Journal of Forestry Research (2025) 36:78
https://doi.org/10.1007/s11676-025-01868-1

REVIEW ARTICLE

Management of sessile oak (*Quercus petraea* (Matt.) Liebl.), a major forest species in Europe

Valeriu-Norocel Nicolescu[1] · Torsten Vor[2] · Robert Brus[3] · Martina Đodan[4] · Sanja Perić[4] · Vilém Podrázský[5] · Siniša Andrašev[6] · Evgeni Tsavkov[7] · Sezgin Ayan[8] · Cengiz Yücedağ[9] · Pande Trajkov[10] · Dana Dina Kolevska[10] · Cornelia Buzatu-Goanță[11] · Michal Pástor[12,13] · Vladimír Mačejovský[12] · Juraj Modranský[13] · Marcin Klisz[14] · Wojciech Gil[14] · Vasyl Lavnyy[15] · Palle Madsen[16] · Nicola La Porta[17] · Debbie Bartlett[18]

Received: 14 February 2025 / Accepted: 10 April 2025

Abstract Sessile oak (*Quercus petraea* (Matt.) Liebl.) is widely distributed across most of Europe particularly the hills and lower mountain ranges, so is considered "the oak of the mountains". This species grows on a wide variety of soils and at altitudes ranging from sea level to 2200 m, especially in Atlantic and sub-Mediterranean climates, and it is sensitive to low winter temperatures, early and late frosts, as well as high summer temperatures. Sessile oak forms both pure and mixed stands especially with broadleaves such as European beech, European hornbeam, small-leaved lime and *Acer* spp. These form the understorey of sessile oak stands, promoting the natural shedding of lower branches of the oak and protecting the trunk against epicormic branches. Sessile oak is a long-lived, light-demanding and wind-firm species, owing to its taproot and heart-shaped root system. Its timber, one of the most valuable in Europe, is important for furniture-making (both solid wood and veneer), construction, barrels, railway sleepers, and is also used as fuelwood. It is one of the few major tree species in Europe that is regenerated by seed (naturally or artificially) and by stump shoots in high forest, coppice-with-standards and coppice forests. Sessile oak forests are treated in both regular and irregular systems involving silvicultural techniques such as uniform shelterwood, group shelterwood, irregular shelterwood, irregular high forest, coppice-with-standards and simple

Corresponding editor: Lei Yu

The online version is available at https://link.springer.com/.

✉ Valeriu-Norocel Nicolescu
nvnicolescu@unitbv.ro

[1] Faculty of Silviculture and Forest Engineering, University Transilvania of Brasov, Sirul Beethoven 1, 500123 Brasov, Romania

[2] Hawk University of Applied Sciences and Arts, Büsgenweg 1A, Göttingen, Germany

[3] Biotechnical Faculty, University of Ljubljana, Jamnikarjeva ulica 101, 1000 Ljubljana, Slovenia

[4] Croatian Forest Research Institute, Cvjetno naselje 41, 10450 Jastrebarsko, Croatia

[5] Faculty of Forestry and Wood Sciences, Czech University of Agriculture in Prague, Kamýcká 129, 16521 Prague 6-Suchdol, Czech Republic

[6] Institute of Lowland Forestry and Environment, Antona Čehova 13d, 21102 Novi Sad, Serbia

[7] Department of Dendrology, University of Forestry, 10 Kliment Ohridsky Blvd., 1797 Sofia, Bulgaria

[8] Department of Silviculture, Faculty of Forestry, Kastamonu University, Kuzeykent Campus, 37100 Kastamonu, Turkey

[9] Faculty of Engineering and Architecture, Department of Landscape Architecture, Burdur Mehmet Akif Ersoy University, İstiklal Yerleşkesi, 15030 Burdur, Turkey

[10] Hans Em Faculty of Forest Sciences, Landscape Architecture and Environmental Engineering, Ss. Cyril and Methodius University in Skopje (UKIM), 16 Makedonska brigada St. No. 1, 1000 Skopje, North Macedonia

[11] Department of Silviculture, Faculty of Engineering and Applied Technologies, University of Life Sciences "King Michael I", Calea Aradului 119, 300645 Timisoara, Romania

[12] National Forest Centre–Forest Research Institute Zvolen, T. G. Masaryka 2175, 960 01 Zvolen, Slovak Republic

[13] Faculty of Ecology and Environmental Sciences, Technical University in Zvolen, T.G. Masaryka 24, 960 01 Zvolen, Slovak Republic

[14] Department of Silviculture and Forest Tree Genetics, Forest Research Institute, Braci Lesnej Street 3, Sekocin Stary, 05-090 Raszyn, Poland

[15] Department of Silviculture, Ukrainian National Forestry University, 103, Gen. Chuprynkyst., Lviv 79057, Ukraine

Published online: 04 June 2025

coppice. Young naturally regenerated stands are managed by weeding, release cutting and cleaning-respacing, keeping the stands quite dense for good natural pruning. Plantations are based on (1) 2–4-year old bare-root or container-grown seedlings produced in nurseries using seeds from genetic resources, seed stands and seed orchards. The density of sessile oak plantations (mostly in rows, but also in clusters) is usually between 4000 and 6000 plants ha^{-1}. Sessile oak silviculture of mature stands includes crown thinning, focusing on final crop trees (usually a maximum of 100 individuals ha^{-1}) and targeting the production of large-diameter and high quality trees at long rotation ages (mostly over 120 years, sometimes 250–300 years). In different parts of Europe, conversion of simple coppices and coppice-with-standards to high forests is continuing. Even though management of sessile oak forests is very intensive and expensive, requiring active human intervention, the importance of this species in future European forests will increase in the context of climate change due to its high resistance to disturbance, superior drought tolerance and heat stress resistance.

Keywords Sessile oak · Ecological requirements · Timber · Vulnerabilities · Management

Introduction

Oaks (*Quercus* spp.) are considered the most diverse genus of temperate trees in the northern hemisphere (Gil-Pelegrín et al. 2017). They evolved approximately 60 million years ago in the Paleoarctic (Sork 2024) and are widely distributed worldwide, comprising more than 400 (Kabrick and Vickers 2024), 430 (Boland 2024), 435 (Schweitzer 2024) or almost 500 species of trees and shrubs (Sork 2024).

In Europe there are circa 20 species of oak (Flies 1993; Löf 2024), compared to 100 species in North America and 150 species in Central and South America (Kabrick and Vickers 2024). The number of oak species in Europe is considered to be 22 by Medina et al. (2024), 27 by Savill and Kanowski (1993) or even 30 according to Lyubenova et al. (2024). These species are divided into two groups: those from the temperate regions (e.g., pedunculate oak *Quercus robur* L., sessile oak *Q. petraea* (Matt.) Liebl., Hungarian oak *Q. frainetto* Ten.), as well as those from the Mediterranean regions (e.g., cork oak *Quercus suber* L., holm oak *Q. ilex* L., downy oak *Q. pubescens* Willd., Pyrenean oak *Q. pyrenaica* Willd.) (Flies 1993). Out of these species, only three involving sessile oak, pedunculate oak and cork oak have a significant economic importance in Europe (Savill and Kanowski 1993).

Among oaks, which are the most important broadleaved species in Europe, covering about 21 million ha (Dincă 1983; Lemaire 2010; Zadworny et al. 2014), the most widely distributed across most of the continent are pedunculate and sessile oaks. They reach northwards to southern Norway and Sweden, and southwards to the northern part of the Iberian Peninsula, southern Italy, the Balkan Peninsula and Turkey (Haralamb 1967; Lemaire 2010; Eaton et al. 2016; Girard et al. 2022). However, sessile oak is mainly concentrated in the more sub-Atlantic regions, where its climatic requirements resemble those of European beech (*Fagus sylvatica* L.) (Fig. 1).

As it is found particularly in the hills and lower mountain ranges, the species is rightfully regarded as"the oak of the mountains" (Joyce et al. 1998).

