

REVIEW PAPER

Sessile oak (*Quercus petraea* [Matt.] Liebl.) and its adaptation strategies in the context of global climate change: a review

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Abstract

This paper provides characteristic and a comprehensive overview of the adaptation strategies of sessile oak (*Quercus petraea* [Matt.] Liebl.) in the context of global climate change (GCC). The GCC is primarily manifested by increasing air temperatures and changing precipitation distribution. It poses a significant challenge to tree species including sessile oak, affecting its capacity for adaptation and survival. Despite the challenge, sessile oak shows significant drought tolerance due to its deep-reaching root system, which allows the tree to use available water more efficiently. Other adaptive strategies include the establishment of mixed stands that increase the resilience and biodiversity of the ecosystem. Adjustments of stand density through tending interventions play a significant role, helping to improve the stress resistance of stands. Additionally, coppice forest cultivation is applied on extremely dry sites. The sessile oak is also significant for its ecological plasticity – its ability to thrive on versatile soil and climatic conditions makes it a promising tree species for future forest management. Mixed stands with sessile oak and other tree species can enhance the ecosystem services of forests and also increase their endurance to GCC events. However, sessile oak faces several challenges, including the increasing risk of damage from pests and pathogens that require targeted measures for its protection and sustainable cultivation. The literature review suggests that a comprehensive understanding of sessile oak's ecological requirements and interactions with the environment is crucial for its successful adaptation to GCC and the formulation of effective strategies for its protection and use in forest management.

Key words: ecological demands; mitigation; mixed stands; drought stress; resilience; sustainable management

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1. Introduction

The ongoing global climate change (GCC) causes a rise in average air temperature and changes in the temporal and spatial distribution of precipitation (Seidl et al. 2017). This increases evaporative demand and leads to gradual modifications in vegetation across ecosystems worldwide (Gonzalez et al. 2010). On regional scales, the impact of GCC on vegetation can best be observed in the shift of forest altitudinal zones (hereafter FAZ), which is characterized by climatic parameters such as annual mean air temperature, annual precipitation, and the length of the growing season (Bertrand et al. 2011; Čermák et al. 2021). According to Machar et al. (2017), the GCC will increase the areal distribution of lower FAZs (primarily the 1st and 2nd FAZ) in the Czech Republic (CZ) and shift them to higher altitudes. Concerning aridity,

even the 1st FAZ will begin to experience conditions that have not been seen there before. Within the FAZ shift, the processes of interspecific competition, different phenotypic plasticity, and different adaptability of dominant species in each FAZ are yet to be ascertained (Iverson & McKenzie 2013). Drought increases the risk of mortality, reduces growth of some species in the ecosystem, and alters ecohydrological relationships (Bigler et al. 2006). Kozłowski (1982) and Boisvenue & Running (2006) report that the quantity, availability, and distribution of water throughout the year, together with temperature, are the primary limiting climatic factors for the distribution of herbaceous and woody vegetation, their species structure, and overall biomass production.

In the anticipated FAZ shift, various studies suggest that oak will dominate under changing environmental conditions (Hanewinkel et al. 2013; Čermák et al.

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2021). However, oak also suffers from negative effects of environmental change, such as drought or increased air temperature. Yet it ranks among drought-tolerant tree species compared to, e.g., European beech (Hacke & Sauter 1995).

Drought and higher air temperatures can affect the oak in various ways. The principal indicators of oak damage are crown defoliation, growth anomalies, and increased tree mortality (Thomas et al. 2002; Arend et al. 2011). When low precipitation and high temperatures occur during the peak growing season, negative radial growth variation is common in oak, which can result in a decrease in overall oak stand production (Neuwirth et al. 2004). Therefore, due to increasing average air temperatures and their variability (Schär et al. 2004), the probability of extreme negative growth responses in oak is also expected to grow (Sedmáková et al. 2021).

Dieback of oak stands usually takes relatively long (Andersson et al. 2011; Sohar et al. 2014), with competition and tree size playing a significant role in the decline of oak health (Matula et al. 2015). Therefore, reducing competitive pressure in oak stands by, for example, thinning (Aldea et al. 2017) appears to be an appropriate adaptation strategy to mitigate the effects of extreme drought (Fig. 1).

On the other hand, closed stands mitigate fluctuations of high air temperatures, improve moisture conditions within the stand, and moderate the impacts of extreme drought (Bhatta & Vetaas 2016). However, the optimum level of canopy opening and less competition pressure, beneficial for oak in the context of GCC, is still undefined. Overall, the influence of oak stand density on growth response to climatic extremes is relatively unresearched (Sedmáková et al. 2021). Growing oak in a mixture with an additional tree species, such as beech or pine, appears to be a convenient way of adapting to GCC (Pretzsch et al. 2015, 2020). This is because mixed stands can not only provide better stand stability, but due to different ecological requirements, they can better manage the available resources. Thus, there is more mutual beneficiality at work than fierce competition (Pretzsch et al. 2013; del Río et al. 2022). However, for any proposed adaptation to succeed (whether it is a modified management of oak stands or growing oak in mixtures with other tree species), knowledge of its ecological requirements, especially its response to changing environmental conditions, is key to success. Therefore, the main objective of this paper is to provide a comprehensive review of existing knowledge on sessile oak properties and characteristics with main focus on its adaptation strategies in response to changing environmental conditions.



