal challenges posed by climate change, biodiversity loss and the destruction of forest ecosystems by invasive pathogens and insect pests. It focuses on the declining health of Europe's oak-dominated forests and the decreasing value of the ecosystem services they provide. The paper also looks at trends in the development of social ecosystem services and emphasises the urgent need to protect and enhance these vital landscapes. Focusing on innovative strategies to identify, assess and develop criteria for oak micro-retreats and thus improve the adaptation of oaks to changing environmental conditions (through FAM), OAKLAND makes an important contribution to the EU Biodiversity Strategy 2030 by promoting sustainable forest management and increasing the resilience of vulnerable forest ecosystems in the face of global climate change. One of the most important societal impacts of the project lies in its potential to inform and influence policy frameworks for biodiversity conservation and climate adaptation. By generating robust, high-resolution data on oak forest biodiversity and ecosystem dynamics, OAKLAND aims to provide policy makers with the insights needed to develop adaptive management strategies that are both effective and socially acceptable. The project will help to develop guidelines and best practices for the integration of adaptation strategies for tree species into national and regional forest management policies and ultimately promote a collaborative approach to biodiversity conservation in different European countries. In addition, OAKLAND focuses on the co-migration dynamics between oak and its dependent species. The proposed biodiversity categorisation system will provide a deeper understanding of the interactions between species in oak-dominated ecosystems. This knowledge is crucial for the development of measures that are not limited to tree species, but also to broader communities of oak-dependent organisms. By prioritising conservation needs in high-risk areas (e.g., at the trailing edges of the oak distribution range), the project directly contributes to the formulation of targeted actions that respond to the specific challenges of sensitive ecosystems facing new threats (e.g., insect pests, oomycetes and/or pathogenic fungi). The strategy to involve stakeholders in the project is an essential part of its societal relevance. OAKLAND will actively involve a wide range of stakeholders, including forest managers, conservation organisations, NGOs, local communities and policy makers. Case studies and sociological research will be used to identify key criteria for social relevance in order to recognise and capture changes in social value in specific situations. Fostering collaborative partnerships will ensure that the knowledge gained is made available and adapted to those directly involved in forest management and conservation activities. Workshops, training and stakeholder consultations will facilitate knowledge sharing and promote a collaborative approach to developing effective solutions. OAKLAND will also engage with end users by providing tools such as the proposed forest conservation geoportal, which will serve as a platform for sharing data and best practices. This accessibility will enable stakeholders to make informed decisions regarding forest management and conservation, ultimately leading to greater societal benefits, including improved ecosystem services, increased resilience to climate change and the conservation of oak-associated biodiversity.

The OAKLAND project offers significant transnational added value by fostering collaboration among several European countries distributed along the latitudinal gradient—from the southernmost (Bulgaria) to the northernmost (Sweden) limit of the oak distribution range—to address the common challenges posed by climate change and biodiversity loss in oak-dominated forests. By integrating diverse ecological, social, and policy contexts from Sweden, Lithuania, Poland, Romania, and Bulgaria, the project enhances the understanding of regional, climate-driven differences in forest dynamics and conservation needs. This collaborative approach promotes the sharing of knowledge and best practices, facilitating the development of harmonised strategies for forest management that can be applied across borders. Moreover, the outputs of the project will inform EU-wide policies and initiatives aimed at biodiversity conservation, contributing to the overarching goals of the EU Biodiversity Strategy for 2030.

Author Contributions: Conceptualisation, A.L. and T.O.; methodology, A.L., M.B. and T.O.; validation, J.N. and A.M.; formal analysis, P.B. and J.N.; investigation, J.N. and M.B.; resources, J.N.; data curation, A.M.; writing—original draft preparation, A.L., M.B., A.M. and T.O.; writing—review and editing, J.N. and K.D.; visualisation, K.D.; supervision, T.O.; project administration, P.B.; funding acquisition, J.N. All authors have read and agreed to the published version of the manuscript.

Funding: The research was supported by the Bialystok University of Technology (WZ/WB-INL/2/2024) and funded by the Science Fund of the Ministry of Science and Higher Education in Poland, Bulgarian Operational Programme Science and Education for Smart Growth 2014–2020, co-financed by the European Union through the European Structural and Investment Funds (Grant BG05M2OP001-

1.002-0012) and EU programme Erazmus + for Higher education students and staff (Contract No 2019-1-BG01-KA103-061642).

Conflicts of Interest: The authors declare no conflicts of interest.

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