Regarding sessile oak, a species belonging to the subgenus *Lepidobalanus* (Endl.) Oerst (white oaks), section *Roburoides* Schw, series *Sessiliflorae* Loj., two opinions exist in Europe in terms of its systematics:

- There are three *species* belonging to the group of sessile oak namely *Quercus petraea* (Matt.) Liebl., Dalmatian oak *Quercus dalechampii* Ten., and Transylvanian oak *Quercus polycarpa* Schur, as acknowledged in Bulgaria [Ganchev and Bondev 1966; Assyov and Petrova (eds) 2012]; Serbia (Jovanović 2000) or Romania (Negulescu and Săvulescu 1957, 1965). In Serbia, the three species are designated collectively as *Q. petraea* agg Ehrendorfer (Jovanović 2000).
- Sessile oak includes three *subspecies* as in Romania (*Quercus petraea ssp. petraea* (Liebl.) Soó, *Q. petraea ssp. dalechampii* (Ten.) Soó, and *Q. petraea ssp. polycarpa* (Schur) Soó), but only one species, *Q. petraea* (Matt.) Liebl., being considered (Stănescu 1979; Stănescu et al. 1997; Șofletea and Curtu 2007). Three subspecies of sessile oak are also acknowledged in Tur-

Fig. 1 Distribution map of sessile oak (source: Caudullo et al. 2017)

[16] InNova Silva ApS, Hojen Tang 80, 7100 Vejle, Denmark

[17] Foundation Edmund Mach (FEM), Via Edmund Mach, 2, 38010 S. Michele a/Adige, Italy

[18] Faculty of Engineering & Science, University of Greenwich, Central Avenue, Chatham Maritime, Medway, Kent ME4 4TB, UK

key: *Quercus petraea ssp. petraea*, *Q. petraea ssp. iberica* (Steven ex M.Bieb.) Krassiln., and *Q. petraea ssp. pinnatiloba* (C. Koch) Menitsky (Meșe et al. 2023).

Sessile oak covers important areas of forestlands—from hundreds of thousands to millions of hectares—in European countries such as France, Germany, Romania, Bulgaria, Poland, Serbia, Turkey, Bosnia and Herzegovina, Czech Republic (Table 1).

The presence of sessile oak either as individual species or together with pedunculate oak in different countries has two reasons:

a. In the majority of countries, sessile oak and pedunculate oak are now considered as part of a syngameon which is characterized by hybridization and introgression among the closely related oak species (Goicoechea et al. 2012; Cannon and Petit 2020, cited by Kohler et al. 2020). However, these also persist as individual species, therefore constituting separated taxa that occupy partially different ecological niches, with a large overlap in soil pH and climatic site conditions (Höltken et al. 2012; Neophytou et al. 2010; Reutimann et al. 2020; Leroy et al. 2020, all cited by Kohler et al. 2020).
b. In other countries, sessile and pedunculate oak are not distinguished as separate species as both are very variable morphologically but share the same chloroplastic DNA, transmitted through the acorns (Ducci et al. 2017) and can naturally hybridise asymmetrically (*Q. petraea* preferentially pollinates *Q. robur*, Ducci et al. 2017, with the leaf characteristics of the hybrids being more similar to those of the female parent, rather than intermediate

Table 1 Area covered by sessile oak in different European countries

Country	Area covered by sessile oak (and pedunculate oak) (ha)	Source	Comments
France	4,151,000 ± 81,000* 1,843,000 ± 58,000** 777,000 ± 39,000***	IGN 2024	*Area (overall) of stands where sessile oak is found ** Area of stands where sessile oak is the dominant species *** Area of pure sessile oak stands
Poland	732,832.6 (sessile and pedunculate oak)	https://www.bdl.lasy.gov.pl/portal/ 2023	Sessile oak and pedunculate oak are not distinguished in forest management plans
Romania	582,826.95	https://roifn.ro/site/rezultate-ifn-2	8.41% of total forest area
Germany	564,000	Vor pers.comm	5.18% of total forest area
Bulgaria	425,300	Bozhinov 1999	19.1% of area covered by broadleaves
Hungary	367,400 (sessile and pedunculate oak)	Solymos 1993	Both species: 22.9% of total forest area Sessile oak: 12% of total growing stock
Turkey	242,381.8	Fosso and Karahalil 2023	
Bosnia and Herzegovina	230,700	Višnjić et al. 2018	
Serbia	223,692.46	Andrašev pers.comm	7.84% of total forest area
United Kingdom	219,000 (sessile oak and pedunculate oak)	Forest Research 2024	There is no distinction between sessile oak and pedunculate oak
Czech Republic	203,500 (sessile and pedunculate oak)	MZe 2022	There is no distinction between sessile oak and pedunculate oak
North Macedonia	174,474.86	Trajkov pers.comm	19.55% of forests with management plans; 163 036 ha as coppice
Austria	146,000 (sessile and pedunculate oak)	Hochbichler 1993	About 4% of total forest area
Ukraine	114,570.1	Lavnyy pers.comm	
Denmark	73,919	Nord-Larsen et al. 2023	14.96% of total forest area; there is no distinction between sessile oak and pedunculate oak
Italy	61,045	Gasparini et al. 2022	0.55% of total forest area
Croatia	38,301	Dubravac et al. 2018	
Slovakia	10,040.29	Bednárová 2023; Green Report 2023	
Slovenia	–	Skudnik et al. 2021	5.3% of total growing stock of national forests (2018)

of those of both parents, Ducousso and Bordacs 2004), infrequently, but significantly (Bonfils et al. 2015) (e.g., hybridisation rate of 8.4%, Streiff et al. 1999). This phenomenon generates individuals showing intermediate traits or dominance of one, therefore it can be difficult to characterize them unequivocally by observations only (Aas 2014; Jensen et al. 2009, both cited by Eaton et al. 2016).

France, with the famous provenances of Tronçais (Fig. 2), Bellême, Bercé, Blois, Reno-Valdieu exhibiting almost monospecific and regular high forests, with 120–200 individuals ha^{-1} and a standing volume of 450–600 m^3 ha^{-1} (or even more) at a rotation age of circa 200 years (Balleux 2005), is the most important European country for sessile oak.

The species, considered as the 'King of French Forests' (https://www.onf.fr/vivre-la-foret/raconte-moi-la-foret/comprendre-la-foret/explorer-la-nature-en-foret/%2B/1ca7::le-chene-sessile.html), represents 12% (333 ± 13 million m^3) of the total standing volume, and a total current annual increment of 6.9 ± 0.3 million m^3, compared to the annual harvest of 3.4 ± 0.4 million m^3 (IGN 2024). Consequently, France is the foremost producer of oak timber in Europe and the second in the world, after the USA (Bary-Lenger and Nebout 1993).

Fig. 2 Sessile oak tree (355 years old, 156 cm in diameter, 35 m in height), called 'Charles Louis Philippe', in Forêt de Tronçais, France (photo V.N. Nicolescu)

In Germany, oaks (sessile and pedunculate) form the second most abundant broadleaved tree species group after European beech (Thünen Institut 2014, cited by Kohler et al. 2020). Among German sessile oak provenances, the most famous is that from Spessart Forest (Bavaria), where high-quality veneer logs are typically harvested when 300–400 years old (Viney and Pardé 1960; Hemery and Simblet 2014; https://talaricohardwoods.com/spessart-forest/; https://mbveneer.com/veneercatalogpage/spessart-oak-wood-veneer/). In 1920's, the great American ecologist and writer Aldo Leopold wrote that the Spessart "…bears the most magnificent oaks in the world. American cabinet makers, when they want the last word in quality, use Spessart oak" (Leopold 1953).

Sessile oak is of great ecological interest as it enhances forest biodiversity, an important management goal in recent times (Stimm et al. 2022), providing habitat and food source of a great variety of insects (over 1000 species thrive on sessile oak trees, Bußler 2014), mammals, birds, fungi, lichens, and moss species (Annighöfer et al. 2015; Leonardsson et al. 2015; Eaton et al. 2016; Löf 2024).