Fig. 1. Active forest management promotes the health status of sessile oak stands.

2. Characteristics and morphology of sessile oak

The sessile oak is a long-lived (it can live for over 1,000 years; Eaton et al. 2016) deciduous tree species native to Europe. It can grow up to 40 m tall and reach a diameter at breast height (dbh) of 3 to 4 m (Prentice & Helmisaari 1991; Praciak et al. 2013). In CZ, however, it commonly reaches a height of 30 m and a dbh of up to 1 m (Úradník & Maděra 2001). It has a deep root system that increases water availability and its drought resistance. This characteristics is crucial under climate change scenarios where drought and warming are predominant factors eliciting increased tree mortality (Praciak et al. 2013; Aubin et al. 2016). Conversely, European beech forms up to three-story stands and undergoes independent development over a large area, benefiting from its shade-tolerant growth at a younger age (Fuchs et al. 2024). Within *Quercus* spp., sessile oak is classified as moderately sensitive to drought stress (Dickson & Tomlinson 1996; Fig. 2). Sessile oak leaf petioles are longer than 1 cm, and acorns are nearly sessile or only on short peduncles (up to 1.5 cm; Buriánek et al. 2013; Fig. 3).

Historical sources describing the spread of coppices in low and coppice-with-standards forests in the region of Central Europe date back to the late 19th century. From then, until the 1930s, the coverage of coppice forests in CZ ranged between 87 and 97 thousand ha (Kadavý et al. 2011). Although in the second half of the 20th century, we saw a conversion of coppice (low forests) to high forests (Hédl et al. 2010; Altman et al. 2013), the sessile oak is among the primary stand-forming species of low forests in Central Europe (Matula et al. 2012). In CZ, only 0.4%



Fig. 2. Sessile oak has a higher (e.g., than Scots pine) resilience capacity to climate change at various sites.

of the total forest area is managed as coppices or coppice-with-standards recently (approximately 11,700 ha of forest area; Unrau et al. 2018). The largest share of coppices in Europe can be found in Southern Europe (Unrau et al. 2018; Buckley 2020).

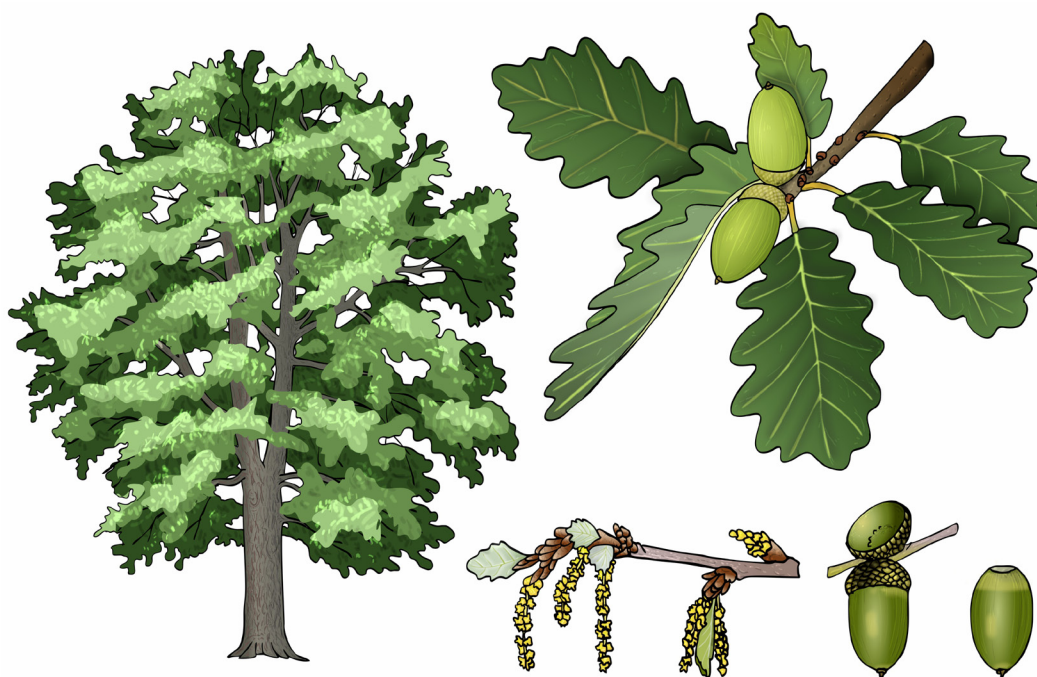


Fig. 3. Habitus, annual shoot with leaves, seeds, and fruits (acorns) of sessile oak (*Quercus petraea* [Matt.] Liebl.).

Vegetatively reproduced oaks (*Quercus* spp.) bear fruit between 40 and 100 years of age (Ducousso & Bordacs 2004), while stump sprouts often start fructification as early as 20 years of age. Mast years repeat every four to eight years, and acorns have high germination rates, retained until spring (Svoboda 1955). Due to climate change, the increasing air temperatures and the changing distribution of precipitation increase fructification periodicity up to ten years. It has been recorded in many oak species (Curtu et al. 2015). Acorns are often spread by zoochoric dispersal over relatively long distances, especially by the Eurasian jay (Eaton et al. 2016). Fertile oak pollen can be dispersed up to a radius of more than 100 km from the source, as found by models evaluating pollen release, viability, and deposition (Schueler & Schlünzen 2006).

3. Sessile oak distribution range

The sessile oak is a widely distributed species in Europe, occurring naturally from Northern Spain to Southern Scandinavia and from Ireland to Eastern Europe and Turkey (Ducousso & Bordacs 2004; Fig. 4), where it can be found up to around 2,000 m a.s.l. (Aas 1991). The geographic range of oak includes relatively warmer habitats with average air temperatures between 5 and 14 °C and annual precipitation of 450–1,300 mm (Kölling 2007). In CZ, it is most commonly found from lowlands to hills, rarely up to mountain foothills, with maximum elevations of 750–850 m a.s.l. (Úradníček & Maděra 2001;

Sharma et al. 2016; Vacek et al. 2019b). Oaks (i.e. including *Q. robur* L., *Q. pubescens* Willd. and other less frequent species; e.g., Úradníček & Maděra 2001) account for 7.4% of the current forest species composition in CZ (MZe 2020). Their representation in the natural species composition is estimated at 19.4%. The framework strategy plans a slight increase of oaks share to 9% (MZe 2019).

Climate simulations and scenarios show a shift in the tree species composition in Central Europe in the coming decades (Hanewinkel et al. 2013). Oak is considered a promising tree species in connection to this shift, capable of reducing the risks associated with GCC (Spellmann et al. 2011). Consequently, it is expected to increase its representation in unmixed stands of Scots pine in dry habitats of lower elevations (Zerbe 2002; Schröder et al. 2007; Noack 2011) and, primarily in Central Europe, to gradually replace the current dominant stands of Norway spruce that are already significantly plagued by GCC impacts (Hlásny & Turčáni 2013; Pretzsch et al. 2020).

4. Taxonomic classification

The history of the taxonomic classification of oaks illustrates the development of botanical nomenclature, with *Quercus* spp. as a taxonomical challenge to determine, not only within Central Europe but globally (Buriánek et al. 2013; Cuypers & Reydon 2023). This is confirmed by the fact that this genus includes approximately 600 extant species of trees and shrubs that grow in many

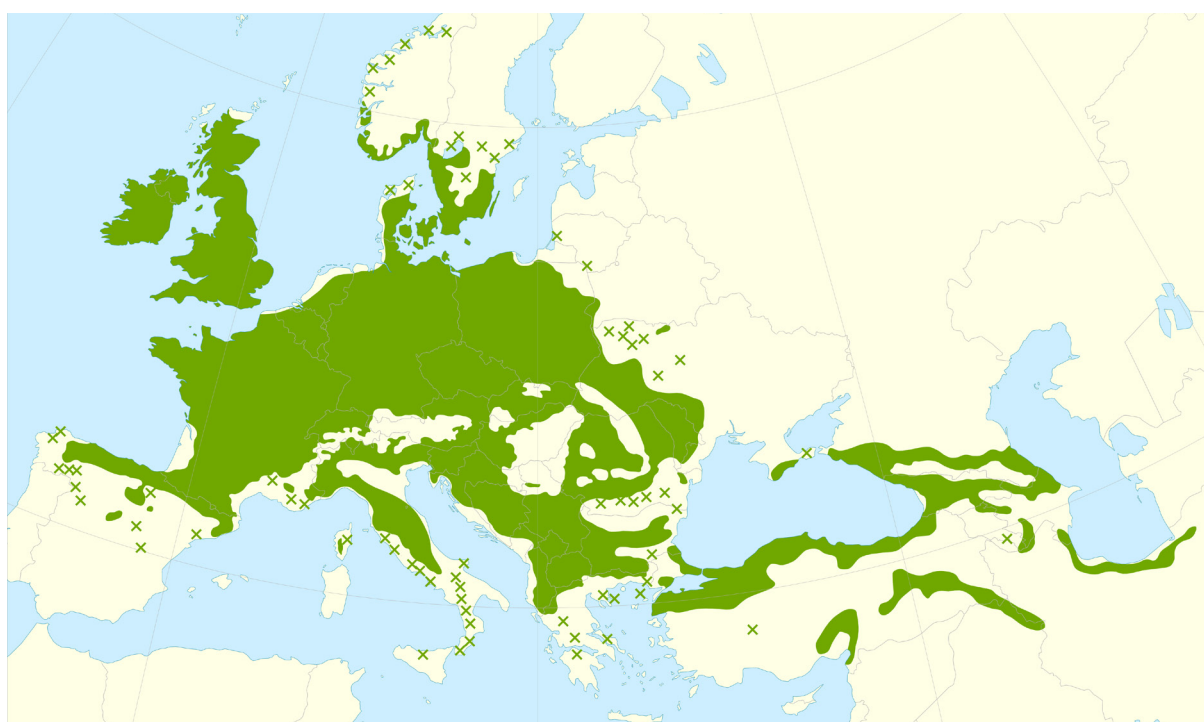


Fig. 4. Natural distribution range of sessile oak in Europe (Caudullo et al. 2017).

regions of the Northern Hemisphere (Mabberley 2017). The sessile oak has a long history of taxonomic classification, but it has been subject to taxonomic pluralism until recently, particularly with pedunculate oak (*Quercus robur* L.; Cuypers & Reydon 2023), as the two species often hybridize with each other (Burger 1975; Aas 1993; Muir et al. 2000; Petit et al. 2004; Gerber et al. 2014).