Due to its high resistance to storms (the effect of deep rooting) and superior drought tolerance, enhancing the mechanical stability and so reducing the vulnerability of forest stands to disturbance, its importance in European forests (i.e. absolute and relative share of forest cover) is expected to increase in the context of climate change (Kuehne et al. 2020; Kohler et al. 2020; Kanjevac et al. 2021; Girard et al. 2022; Stimm et al. 2022; Černý et al. 2024b; Konic et al. 2024). These two traits are supplemented by the superior heat stress resistance of sessile oak, the species being the more heat-tolerant when compared to other important forest species such as *Picea abies* (L.) H. Karst, *Abies alba* Mill., *Fagus sylvatica* L. and *Pinus sylvestris* L. (Húdoková et al. 2022), with similar levels of heat tolerance when compared to *Quercus pubescens* Willd., *Q. robur* L. and *Q. rubra* L. (Hauck et al. 2025). Sessile oak has also demonstrated the high heat-tolerance (heat stress resistance) having the highest leaf critical temperature (corresponds to the initial collapse of the photosystem II (PSII), the most thermo-sensitive component of photosynthesis—and the disruption of electron's pathway, which is typically followed by leaf necrosis and death, Krause et al. 2010, cited by Gauthey et al. 2024), compared to species growing naturally in warmer and drier climates such as *Quercus ilex* L. and *Q. coccifera* L. (Gauthey et al. 2024).

The natural range of sessile oak is predicted to shift towards the north and northeast (in areas where changes in precipitation distribution and rising air temperatures are expected, Černý et al. 2024b) in response to the ongoing and predicted changes in European climate, sessile oak becoming the most important broadleaved species for the future natural vegetation of Europe (Andrzejczyk

et al. 2023). Consequently, sessile oak can be an important component of climate-resilient mixed-species forests, which are being considered as an option to meet the challenges of climate change (Annighöfer et al. 2015; Skiadaresis et al. 2016; Kohler et al. 2020; Stimm et al. 2022; Hauck et al. 2025).

With its straight trunk, often clearly developed high in the crown (a rare trait among the broadleaves, Brus 2011), it is a major timber species in many regions of Europe (Mölder et al. 2019; Gribbe et al. 2024), it is one of the most economically valuable hardwood tree species on our continent (Trouvé et al. 2017; Kohler et al. 2020; Kuehne et al. 2020; Kanjevac et al. 2021). Consequently sessile oak is suitable for multifunctional forest management including valuable wood production, a major management goal of oak silviculture (Stimm et al. 2022).

Last but not least, sessile oak forests provide many ecosystem services such as air quality, recreation, aesthetics, and watershed protection (Löf 2024). The species also has a cultural significance, many old sessile oak trees being designated as"nature monuments" (i.e. 352 individuals (1.3%) out of 28,304 trees in Poland, Zarzyński 2019).

Currently there is no comprehensive summary of the silviculture and management of sessile oak in Europe that can be used to inform its future role in different countries. This paper provides a comprehensive overview of key factors influencing the management of sessile oak and then summarises European silvicultural experience with the species, covering aspects such as stand establishment, early silvicultural interventions such as release cutting and cleaning-respacing, commercial thinning and pruning, as well as the potential use of close-to-nature silvicultural regimes. The focus is upon the impacts upon timber production.

Sessile oak characteristics influencing management

Site and climate

Sessile oak has a very wide ecological niche, being relatively indifferent to geological substrate and soil nutrients so it can be found on poor, stony, sandy, or clayey, as well as on limestone/calcareous soils (Yaltırık 1984; Jacamon 1987; Delkov 1992; Joyce et al. 1998; Michiels 2014; Bartsch et al. 2020; CNPF 2023). However, it grows best on fertile, moist (with constant humidity/high water availability, Stănescu 1979; Spiecker 2021), deep (over 50 cm, allowing deep rooting), well-structured, well-drained and not compacted Cambisols and Luvisols (Boratyńska 1979; Boudru 1989a; Delkov 1992; Filipovskij et al. 1996; Filipovski 1997; Sevrin 1997; Savill 2013; CNPF 2023). Suitable soils for sessile oak are moderately acidic to neutral (pH 4.4–7.3, Timbal and Aussenac 1996; Pagan 1999; Sarvaš et al. 2010), but it can also be found on highly acidic soils (pH 2.5–3.5) (Brus 2011; Bončina et al. 2021).

Sessile oak does not tolerate a high (Pagan 1999; Sarvaš et al. 2010), or erratically variable water table (Savill 2013) or floodplains with stagnant water (Negulescu and Săvulescu 1957, 1965; Ugrenović and Potočić 1963; Kerr and Evans 1993; Ducousso and Bordacs 2004; Aas 2014). It tolerates soils with pseudogley (Rameau et al. 1989), but regeneration and growth are affected on plateaus and terraces with argillic, heavy-textured soils (Boppe 1889; Negulescu and Săvulescu 1957, 1965; Stănescu 1979; Stănescu et al. 1997).

Sessile oak is found mostly on mountain slopes and hilltops (Eaton et al. 2016; Nyamjav 2022), but also on the plains (Negulescu and Săvulescu 1957, 1965). Across Europe, its altitudinal range is very wide, from sea level to 2200 m above sea level (a.s.l.) (Table 2).

Table 2 Altitudes where sessile oak is found in Europe

Altitude (m a.s.l.)	Country	Source	Observations
0 (minimum)	Bulgaria Turkey	Radkov and Minkov 1963 Meşe et al. 2023	Ssp. *iberica*
(30) 200–750 (1000)	Slovenia	Brus 2011; Bončina et al. 2021	
300–1300	Serbia	Krstić et al. 2001	
400–800 (900)	Romania	Stănescu 1979; Stănescu et al. 1997	Exceptional 1,300 m
Up to 500	Poland	Klisz pers.comm	
Up to 580	Germany	Bartsch et al. 2020	Exceptional 1800 m
(600) 900–1100	North Macedonia	Filipovskij et al. 1996	Exceptional 1300 m
Up to 750–850	Czech Republic	Úradníček 2004; Vacek et al. 2019	
Up to 780	Slovakia	Pagan 1999	Exceptional 1145 m
800–1000	Bulgaria	Radkov and Minkov 1963	Exceptional 1300–1400 (1600) m
Up to 1300	Croatia	Sever et al. 2022	
2200 (maximum)	Turkey	Meşe et al. 2023	Ssp. *pinnatiloba*

The species prefers warm, sunny and south- or south-west facing slopes, where summer warmth stimulates fast growth (Ugrenović and Potočić 1963; Negulescu and Săvulescu 1957, 1965; Boudru 1989a; Savill 2013). Sessile oak is a heat-loving tree species, which prefers Atlantic to sub-Mediterranean climates (Jacamon 1987; Bartsch et al. 2020), with mean annual temperatures of 5–11.5 °C (Germany, Michiels 2014), (7) 8–10 (12) °C (Slovenia, Brus 2011; Bončina et al. 2021), 7.9–10.3 °C (Serbia, Krstić et al. 2001), 8 °C (Czech Republic, Černý et al. 2024b), 8–10 °C (Romania, Șofletea and Curtu 2007), 8.5 °C (Slovakia, Pagan 1999), 9 °C (North Macedonia, Filipovskij et al. 1996), even 11 °C (Turkey, Șahin 2020). It prefers a mean annual rainfall of minimum 500 mm yr^{-1} (Germany, Michiels 2014), and grows in areas with 600–800 mm yr^{-1} (Romania, Șofletea and Curtu 2007), 626–944 mm yr^{-1} (Serbia, Krstić et al. 2001), 700–1200 mm yr^{-1} (Croatia, Sever et al. 2022), up to 800 mm yr^{-1} (Slovakia, Pagan 1999), 800–850 mm yr^{-1} (North Macedonia, Filipovskij et al. 1996), (800) 1000–1700 (2000) mm yr^{-1} (Slovenia, Brus 2011; Bončina et al. 2021) precipitations. In rare cases, it can grow successfully with 400 mm yr^{-1} of precipitations (Romania, Haralamb 1967; Czech Republic, Černý et al. 2024b).