One of the first known scientific names for *Q. petraea* [Matt.] Liebl. and *Q. robur* L. came from the Swedish naturalist Carl Linné, who collectively named both species *Q. robur* L. in his *Species Plantarum* (1753). In his earlier work, *Flora Sueica* (1745), he most likely considered what we now know as *Q. petraea* [Matt.] Liebl. as a variety of *Q. robur* L. referred to as *Q. latifolia* Steud. (see Gardiner 1975), for which the Swiss botanist Caspar Bauhin (1560–1624) first used the short peduncles as a diagnostic character (Gardiner 1975; Cristofolini 2023). The German botanist Heinrich Gottfried von Mattuschka, who described the taxon in his *Flora Silesiaca* (1777) and also considered it a variety of *Q. robur* L. (*Quercus robur* var. *petraea* Matt; Gardiner 1975), was the first to apply the *petraea* specific epithet to botanical nomenclature. It was listed as a fully acknowledged taxon at the species level by another German botanist, Franz Kaspar Lieblein, in *Flora Fuldensis* (1784). He provided an identical description to von Mattuschka's, which is still used in scientific papers today, without giving a reason why the variety was elevated to a separate taxon (Gardiner 1975; Cuypers & Reydon 2023).

5. Ecological requirements and growth response of sessile oak to changing environmental conditions

The sessile oak is a light-demanding species whose mature canopy cover allows a large amount of light to penetrate the undergrowth, supporting natural regeneration (Ellenberg 2009). It is the dominant tree species in acidophilous and thermophilic oak woodlands, and it also naturally forms mixed stands with European beech, European hornbeam, Scots pine, silver fir, and limes (Vacek et al. 2016, 2018b; Hájek et al. 2020). Sessile oak thrives in a wide range of climatic conditions from dry to humid sites, and tolerates pH levels from 3.5 to 9 (Ducousso & Bordacs 2004; Fig. 5). In contrast, European beech requires a humid atmosphere with precipitation evenly distributed throughout the year and it is less tolerant to drought than sessile oak (Fuchs et al. 2024). Frost damage to sprouting buds and leaves occurs when air temperature drops to -3°C or less. Due to late germination (late April to early May), frost damage is rare in sessile oak (Praciak et al. 2013; Savill 2019). Climate change significantly impacts the phenology of sessile oak, especially influencing the timing of bud burst, which air temperature predominantly controls (Perot et al. 2021). Moreover, it was shown that the stability of the timing of spring phenophases tends to be greater than the variability observed in autumn senescence. Furthermore, a clear longitudinal gradient in the timing of bud burst



Fig. 5. Sessile oak growing at rocky terrain.

was observed for sessile oak, with a delay from east to west of 0.5–1.4 days per degree of longitude (Gafenco et al. 2022).

Local adaptation of populations to climatic conditions is also crucial in the context of vegetative bud phenology in long-lived plant species, such as forest trees. This adaptation significantly influences their productivity, adaptability and distribution, highlighting the complex interaction between genetic factors and external environmental conditions in determining phenological patterns (Derory et al. 2006).

Radial increment of oaks was negatively correlated with minimum air temperatures (Michelot et al. 2012; Manso et al. 2015) and with atmospheric water vapor pressure deficit (Aldea et al. 2017). Conversely, positive correlations have been proved between increment and irradiance (Monteith 1972; Aldea et al. 2017), as well as with precipitation (Michelot et al. 2012; Sohar et al. 2014; Aldea et al. 2017) and the amount of live foliage in the ecosystem, which is the “production unit” of the stand (Černý et al. 2020; Parker 2020; Černý & Pokorný 2021). In fully stocked undefoliated oak stands, the maximum leaf area index (LAI) value ranges from 2.2–6.0 m² m⁻² in production forests (Bequet et al. 2012; Černý et al. 2019) and around 7 m² m⁻² in natural forests (Cutini et al. 1998; Čermák 1998; Glathorn et al. 2017).

Because the annual ring boundaries of ring-porous trees are defined by the minimum wood density caused by the large diameter of the vessels of the earlywood, the radial growth starts before budburst, using carbohydrate reserves that have been stored in the previous year (Bréda & Granier 1996; Barbaroux & Bréda 2002). The large vessels of earlywood are formed in early spring to reestablish tracheids for water and solutes to transport in the xylem after winter embolisms have blocked previously formed xylem cells (Tyree & Cochard 1996). Thus, radial increment in oak occurs mainly in spring, and its growth is completed earlier than in beech (Michelot et al. 2012).

In dry conditions, oaks keep the stomata open longer than Scots pine (Poyatos et al. 2008). They draw about 72% of their water from a depth of 30 to 45 cm in mixed stands (Bello et al. 2019a), but their deep-reaching root system can extract water during periods of reduced water availability in the soil (Bréda et al. 1995; Praciak 2013; Aubin et al. 2016), thereby increasing their drought resistance. Sessile oak has also shown a high capacity for resilience and adaptation to different environmental conditions (Merlin et al. 2015). Conversely, European beech has been reported to experience a growth decline related to recent climate warming, suggesting a vulnerability to prolonged drought conditions (Fuchs et al. 2024). Tree species respond differently to drought stress during the growing season (Merlin et al. 2015). Sessile oak belongs to tree species with higher resistance, especially during summer droughts (Toigo et al. 2015; Vanhellemont et al. 2019), however being more susceptible to drought stress compared to pedunculate oak (Annighöfer et al.

2015). In a large-scale pan-European study, Steckel et al. (2020) demonstrated the higher resistance and resilience (ability to restore structure and growth to the pre-drought state) of oak, specifically in mixed stands compared to pine stands. This fact is supported by Ouédraogo et al. (2013), who compared the prosperity of a wide range of broadleaved tree species in Central Africa and concluded that slow-growing tree species are better predisposed to survive periods of drought. Also, a study of roughly 200-year-old oak stands at the northern limit of the genus distribution in Finland confirmed the long-term resistance of these individuals to short-term summer droughts. Although the weakened individuals reduced their radial increment with the onset of the short-term droughts, it was not completely inhibited until after about ten years of recurrent summer short-term droughts. In the long term, healthy individuals showed both higher radial increment and greater ability to cope with changing environmental conditions (Sohar et al. 2014).

Oak coppices transpire significantly more during favorable conditions as well as under conditions of reduced water availability (e.g., 2015) than high-forest production stands, both as individuals and as the whole stand (Stojanović et al. 2017). This is likely due to increased water availability through the extensive root system of old stumps, which enables coppices to use water from deeper in the soil profile during short-term droughts (Pietras et al. 2015). It contributes to maintaining higher stomatal conductance during the drought and leads to downregulation of photosynthetic assimilation (Holišová et al. 2016). In addition, a higher volume yield of total aboveground biomass has also been demonstrated in coppices than in high forests (e.g., Dickmann et al. 1996; Pietras et al. 2015), and therefore, oak coppices appear to be an appropriate management method in sites characterized by frequent or extreme short-term droughts (Pietras et al. 2015; Stojanović et al. 2017; Fig. 6).

Higher nutrient availability generally leads to limited development and growth of the root system of forest tree species, which is a disadvantage compared to more developed root systems on poorer sites. Nutrient availability and translocation (movement) within the plant are also severely limited when water availability is reduced (Girjaveni et al. 2018). In addition, the morphological and physiological characteristics of woody species growing in rich habitats (e.g., reduced root-to-leaf area ratio, increased stomatal conductance, more intense height increment, larger tracheid diameter, and lower mycelial mycorrhizal fungi proportion) pose a greater risk of embolism due to imbalances in reduced water availability and demand (Gessler et al. 2016). Drought can also trigger phytophthora dieback (*Phytophthora cinnamomi* Rands) and exacerbate the impact of a number of insect pests and fungi on oak health (Linder et al. 2008). Radial growth of sessile oak is highly susceptible to abiotic and biotic damage (Wiley et al. 2013; Palacio et al. 2014).



Fig. 6. The significant ability of sessile oak to produce stump sprouts when young gradually decreases with age. Sprouts have a better resistance to drought due to their developed root system.

Tree mortality following a significant drought period typically exhibits a species-specific pattern. Desprez-Loustau et al. (2006) describe a higher susceptibility of pedunculate oak to the water deficit and root pathogens compared to sessile oak based on an analysis of the impact of a significantly dry year in 1976 in France.

The photosynthesis of broadleaved tree species responds more sensitively to short-term elevated atmospheric CO₂ concentrations than that of conifers. Of the broadleaved, sessile oak and beech are among the more responsive species than, e.g., hornbeam, cherry, or lime. When elevated concentrations took longer (more than a year), differences were no longer found between the broadleaves and conifers (Linder et al. 2008). Increased atmospheric CO₂ concentrations led to a decrease in water consumption by less than 10% (Leuzinger & Körner 2007).

Excessive precipitation before the start of the growing season negatively affected the growth of the pedunculate oak. Individuals with symptoms of weakening responded more sensitively to climate fluctuations than healthy trees. A greater supply of available calcium in the soil around the trees increased the trees' ability to resiliently respond to water stress. In contrast, trees in sites with lower soil calcium availability responded minimally to stress, which resulted in more frequent dieback (Rozas & Sampedro 2013).

The radial increment of Scots pine and pedunculate oak does not only depend on the total annual precipitation, but also on its distribution within the growing season and in individual months. For both tree species, the closest correlation between growth and precipitation was found in April and May, while the correlation with summer rainfall was less significant, especially for oak. Winter precipitation also has a positive effect on annual increment, mainly due to the increase in soil moisture for the spring season (Matveev et al. 2018).