It is drought tolerant (Bréda et al. 1993b; Bonfils et al. 2015; Spiecker 2021; CNPF 2023; Černý et al. 2024a; Hauck et al. 2025), having a high tolerance to dry sites (changes in water availability, Nyamjav 2022), due to the deep taproot (can extract water during periods of reduced water availability from deep in the soil, Černý et al. 2024b) and xeromorphic leaf structures. During strong drought stress, sessile oak trees regulate their water intake by partially closing their stomata to conserve water by decreasing transpiration and maintain leaf water potential, which results in improved water use efficiency (WUE) (Thomas and Gausling 2000; Meeran et al. 2025). (WUE is a functional trait expressing at the tree level the trade-off between biomass production and water loss by transpiration, linking the tree carbon assimilation and water loss, Rabarijaona et al. 2022). Transpiration intensity returns to full level after hydration (Bréda et al. 1993a, b). There is a local adaptation of sessile oak in terms of drought response strategy, with a large variability of WUE within populations, suggesting large genetic diversity. In addition there are significant differences in WUE among populations of sessile oak but a much larger variability was observed within than between populations (Rabarijaona et al. 2022). As mature trees benefit from deeper root system, enhanced water storage and accumulated carbohydrates, promoting mixed-age stands could enhance resistance to drought, as trees of different ages and sizes employ varied strategies to cope with drought stress (Meeran et al. 2025). However, drought can lead to a significant reduction in secondary growth of sessile oak trees (Cedro 2007; Meeran et al. 2025), and they may not recover to their pre-drought growth level in the subsequent year (Bose et al. 2021). In response to drought, populations of sessile oak with a higher increase in WUE showed a lower decrease in radial growth (Rabarijaona et al. 2022). Higher WUE can increase the establishment and survival of trees under water-deficit conditions, and enhancing WUE is crucial for maximizing forest carbon assimilation capacity while conserving water resources (Petrík et al. 2024).

Unfortunately, drought stress could become a primary cause of forest dieback in the near future and may also cause genetic diversity loss in sessile oak populations that have reduced plasticity and adaptive potential (Borovics and Mátyás 2013, cited by Černý et al. 2024b). In mixed stands, sessile oak manages drought better than European beech, wild cherry (*Prunus avium* L.), large-leaved lime (*Tilia platyphyllos* Scop.) and sycamore (*Acer pseudoplatanus* L.) (Scherrer et al. 2011, cited by Bonfils et al. 2015). Therefore, it is considered as one of the species only 'partially threatened' in comparison to the 'most threatened' species (silver fir *Abies alba* Mill., Norway spruce *Picea abies* (L.) Karst., European larch *Larix decidua* Mill., and Scots pine *Pinus sylvestris* L.) by the climate changes predicted for 2041–2060 (Dyderski et al. 2025). On the contrary, sessile oak could be a 'beneficiary' of these changes (Bonfils et al. 2015), and could even increase its current range/gain potential niche in Europe (Dyderski et al. 2025).

Species composition

Throughout its native range sessile oak, a climax species is found in both pure and mixed stands. The pure stands (one-storeyed, uniform, without any undergrowth) are found mostly in the hilly areas, on warm and dry sites (e.g., plateaus, sunny ridges, south-facing slopes), as in Bulgaria and Romania (Anonymous 1956; Negulescu and Săvulescu 1957, 1965; Pașcovschi and Leandru 1958; Petrescu 1971; Stănescu 1979; Anonymous 1986; Stănescu et al. 1997).

In Central and south-eastern part of Europe, sessile oak is also part of mixed stands including mostly European beech, European hornbeam (*Carpinus betulus* L.), small-leaved lime (*Tilia cordata* Mill.), elm (*Ulmus* spp.), wild cherry, field maple (*Acer campestre* L.), Norway maple (*Acer platanoides* L.), common ash (*Fraxinus excelsior* L.), manna ash (*Fraxinus ornus* L.), narrow-leaved ash (*Fraxinus angustifolia* Wahl), and *Sorbus* spp.. Other oak species such as pedunculate oak, Hungarian oak and Turkey oak, are also present in these regions (Negulescu and Săvulescu 1957, 1965; Stănescu 1979; Rauš et al. 1992; Stănescu et al. 1997; Doniță et al. 2005; Tomić and Rakonjac 2011; Bončina et al. 2021). In the south-east and south of Europe, with sub-Mediterranean and Mediterranean climates sessile oak is found mixed with Oriental beech (*Fagus orientalis* Lipsky), Oriental hornbeam (*Carpinus orientalis* Mill.), downy oak,

sweet chestnut (*Castanea sativa* Mill.), and even conifers such as oriental spruce (*Picea orientalis* (L.) Link) (Yaltırık, 1984; Güngördü 1999; Ellenberg and Leuschner 2010; Genç 2012; Öztürk 2013). Growing sessile oak in mixtures with additional tree species is considered to be a convenient way of adapting to global climate change (Pretzsch et al. 2015, 2020, both cited by Černý et al. 2024b), because these show higher resilience to drought stress, can provide better stand stability and can better utilize the available resources (Černý et al. 2024b).

Root system

On favourable, deep, non-compacted and well-drained, soils, sessile oak shows a definite, strong taproot (Negulescu and Săvulescu 1957, 1965; Stănescu 1979; Andrzejczyk 2009; Brus 2011), often penetrating to a depth of 1.5–2 m when young (Lorentz and Parade 1883; Bary-Lenger and Nebout 1993; Joyce et al. 1998). Later in life, the root system develops into a heart-shaped form (Joyce et al. 1998). This system includes dense shallow roots as well as lateral roots, developed all along the taproot, colonizing the upper soil and anchoring the trees, which gives sessile oak structural stability against windthrow and allows the species to withstand moderate drought by accessing deeper water (Boudru 1989a; Bary-Lenger and Nebout 1993; Praciak et al. 2013, cited by Eaton et al. 2016; Sever et al. 2022). However, the species can be windthrown when its root system is affected by soil conditions (i.e. on shallow soils, with less than 60 cm rootable depth, Kerr and Evans 1993, or soils with high water table, where the taproot can not develop, Bary-Lenger and Nebout 1993), or when in full leaf, by a combination of summer gales and high precipitation (Joyce et al. 1998).

Shade tolerance

When young (seedling stage), sessile oak trees are relatively tolerant to shade (Poskin 1926, 1949; Petrescu 1971; Delkov 1992; Niinemets and Valladares 2006). Under a mature stand, with closed canopy, sessile oak seedlings can persist for a maximum of 2 years (coppice stand, Balleux 2005), 2–3 years (Jacamon 1987; Haugh 1907, Bondarenko 1987, both in Worrell and Nixon 1991), 3 years (light intensity 4.5% of full light, Ciumac 1967), 4–6 years (Negulescu and Stănescu 1964; Negulescu and Săvulescu 1957, 1965; Stănescu 1979), then degenerate and eventually die out (Çalışkan et al. 2004). Under a loose canopy (crown cover 60–80%), sessile oak seedlings can survive for 5 years (Ciumac 1967; Constantinescu 1973). The light compensation point (i.e. light intensity where the rate of photosynthesis exactly matches the rate of cellular respiration) for sessile oak seedlings is 2–6% of full light, so they can be considered as 'shade plants' (Worrell and Nixon 1991).

The young plants tolerate more shade before the thicket phase (mean diameter at breast height 5 cm, Joyce et al. 1998), after which the light requirements increase, therefore sessile oak is generally considered as a 'genuine' light-demanding species, even less than pedunculate oak (Jolyet 1916; Drăcea 1923; Poskin 1926, 1949; Negulescu and Săvulescu 1957, 1965; Ciumac 1959, 1965; Petrescu 1971; Schütz and Badoux 1979; Stănescu 1979; Evans 1984; Lanier 1986; Jacamon 1987; Bary-Lenger et al. 1988; Boudru 1989a; Bary-Lenger and Nebout 1993; Kerr and Evans 1993; Bastien 1997; Savill 1991, 2013; Sevrin 1997; Stănescu et al. 1997; Joyce et al. 1998; Balleux 2005; Lemaire 2010; CRPF Bourgogne 2012; Nyamjav 2022). However, there are some exceptions. Authors such as Rameau et al. (1989), Bonfils et al. (2015) or CNPF (2023) consider sessile oak as medium shade-tolerant, whereas Puchalski and Prusinkiewicz (1990) consider it shade-tolerant!

Branching and natural pruning

In stands, sessile oak trees have a long straight trunk, are less branched than pedunculate oak with generally thinner branches (Sarvaš et al. 2007, 2010). It exhibits a hierarchical branching structure (Ugrenović and Potočić 1963), with the main branches dividing through a regular transition into secondary branches and branchlets (Haralamb 1967). The crown is more regularly shaped and slightly narrower than in pedunculate oak (Brus 2011). A major problem of sessile oak silviculture, reducing the quality of its wood and making it unusable for high quality products such as veneer, is the occurrence and growth of epicormic branches (water sprouts, lammas shoots, Fig. 3), a trait which is believed to be highly heritable (Kanowski et al. 1991, cited by Savill 1991, 2013).