6. Oak silviculture under global climate change

A range of abiotic and secondary biotic disturbances are currently occurring in synergy with GCC in forest stands (Seidl et al. 2017; Šimůnek et al. 2020; Vacek et al. 2023). In the case of oaks, some species are known for their relatively high resilience and ability to adapt to different conditions (Vacek et al. 2018a; Šimková et al. 2023). Conversely, due to climate change, where drought and warming are becoming predominant factors causing increased tree mortality, sessile oak may also respond positively with increased increment (Vančura et al. 2022). In addition, various oak species have become

common tree species in the afforestation of agricultural lands in recent years due to their resistance to climatic extremes (Cukor et al. 2017a, 2017b, 2022).

Alternative adaptation and mitigation measures in sessile oak stands include mixing species in forest stands (Steckel et al. 2020), adjusting stand density through tending operations (Korpeľ et al. 1991; Chroust 1997), or coppicing, which increases resistance to reduced soil water availability (Pietras et al. 2015; Holířová et al. 2016; Stojanović et al. 2016).

Species mixing is becoming one of the principal management tools in European forests, as mixed stands provide a variety of ecosystem services while reducing the risks associated with GCC (Steckel et al. 2019; Vacek et al. 2021; del Río et al. 2022; Brabec et al. 2023; Vospernik et al. 2023). A mixture of sessile oak and Scots pine resulted in increased production of both species compared to both group mixing (Bieng et al. 2013) and unmixed stands (Pretzsch et al. 2018; Steckel et al. 2019; Pretzsch et al. 2020). In a pan-European study, an annual volume increment of $10.5 \text{ m}^3 \text{ ha}^{-1}$ (stock of $418 \text{ m}^3 \text{ ha}^{-1}$) was recorded in mixed oak-pine stands compared to $9.1 \text{ m}^3 \text{ ha}^{-1}$ (stock of $360 \text{ m}^3 \text{ ha}^{-1}$) in unmixed oak stands (Pretzsch et al. 2020). Steckel et al. (2019) came to similar conclusions in their study, which included monocultures and mixed stands of oak and pine in Germany and Denmark. The same effect was also found in a mixture of pine and pedunculate oak, where an increase in volume increment was observed, which was relatively constant throughout the development of the stands regardless of the nature of the habitat and the tending interventions made (Lu et al. 2016). Furthermore, the admixture of broadleaves, including sessile oak, increases the efficiency of the stand's solar radiation use in photosynthetic assimilation (Pretzsch et al. 2012), which is positively reflected in the stand volume production (Vose & Allen 1988; Landsberg & Sands 2011).

In a study of mixed stands and monocultures of oak and pine that monitored the response of these tree species to drought, oak was found to be more resistant and resilient to this stressor in mixtures compared to both monocultures (Steckel et al. 2020). This demonstrates, as do the results from other studies, the lower sensitivity of sessile and pedunculate oaks (Kölling & Zimmermann 2007; Zang et al. 2011; Bello et al. 2019b), as well as other *Quercus* spp. (Galiano et al. 2010), to drought stress compared to pine stands.

The beech-oak mixture also showed an average increase in volume increment of 24% compared to monocultures. A higher effect was observed on poorer sites (Pretzsch et al. 2020). Unmixed stands of both sessile oak and Scots pine primarily use available water near the soil surface. In contrast, in mixed stands of these tree species, oak water use shifts to deeper layers, with smaller-sized oaks in particular benefiting, as demonstrated by studies of water use employing isotopes and water potential of

leaves (Bello et al. 2019a). This is even though oak roots have been found to grow to less deep in mixed stands than in monocultures, whereas the trend is reversed for Scots pine (Kacálek et al. 2017). In sandy soils of natural pine habitats, the roots of Scots pine generally penetrate deeper than oak roots (Jeník et al. 2014).

The single admixture of sessile oak and Norway spruce in pine stands resulted in only minimal differences in the physical and chemical properties of the organic topsoil layer (Peřina 1973). A more pronounced effect of stand mixtures was observed in stands growing on nutrient-limited sites (Kacálek et al. 2017). It was found that in mixed oak-pine stands, the decomposition of the assimilative apparatus of oak was 44% faster than that of pine needles, while the decomposition of oak roots was 46% slower than that of pine roots (Barba et al. 2016). Prietzel (2004) studied changes in the characteristics of humic substances (i.e. natural organic substances produced by the decomposition of predominately plant residues) in stands of Scots pine with admixed European beech and sessile oak. In this study, he reported that European beech showed a more favorable effect on the properties of the top organic layer of the soil than sessile oak. Schua et al. (2007) and Schröder et al. (2009) also observed a slow improvement of soil conditions in natural pine sites due to the admixture of sessile oak. On the contrary, Blońska et al. (2013) found a positive effect of oak admixture on topsoil humus and vegetation on these sites on sandy soils. Adding sessile oak to a stand also has a positive effect on nutrient cycling and ecosystem biodiversity (Lehmann 2008).

The growing stock of the stand as well as other parameters are highly variable with age (Tab. 1). With an age range of 40–126 years, the stock of oak monocultures across Europe varies between 109.5 – $647.7 \text{ m}^3 \text{ ha}^{-1}$ (Pretzsch et al. 2020). In CZ, oak silviculture has been studied, for example, by Klíma (2010), who evaluated different types of thinning in terms of whole stand production. Although Klíma (2010) did not find significant differences in dendrometric parameters between the two management practices (thinning from below or from above), Slodičák & Novák (2007) or Poleno et al. (2009) recommend, in the context of changing environmental conditions, the use of positive selection and heavier thinning from above in sessile oak stands, removing competitive and lower quality individuals to support the target trees.

An important aspect of forest management in recent years has been the focus on the quality of the individual tree species, i.e. the promotion of quality individuals in the stand. Štefančík & Pástor (2023) and Štefančík (2021) evaluate a nearly 25-year experiment on the quality production of promising sessile oak individuals. Varying the intensity of release of a target number of 160 quality trees had a negative effect on the stand basal area and stock in the case of intense thinning, and even after almost 25 years, there was no statistically significant positive

Table 1. Summary of production parameters of sessile oak-dominated forest stands in Europe.

Study	Country	Altitude (m a.s.l.)	Age (year)	Dbh (cm)	Height (m)	Basal area (m ² ha ⁻¹)	Growing stock (m ³ ha ⁻¹)	Density (trees ha ⁻¹)
Březina & Dobrovolný (2011)	Czechia	440	126	—	—	—	312	—
Březina & Dobrovolný (2011)	Czechia	440	119	—	—	—	368	—
Bobinac et al. (2019)	Serbia	520–540	150	24.6–41.7	19.2–24.4	36.0	471	275
Bobinac et al. (2019)	Serbia	520–540	150	37.2–46.3	21.6–22.9	31.4	389	193
Bölöni et al. (2017)	Hungary	200–700	80–99	26.9	18.3	27.6	303	511
Bölöni et al. (2017)	Hungary	200–700	100–119	31.2	20.9	32.5	400	472
Bölöni et al. (2017)*	Hungary	200–700	120–165	29.7	18.8	27.9	312	515
Černý & Dušek (2022)	Czechia	251	111	32.8	25.5	40.1	476	420
Dobrovolný & Macháček (2012)	Czechia	380	73	24.1	21.9	31.8	378	672
Klíma (2010)	Czechia	250	66	24.6	22.9	21.7	231	444
Klíma (2010)	Czechia	250	66	23.1	21.4	24.6	259	564
Petritan et al. (2012)*	Romania	350–620	—	23.1–52.0	13.9–30.9	26.4	423	131
Pretzsch et al. (2020)	Czechia	265	95	23.4	17.6	31.0	226	547
Pretzsch et al. (2020)	Czechia	400	76	22.6	21.1	31.4	285	714
Štefančík (2021)	Slovakia	360	67	17.3–19.2	20.2–21.4	30.2–33.2	332–363	1,040–1,400
Štefančík & Pástor (2023)	Slovakia	314	58	19.7	19.9–20.6	24.2–25.4	228–230	1,186–1,491

Note:*Natural forest reserve.

effect in radial increment, dbh, tree height, or crown area of the promising individuals observed. The tending intervention, where three competitors were removed at the beginning, also had a negative effect on the reduction of the number of promising trees (from 160 to 120 trees per hectare).

7. Threats and diseases of the sessile oak

Forest vitality is influenced by a variety of biotic and abiotic stresses that may interact. Consequently, the extent of tree defoliation is subject to both long-term changes and short-term risks that need to be monitored in the context of ongoing climate change (Toigo et al. 2020). Although sessile oak has a high potential to cope with the anticipated GCC-altered growth conditions (Arab et al. 2022), drought stress could become a primary cause of forest dieback in the near future (Petritan et al. 2021) and may also cause genetic diversity loss in sessile oak populations that have reduced plasticity and adaptive potential (Borovics & Mátyás 2013). This is also confirmed by the declining health of oak stands (increased defoliation) in the Czech Republic over the last decade as a result of adverse climatic developments (Vejpustková et al. 2019). Moreover, it also contributes to reduced recruitment and, consequently, higher mortality, which increases towards its xeric limit (Bertini et al. 2011; Berki et al. 2016; Petritan et al. 2021). Drought-weakened individuals are then attacked by, e.g., *Xyphidria longicollis* Geoffroy (Pažoutová et al. 2010) or the bark beetle *Scolytus intricatus* Ratzeburg, which is usually univoltine (i.e. has one generation per year), but in dry years under Central European conditions, a second generation has also been observed (Mezei et al. 2022). This pest can also be a vector of tracheomycosis diseases due to its symbiotic relationship with fungi (e.g., genus *Ophiostoma*; Marković & Stojanović 2003).