Because of this defect, sessile oak logs are downgraded in EU quality standards from class A to classes B or C (Baylot and Vautherin 1992; Anonymous 1997). The practical way of preventing and controlling the occurrence and growth of epicormics from final crop trees with large crowns is to grow them with an understorey of shade-tolerant species (e.g., European beech, European hornbeam) and to perform light and frequent silvicultural interventions (Bagneris 1873, 1876; Lorentz and Parade 1883; Boppe 1889; Antonesco 1911; Drăcea 1923; Evans 1983, 1984; Kerr and Evans 1993; Schütz 1993; Jarret 1996; Sevrin 1997; Joyce et al. 1998; Sardin 2008; Lemaire 2010; Spiecker 2021; Nicolescu et al. 2022). The manual removal of such branches on the lower part of the stem (Sevrin 1997) will be presented in detail in the paragraph on pruning. Sessile oak is a better self-pruner than the pedunculate oak and its trunk can be

Fig. 3 Epicormic branches on a mature sessile oak tree (photo V.N. Nicolescu)

followed to the tip (Haralamb 1967). Pruning is induced by competition of neighbouring trees: branches die soon after being shaded and the dead branches break off, improving wood quality (Spiecker 2021). The best species to use in the undergrowth in order to shade the sessile oak trunk and help its natural pruning are shade-tolerant ones such as European beech, European hornbeam, small-leaved lime, and field maple (Jolyet 1916; Poskin 1926; Kenk 1978; Schütz and Badoux 1979; Duplat 1992; Bary-Lenger and Nebout 1993; Jarret et al. 1996; Bastien 1997). Interestingly, their use in sessile oak-dominated stands to promote natural shedding of lower branches, control the occurrence and growth of epicormic branches, inhibit development of ground vegetation and increase regeneration of shade-tolerant species, which could be an impediment to the regeneration of sessile oak, was already advocated at the end of the nineteenth century (Bagneris 1878; Broilliard 1881; Boppe 1889). The practical ways of promoting the existing understorey in sessile oak stands, as well as establishing it when missing, will be presented in detail in the section on management of sessile oak for wood production.

Life span

Sessile oak is a long-living species, trees over 300 years being recorded in countries like Austria (374 ± 60 years), The Netherlands (324 ± 20 years), Switzerland (324 ± 50 years), Belgium (324 ± 50 years). In other countries like France (444 ± 40 years), Italy (424 ± 100 years), Albania (474 years), and Poland (404 ± 20 years), the record sessile oak trees have ages over 400 years, while the age records of sessile oak trees are older than 500 years in Spain (924 ± 100 years), Germany (516 ± 50 years), Bulgaria (645 years), and Serbia (524 ± 50 years). The oldest sessile oak in the world, called *Big-Belly Oak* and aged 1022 ± 10 years, is found in the UK (Severnake Forest) (all above records were extracted from https://www.monumentaltrees.com/en/trees/sessileoak/records).

Growth performance in Europe

Sessile oak grows slowly *in height* in youth (it is a species with slow initial height increment, Poskin 1926; Lanier 1986; Bary-Lenger et al. 1988): in the first year the aerial part of the seedling is 15–20 cm length, while the root reaches 40–50 cm in length, as the 1-year growth is concentrated in the root system (Nicolescu et al. 2022). The tree grows 10–20 cm a^{-1} in the first 5–8 years (Evans 1984), speeds up (after root elongation) in the next 10 years (up to 50 cm a^{-1} between age 10 and 20, Evans 1984) and grows quite quickly on good sites but only after the age of 20 (Haralamb 1967). Its height increment is sustained until the age of 100 (120) years (Negulescu and Săvulescu 1957, 1965; Stănescu 1979; Stănescu et al. 1997). In height, record sessile oak trees over 40 m were found in countries including France (48.40 m, world record, in the famous Forêt de Bercé), Germany (44.60 m), and UK (41.00 m) (https://monumentaltrees.com/en/trees/sessileoak/records). In Poland, a record sessile oak tree of 43 m in height (127 cm in diameter, 300–400 years old) was found (Zaręba 1993). In Turkey (Yaltırık and Efe 1994) and Slovakia (Halaj and Petráš 1998), sessile oak trees have reached heights up to 40 m. In the past, sessile oak trees up to 45 m in height were also found in Romania (Ronișoara-Maramureș provenance, Negulescu and Săvulescu 1965).

Records of sessile oak trees over 200 cm *in diameter* in several European countries are as follows (https://monumentaltrees.com/en/trees/sessileoak/records): 446 cm (UK, the world record, at Marton Oak), 382 cm (Spain), 255 cm (France), 245 cm (Hungary), 242 cm (Germany), 232 cm (Albania), 223 cm (Bulgaria), 202 cm (Austria). Its radial growth is less climate sensitive than that of European beech, Scots pine or Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) (Gribbe et al. 2024). Radial growth of sessile oak is more vulnerable to drought in moister rather than on drier sites (Trouvé et al. 2017) and the biomass performance decreased under reduced water supply (Nyamjav 2022).

The main annual *volume increment* of pure sessile oak stands at different old ages in several European countries depends on the site potential/production class (Table 3).

Table 3 Mean annual volume increment of sessile oak stands at different old ages and in selected European countries

Country	Mean annual volume increment (m^3 yr^{-1} ha^{-1})	Reference	Observations
Bulgaria	3.29 (low productivity sites)–6.11 (high productivity sites)	Bogdanov 1975	Age 100 years
Czech Republic	5–8 5–10*	Podrázský pers.comm	*In Dauerwald, close-to-nature forests
Romania	4.1 (lowest -5th—production class)—10.2 (highest—1st—production class)* 3.2 (lowest—5th—production class)—9.2 (highest—1st—production class)**	Giurgiu and Drăghiciu 2004	*High forest, rotation age 120 years (5th production class)—140 years (1st production class) **Coppice, rotation age 100 years (5th production class)—120 years (1st production class)
Slovakia	2.6–10.9	Halaj and Petráš 1998	
Slovenia	3.6–5.0 (poor sites)…6.3–6.9 (good sites)	Bončina et al. 2021	Age 100 years
Germany	3.7–11.5	Albert et al. 2021	Age 100 years
Poland	4.5 (poorest site conditions)–8.4 (optimal site conditions)	Szymkiewicz 2001	Age 140 years
Ukraine	4.0 (lowest—IIIrd—site class)–6.2 (highest—Ist—site class)	Anonymous 1987	Age 110 years

Timber: quality, uses and prices

Sessile oak wood is ring-porous, and the proportion of earlywood to latewood determines the working and strength properties of the timber. As earlywood width tends to remain constant irrespective of growth rate, one may encounter two opposite situations (Joyce et al. 1998):

- Rapidly growing oak trees will contain a high proportion of latewood relative to earlywood, resulting in high strength properties, greater shrinkage and somewhat poor workability;
- Slow growing oak trees contain growth rings consisting almost entirely of earlywood resulting in poor strength properties, lower shrinkage but good workability.

Its wood is dense (Table 4), hard, elastic; it shrinks depending on growth rate (see above), and its strength properties, including bending strength, are excellent (Keše 2016).

The wood density increases from the bark to the core (Enchev 1972). It is the growing conditions (climatic, soil fertility), which determine the earlywood (consisting mainly of large vessels)/latewood (includes mainly fibres and to a lesser extent vessels) ratio (Bergès et al. 2008). Sessile oak wood dries slowly and has a tendency to split and check unless care is taken in kiln drying. The heartwood is classed as durable (Venet and Keller 1986, cited by Cavaignac 2007) and resists penetration by preservatives (class 4, non penetrable, ur-biowooeb.cirad.fr). Sapwood is perishable but permeable and is confined to the outer 10–20 (Joyce et al. 1998) or 20–30 (Savill et al. 1993, cited by Savill 2013) growth rings in the tree. The natural durability of sessile oak wood is class 2 (durable) against fungi, and class D (durable) against

Table 4 The density of sessile oak wood reported in different European studies

Wood density (kg m^{-3})	Country	Source	Observations
610–650	Slovakia	Petráš et al. 2021	
650 (mean)	Slovenia	Keše 2016	Range 390–930 kg m^{-3}
673 (mean)	Poland	Vavrčik and Gryc 2012	
690 (mean)	Bulgaria Romania	Blaskova 2004 Filipovici and Amzică 1956	Range 430–960 kg m^{-3}
650–900	Croatia	Đodan pers.comm	
700 (mean)	Belgium	Bary-Lenger and Nebout 1993	Range 600–800 kg m^{-3}
710 (mean)	Germany	Ehmcke and Grosser 2014	Range 430–960 kg m^{-3}
720 (mean)	Ireland UK	Joyce et al. 1998 Savill 2013	
740 (mean)	France	https://ur-biowooeb.cirad.fr/	
803 (mean)	North Macedonia	Nacevski et al. 2015	

insects (dry wood) (ur-biowooeb.cirad.fr). The lifespan of sessile oak wood varies from 15 to 25 years for wood in permanent contact with the ground, from 40 to 50 years for wood exposed to the elements and up to several centuries for timber used for framing/roofing (Bary-Lenger and Nebout 1993). Due to its strength properties and high durability, sessile oak wood is widely used in furniture-making (both as solid wood and veneer) and construction. Important quantities of wood are used for plywood, flooring/parquets, panels, staircases, balustrades, doors, window frames, bridges, railway sleepers, tool handles, agricultural equipment, fencing (poles, posts), vineyard stakes, tanbark, and for construction of roof trusses (Jacamon 1987; Čufar 2006; Savill 2013; Ehmke and Grosser 2014; Magagnotti et al. 2018). Sessile oak also produces fuelwood and charcoal (Ugrenović and Potočić 1963; Ducousso and Bordacs 2004; Ehmcke and Grosser 2014; Jarman and Kofman 2018).

The sessile oak high quality logs for veneer production should fulfill specific criteria (Bary-Lenger and Nebout 1993; Joyce et al. 1998; Spiecker 2021): large diameter, a light clear colour, straight cylindrical stem, straight fibre, centred pith and concentric rings of uniform growth, straight fibre, and absolutely blemish-free stems. The need to use large-diameter logs (class A+, thick-end diameter at least 45 cm, Lemaire 2010; minimum mid-length diameter 50–55 cm, Flot 1988, cited by Bary-Lenger and Nebout 1993) for veneer production is obvious when considering the efficiency of transforming them into veneer (0.6 mm thickness) (Table 5).

In various European countries, where the production of high-quality sessile oak wood is the priority, the diameter of logs for such uses reaches 50–60 cm in Austria (Hochbichler 1993), a minimum of 60 cm in the UK (Evans 1984), 60–70 cm in Ireland (Joyce et al. 1998) and France (stands of good quality, Robert and Généré 2010), 60–80 cm in Germany (Kenk 1993; Vor pers.comm.) or France (CNPF 2023), 70–80 cm in France (Jarret et al. 1996; in stands of exceptional quality, Robert and Généré 2010), even 75–80 cm in France (A and B quality logs, Sardin 2008). However, the determining factors for high quality veneer logs, along with diameter, are (1) ring width and (2) uniform growth (Joyce et al. 1998). Stable uniform growth and the resulting uniform density guarantee the high quality of wood required for oak veneer production. Unfortunately, uniform growth rate can be disrupted by drought phenomena, with increased frequency leading to a decrease in the quality of oakwood (Trouvé et al. 2017). What should be the width of growth rings for different important end-uses such as veneer production? In the past, the veneer producers required very narrow/fine ring growth i.e. maximum 1.5 mm (Palatinate, Germany, Viney and Pardé 1960), 1.5–2.0 mm (Bastien 1997) or 2 mm (Baden-Würtemberg, Germany, Kenk 1978; France, Lorne 1956; Pardé 1978). The narrowest growth rings, 1.0–1.2 (1.5) mm, were produced by sessile oak trees in Spessart (Germany) (Martinot-Lagarde 1970), with a rotation age of 300 years (Vanselow 1956, in Viney and Pardé 1960). Growth rings width of 2.0–2.5 mm were targeted in Austria (Hochbichler 1993), Switzerland (Schütz 1993), and France (Dubois 1988; Jarret et al. 1996; Chaar and Colin 1999) in the past. Currently, the veneer and barrel producers require wood with semi-wide/semi-fine growth rings (2–4 mm) or even wide (over 4 mm) (Lemaire 2010). The wood with fine/narrow growth rings (maximum 2.5 mm) is in demand especially for wine barrels, veneer and interior carpentry, while wood with wider growth rings (over 2.5 mm) is sought for roofing, joinery, alcohol barrels, and solid wood furniture (Sardin 2008). However, what counts most in barrel and veneer production is not so much the width of growth rings, but their evenness/regularity (Sardin 2008; Robert and Généré 2010), as very uneven growth tends to produce difficulties in seasoning and stability (Evans 1984). In silvicultural terms, the option"fine/narrow growth rings" vs"wide growth rings"should be decided early in a stand's life to apply a specific silvicultural regime, which can't be changed subsequently (Sardin 2008). As previously mentioned, a special use of sessile oak wood is for winemaking (logs class A, minimum thick-end diameter 40 cm, Lemaire 2010), in the form of barrels (barrique) or as floating chips or staves added to the wine, in order to modify the tannin, texture, flavour profile and to vary the colour of wine. A 1-m^3 sessile oak wood can produce 6 barrels of 225–228 L, with an individual selling price between 400 and 900 € (Del Alamo-Sanza and Nevares 2019).

A major defect in newly felled oak tree is the so-called shake, either *star shake* (a longitudinal splitting or separation in the wood, radiating from the centre of the log), or *ring shake* (splitting along the growth ring). This defect causes the timber to split along the shake during processing, thereby reducing the value of what may otherwise

Table 5 Yield/efficiency in veneer depending on mid-length diameter of logs (Flot 1988, cited by Bary-Lenger and Nebout 1993)

Mid-length diameter (cm)	Veneer yield (%)	Veneer production (m^2 m^{-3})
45	10	153
50	17	277
55	24	382
60	29	471
65	34	549
70	38	617
75	42	677
80	45	730
85	48	777
90	51	820

be a quality log to that of firewood or fencing material (Joyce et al. 1998). In Britain, about 21% of all oaks may be affected by shake, leading to an annual loss of income of between 3 and 8 million pounds (Hemery and Simblet 2014). Shakes in oak timber occur most commonly on drought-prone sites (Henman 1984, cited by Savill 2013); water stress can trigger shakes in oak trees that have a predisposition to this defect, which is believed to be highly heritable (Kanowski et al. 1991, cited by Savill 2013). The trees flushing latest in any year are also those with largest earlywood vessels, and hence are the most predisposed to shake (Lechowicz 1984; Savill and Mather 1990, both cited by Savill 2013). In this respect, after recognizing such shake-prone trees, it is the role of early thinning to remove them, leaving the shake-free individuals to the end of the rotation (Savill 2013). Sessile oak wood has a very wide range of selling prices, depending on the final-use of logs, with the good oak timber fetching extraordinary high prices (Table 6).