Furthermore, climate change contributes significantly to the increased incidence of biotic pests and pathogens (Tkaczyk 2023). Defoliation of newly sprouted leaves is commonly caused by caterpillars from several insect pests such as *Tortrix viridana* L., *Lymantria dispar* L., and *Operophtera brumata* L. in sessile oak stands (Praciak 2013; Eaton et al. 2016). These, especially in synergy with heavy infestations of oak powdery mildew (*Erysiphe alphitoides* Griffon & Maubl.), can cause a rather significant reduction in the volume production of oak stands (Marçais & Desprez-Loustau 2014). The mildew covers a significant area of the leaf surface and thus prevents photosynthetically active radiation from reaching the leaf surface (Jones 1959), inhibiting the process of photosynthetic assimilation with the impact in reduced volume increment (Vose & Allen 1988; Olascoaga et al. 2016). However, this pathogen can be eliminated relatively successfully in nursery seedlings by regulated watering (see Kasprzyk et al. 2022). Other defoliators that have been recorded feeding on the assimilative apparatus of sessile oak in Central Europe include *Melolontha hippocastani* Fabr. (Martinek et al. 2018; Kula 2022). In the context of increasingly frequent dry periods, the semi-parasitic *Loranthus europaeus* Jacq. is becoming a significant pest in this region, with substantial negative effects on the physiological state of sessile oak (Eliáš 1997; Kubov et al. 2020). The abundance of this semi-parasite has been found to decrease over time in hosts with greater stem diameter (Kubiček et al. 2018). Among the significant pathogens affecting the root system of sessile oak in Central Europe are *Phytophthora* spp. (Tkaczyk et al. 2020) and *Chalara angustata* sp. nov. (Kowalski & Halmschlager 1996). Deer can also be a critical limiting factor for regeneration (Fig. 7), but sessile oak is less damaged by browsing (Vacek et al. 2019a; Fuchs et al. 2021) compared to other broadleaved species (sycamore maple, rowan, and European beech) or silver fir.



Fig. 7. Although sessile oak is not particularly susceptible to browsing damage, it is advisable to protect its regeneration from game by fencing to provide more favourable growing conditions.

A detailed overview of biotic and abiotic damage to sessile oak in Europe can also be found in Thomas et al. (2002), Müller & Gailing (2020), or Tkaczyk (2023).

8. Timber properties and use

In terms of mechanical properties, oak timber is characterized as medium-hard with high resistance and strength in compression, bending, and shear (Požgaj et al. 1997; Vigué & Mikulka 2010). The timber is classified as circularly porous, which can be distinguished by dark heartwood and light sapwood with distinct pith rays that are multi-layered and visible in all directions. In cross-section, macropores can be seen in earlywood and clusters of micropores in latewood (Vavřík & Gryc 2012). The wood is medium to heavy and has an average dry density of 650 to 696 kg m⁻³ (Požgaj et al. 1997; Vavřík & Gryc 2012).

Due to its properties and durability of the heartwood, oak timber has a wide application both in interiors and exteriors. It is used, for example, for hydraulic structures and shipbuilding. Its chief use in interiors is in veneering (sliced veneers), furniture making and carving,

construction joinery (windows, doors, floors, and tiles), and woodturning. Excellent mechanical properties predetermine oak wood for barrel making and, together with beech, for the production of sleepers (Vigué & Mikulka 2010; Blanc-Jolivet & Liesebach 2015). The bark of young trees has historically been used to make decoctions for stomach and intestinal problems, disinfection of dermal diseases etc. Nowadays, the use of oak bark is more for the production of tanning material for leather processing (Úradníček & Maděra 2001). In coppice and coppice-with-standards management, oak is mainly used for faster biomass production (Kadavý et al. 2011).

9. Conclusion

At a time when the GCC is posing increasing challenges to forest ecosystems, the sessile oak and its proper management offer high potential for adaptation and mitigation of the adverse effects of GCC. Its longevity, together with its adaptability to a wide range of climatic and soil conditions, makes sessile oak a promising tree species for future forest management. The deep-rooted sessile oak can use water efficiently and is relatively drought-

tolerant. It is a suitable choice for forest stands in areas where changes in precipitation distribution and rising air temperatures are expected. Its ecological plasticity and ability to form mixed stands with other tree species contribute to increasing the biodiversity of forest ecosystems and their resilience to stressors. In the Czech Republic, the sessile oak's resilience to climate variability makes it particularly valuable for enhancing forest adaptability and ecosystem services, addressing both local and broader environmental challenges. The sessile oak plays a critical role in forest ecosystems and its timber has a wide range of applications in various areas of human activity, from construction to furniture to barrel making. This multifunctionality, together with the durability and aesthetic qualities of oak wood, underlines its significance not only in ecosystems but also in the economy. Despite these positives, the sessile oak still faces significant challenges. These include an increased risk of damage from pests and pathogens due to changing climatic conditions, highlighting the need for targeted conservation and sustainable silvicultural measures.

In the context of the GCC, adaptive and mitigation measures, such as forest stand mixing and adjusting stand density through tending operations, are proving crucial in maintaining the health and productivity of oak forests. Mixed stands, where sessile oak coexists with other tree species, show higher resilience to drought stress, increase biodiversity, and improve forest ecosystem services. Emphasising these adaptation strategies in Czech forest management plans is crucial to maintaining the health of oak-dominated ecosystems under the looming threat of climate change. The importance of sessile oak in forest ecosystems and its contribution to mitigating the impacts of climate change highlight the need to protect it and promote its cultivation as a key element in strategies for climate change adaptation and biodiversity conservation in the Czech Republic and beyond.

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