Table 6 Prices of sessile oak logs in selected European countries

Country	Price of logs used for… (€ m^{-3})					Source	Observations
	Veneer	Sawmilling	Railway sleepers*	Vine stakes	Firewood		
Bulgaria	203.6	127.8	183.3		56.2	Tsavkov pers.comm	Warehouse price
Czech Republic	644	165*–394**			45	Podrázský pers. comm	*Class II; **Classes IIIa and IIIB
Croatia	312*–553**	132***-224****		18	43	Croatian Forests Ltd 2023	*dbh 40–49 cm; **dbh > 70 cm; ***dbh30–49 cm; ****dbh > 50 cm; all stumpage price
North Macedonia		94*–100**			44***–58****	PE National Forests 2023a	*dbh 30–39 cm; **dbh > 50 cm; ***end d 3–7 cm; ****end d 7–16 cm
Serbia	259*–486**	137***–170****		43	31[a]-41[b]	https://srbijasume.rs/kupci/cenovnici-kupci/	*dbh 40–49 cm; **dbh > 60 cm; ***dbh 30–49 cm; ****dbh > 50 cm; [a]class II; [b]class I
Slovakia	580*–700**	300***–400**** 130[a]–160[b]				Pástor pers.comm	1st class: *d 30–39 cm; **d > 60 cm; 3rd class (A): ***d 30–39 cm; ****d > 60 cm; 3rd class (D): d 30–39 cm; d > 60 cm
Slovenia	325*–375**	100				WCM Info Gozd 2024	*d < 50 cm; **d > 50 cm
Ukraine	546					Lavnyy pers.comm	
Romania		140			20	https://www.rosilva.ro/rnp/preturi_vanzare_m_l_p_2024__p_1697.htm	Stumpage price
Germany	Up to 1200 (top prices up to 3700)	Up to 600			30–45	Vor pers.comm	Stumpage price
Denmark		Max 560*			30–70	Madsen pers.comm	*Range 95–560 (mid-diameters 40—+60 cm, classes A-D)

Two examples are interesting related to the price of sessile oak high quality wood:

- In Slovenia, during an auction of valuable wood lots, the average price of logs (1911 pieces) was 442 € m^{-3}; the most expensive individual log was sold with 1751 € m^{-3} (Gozd in Gozdarstvo 2024);
- In Romania, during similar auctions held between 2003 and 2017, the average price of logs (2171 pieces) was 380 € m^{-3}; the price of sessile oak logs reached a maximum of 1162 € m^{-3} (Oprea 2022).

Regeneration ecology

Sessile oak starts producing large amounts of seeds at between 40 and 50 years (UK, Evans 1988; Worrell and Nixon 1991; Kerr and Evans 1993), about 50 years (Hungary, Solymos 1993), over 50 years (Ireland, Joyce et al. 1998), 50–70 years (Germany, Kleinschmit 1993), 60–70 years (Romania, Negulescu and Stănescu 1964; Haralamb 1967; Constantinescu 1976; Stănescu 1979; Stănescu et al. 1997), 60–80 years (Romania, Negulescu and Săvulescu 1957, 1965). The interval between successive mast years ranges widely: 2–5 years (UK, Evans 1988; Kerr and Evans 1993), 2–10 years (UK, Savill and Kanowski 1993; Germany, Haane 2020), 3–4 years (Turkey, Ürgenç 1998; Çanakçı 2011), 3–10 years (Germany, Kleinschmit 1993), 4–6 years (Croatia, Đodan pers.comm.), 4–6 a (Romania, Negulescu and Săvulescu 1957, 1965; Haralamb 1967; Constantinescu 1976; Stănescu 1979; Dămăceanu 1984; Stănescu et al. 1997), 5–7 years (Poland, Andrzejczyk 2009; Romania, Purcelean and Ciumac 1965), 5–8 years (Germany, Ellenberg and Leuschner 2010), 5–10 years (Ireland, Joyce et al. 1998), 6–10 years (Hungary, Solymos 1993), 8 years (Savill 2013). However, under the existing climate changes, the frequency of mast years in sessile oak has increased in recent decades in countries such as Germany (Haane 2020) and Poland (Pesendorfer et al. 2020). The phenomenon of increased seed yield was encountered recently under the same climates (Caignard et al. 2017, cited by Girard et al. 2022). Unfortunately, before germination, the acorns can be badly affected by acorn weevil (*Curculio glandium* Marsham) predation and, on a smaller scale, by the acorn moth (*Cydia splendana* Hübner), making them incapable of germination (Negulescu and Săvulescu 1965; Bary-Lenger and Nebout 1993; Stănescu et al. 1997; Annighöfer et al. 2015; Birkedal et al. 2009, cited by Medina et al. 2024). Under high predation by these pests, the proportion of acorns that could potentially germinate under natural conditions was only ¼ to $^1/_3$ of the total dispersed acorns (Kanjevac et al. 2017).

The density of acorns per m^2 under the stand canopy can be huge: on average 50 acorns m^{-2}, but reaching 800 acorns m^{-2} in excellent mast years (Andrzejczyk 2009). Consequently, natural regeneration by seed of sessile oak can have initial densities of 300 seedlings m^{-2} or even more (Evans 1988) (Fig. 4).

Unfortunately, in mast years, high acorn production frequently results in high seedling densities but with few, if any, surviving (Annighöfer et al. 2015). After the first year, natural elimination can be high with seedling density reduced to a maximum of 100 seedlings m^{-2} by the middle of first growing season (Evans 1988). This is the result of light shortage (sessile oak regeneration is able to persist/survive in shady forest understories at light levels of about 15% of open field conditions, while levels over 20% are necessary for continuous height growth, Röhrig et al. 2006, cited by Kuehne et al. 2020; Babić et al. 2021), winter frosts, summer drought, browsing, and strong competition of ground vegetation and tree species such as European beech, European hornbeam, field maple, small-leaved lime, *Betula* spp., *Salix* spp., (Ciumac 1967; Annighöfer et al. 2015; Mölder et al. 2019; Kuehne et al. 2020; Kanjevac et al. 2021; Stimm et al. 2022). In the second growing season, natural dieback can result in 40–50% of initial density (Ciumac 1967). Consequently, the density of seedlings reaching the sapling stage can be as low as 30,000 individuals ha^{-1} (Dămăceanu 1984). Sessile oak has high aptitude for resprouting (Negulescu and Săvulescu 1957, 1965; Eaton et al. 2016), so it can be coppiced until old: up to 60–80 years (Jacamon 1987) or up to 100 years or even indefinitely (Nicolescu et al. 2018). Its sprouts grow vigorously while young (Stănescu 1979) but the sprouting potential declines gradually with age and production volume decreases after a number of coppice rotations (Joyce et al. 1998).

Fig. 4 Very dense natural regeneration of sessile oak (photo V.N. Nicolescu)

Sessile oak vulnerabilities to abiotic and biotic disturbances

Sessile oak is sensitive to extreme low winter temperatures (Haralamb 1967; Boudru 1989a; Odabaşı et al. 2004a; Brus 2011; Bončina et al. 2021; Kanjevac et al. 2021), which start at (− 10 °C), provoking frost cracks in the trunk (Jacamon 1987; Pagan 1999), which are increased by acid soils (pH 4.0–4.5 °C) (CNPF 2023), sandy or clayey soils, periods of soil flooding during winter time (Bary-Lenger and Nebout 1993; Pagan 1999). Early autumn frosts can cause damage to the non-hardened summer shoots (Radkov and Minkov 1963; Timbal and Aussenac 1996; Chaar and Colin 1999; Genç 2004). It also suffers from late spring frosts (Haralamb 1967; Timbal and Aussenac 1996; Pagan 1999; Öztürk 2013; Bartsch et al. 2020; Ata 2021; Kanjevac et al. 2021), when temperatures of–3 °C will kill new foliage (Savill 2013), as well as leaves or even flowers (Jacamon 1987; Bary-Lenger and Nebout 1993). However, sessile oak is able to avoid such frosts as it is among the last trees to flush, normally in mid- to late April, or even May (Joyce et al. 1998; Savill 2013). Last but not least, sessile oak is sensitive to extremely high summer temperatures, combined with low rainfall, when it can be easily damaged if there is no protection from the canopy above (Zafirov and Kostov 2019; Kanjevac et al. 2021). It is resistant to strong winds so not prone to wind damage (except when this contains salt particles) (Genç 2004), owing to its deep rooting (Michiels 2014; Spiecker 2021).

Sessile oak is currently highly threatened by pests and pathogens in Europe. Fungi, including *Ciboria batschiana* (Zopf) Buchw., *Pythium* spp., *Fusarium* spp., *Rhizoctonia* spp., *Phytophtora* spp. can cause seedling damping-off. *Erysiphe alphitoides* (Griffon &Maubl.) U. Braun & S. Takam causes powdery mildew on sessile oak leaves (Ogris et al. 2009). Other fungi such as *Rosellinia quercina* Hartig, *Armillaria mellea* [Vahl. ex. Fr.] Kummer, *Collybia fusipes* (Bull. ex Fr.) produce the root rot (Stocka 1997; Karadžić and Milijašević 2005; Marcu 2005; Sedlar 2009; Bencheva and Doychev 2018; Puhek 2023). Various fungi species such as *Phellinus dryadeus* (Pers. ex Fr.) Pat, *Phellinus robustus* Karst., *Polyporus sulphureus* Bull. ex Fr, *Fistulina hepatica* Huds. ex Fr., attack standing trees and cause wood rot (Bary-Lenger and Nebout 1993; Marcu 2005). Infestation by the semi-parasitic species *Loranthus europaeus* Jacq. on sessile oak branches has increased in recent decades (Slovenia—Ogris et al. 2009; Bulgaria—Bencheva and Doychev 2018; Czech Republic—Podrázský pers.comm.). It seriously threatens the physiological and growth performance of sessile oak trees, reducing their leaf water potential, transpiration rate, stomatal conductance, so decreasing CO_2 assimilation rate. The reduction in carbon assimilation led to a lower stem increment (both diameter and height) and leaf size in infested sessile oak trees (Kubov et al. 2020). Important insect pests of sessile oak trees are defoliators such as *Thaumatopoea processionea* L., *Tortrix viridana* L., *Lymantria dispar* L., *Operophtera brumata* L., *Erannis defoliaria* (Clerk), *Euproctis chrysorrhoea* L. (Negulescu and Săvulescu 1957, 1965; Krahl-Urban 1959; Bary-Lenger et al. 1988; Marcu and Simon 1995; Vucelja et al. 2012; Bonfils et al. 2015; Bencheva and Doychev 2020; Puhek 2023). The stands affected by these defoliators can be secondarily attacked by very aggressive pests such as *Agrilus biguttatus* (Fabricius), a beetle species involved in the terminal phase of oak decline phenomenon provoking tree death (see below—Lupăștean 2023). In the last decade, many European oak forests have been badly affected by *Corythucha arcuata* (Say), an invasive arthropod causing tree defoliation or increasing susceptibility of the host to various diseases or pests when infestations are severe (Tomescu et al. 2018). This species is the most threatening invasive species in European oak forests, with multiple negative effects on the oaks themselves as well as on the oak forest web (Ciceu et al. 2024). Many insect pests, the majority of them wood boring such as *Cerambyx cerdo* L., *Cerambyx scopolii* Fuesse, *Cossus cossus* L., *Zeuzera pirina* L., affect sessile oak wood, drastically reducing its value (Bary-Lenger and Nebout 1993; Marcu and Simon 1995; Bencheva and Doychev 2018). The most important current health problem of sessile oak is the so called *oak decline*, a deterioration in the vitality of oak populations that has been occurring in Europe since the beginning of the twentieth century (Lupăștean 2023). It is "characterised by cyclic episodes of rapid mortality in local but widespread centres, followed by decreasing and slower mortality" (Thomas et al. 2002). At individual level, the main visible symptom is deteriorating crown condition (Thomas et al. 2002). Many abiotic and biotic factors contribute to this decline, part of the broader problem of forest decline (Führer 1996, in Lyubenova et al. 2024). These factors are grouped into (a) *predisposition* factors (soil changes, mycorrhiza, pollution, genetics), (b) *inciting* factors (drought, other climating factors—waterlogging, cold winters, frost, defoliating insects), and (c) *contributing* factors (pathogens such as *Armillaria* spp., *Phytophthora* spp., *Erysiphe alphitoides*, wood and bark boring insects such as *Agrillus biguttatus*) (Oszako 2000; Karadžić and Milijašević 2005; Gößwein and Lobinger 2014; Bonfils et al. 2015; Bartsch et al. 2020; NW-FVA 2022; Lupăștean 2023; Puhek 2023; Tkaczyk 2023; Gosling et al. 2024) They are also grouped (Gosling et al. 2024) into (I) *primary* [(I) abiotic stressors such as drought, extreme temperatures, poor soils, (II) anthropogenic pressures such as urbanization, deforestation, pollution, and (III) genetic limitations, specifically limited diversity], (II) *secondary* [(a) pathogens like *Phytophthora quercina*T. Jung and T.I. Burgess, *Brenneria goodwinii* Denman et al., (b) insects such as *Agrilus biguttatus* and *Corythucha arcuata* and, (c) parasitic plants

including *Loranthus europaeus*], as well as (III) *interactions between them*, which include combined biotic and abiotic stressors i.e. drought and insect defoliation and pathogens. However, most episodes of oak decline are associated with repeated and prolonged climatic stressors such as drought, waterlogging, frost or unusually high temperatures (Rodríguez-Calcerrada et al. 2017).

Sessile oak trees are widely considered as being prone to game damage affecting the leaves and twigs (roe deer *Capreolus capreolus* L., red deer *Cervus elaphus* L., fallow deer *Dama dama* L.), bark (European hare *Lepus europaeus* Pallas and European rabbit *Oryctolagus cuniculus* L.), acorns (wild boar *Sus scrofa* L., European hare and European rabbit, red squirrel *Sciurus vulgaris* L., European dormouse *Glis glis* L.) (Bary-Lenger and Nebout 1993; Margaletić 2003; Gačić et al. 2006; Vor pers.comm; Klisz pers.comm.; Madsen pers.comm.). Deer browsing can be a critical limiting factor for regeneration of sessile oak, but the species is less damaged by browsing when compared to broadleaves such as *Acer pseudoplatanus* L., *Sorbus aucuparia* L., *Fagus sylvatica* L. or conifers like *Abies alba* Mill. (Vacek et al. 2019 and Fuchs et al. 2021, both cited by Černý et al. 2024b). Consequently, measures such as individual protection of seedlings (netting, repellents: Slovakia, Pástor pers.comm.; Croatia, Margaletić 2003), use of slow-acting rodenticides (Croatia, Margaletić 2003) as well as the fencing of large regeneration areas are common in various European countries (Sweden, Leonardsson et al. 2015; Czech Republic, Podrázský pers.comm.; Denmark, Madsen pers.comm.; Turkey, Ayan pers.comm.; Slovakia, Pástor pers.comm.; Germany, Mölder et al. 2019; Vor pers. comm., Poland, Klisz pers.comm.). However, although these have positive effects protecting the individual trees or large regeneration areas against browsing, treeshelters and fences are expensive (i.e. over 5 € per tree, including posts and cable ties, for treeshelters, or over 6000 €ha^{-1}, in case of fences, as in Germany, Vor pers.comm.).

Management of sessile oak for wood production

Goals

Across Europe, sessile oak management mostly targets the production of large dimension, high-quality, logs for example for veneer, sawtimber, barrels, solid furniture, flooring. This is because, as stressed by Drăcea (1923), over one century ago, *quality* not quantity of sessile oak timber should be the most important preoccupation of foresters. One of the disadvantages of this management focus on high-quality sessile oak timber for the most valuable products such as sawlogs and veneer logs is the long rotations (Löf 2024). These are usually at least 120 years but, especially in the past, in countries such as France, or in traditional regions for sessile oak high-quality production such as Spessart, these can be 240 years or even longer (Table 7).

In countries such as France, the rotation age has decreased over time, as forestry has become more dynamic enabling production of large-diameter trees at younger ages. However, long rotations are still needed to produce the large-diameter logs required by the veneer and barrel industries, but this can easily become unrealistically long for profitable forest management (Madsen pers.comm.). This economic disadvantage is compensated by the high price of the valuable sessile oak timber (Spiecker 2021). The long-term increase in productivity of European forests suggests that current young oak stands could produce as much in 130 years as stands harvested 30 years ago at the age of 180 years (Stimm et al. 2022). An important factor is early and heavy crown thinning, which has a strong positive influence on the growth of final crop trees, which can reach their target diameter much earlier so reducing the rotation age (Stimm et al. 2022). Sessile oak wood is also used for paneling, joinery, construction, doors, windows, and in the mining industry. All these wood products originate from stands treated as high forest or coppice-with-standards, where sessile oak is the dominant tree species (high forest), or from standards (coppice-with-standards). In addition, an important amount of sessile oak wood, originating mostly from coppiced forests, is still sold for firewood (Čufar 2006; Kadunc 2010; Sarvaš et al. 2010; Alexandrov and Dobrev 2015; Öztürk 2013; Giefing et al. 2014). Production of high-quality sessile oak timber requires the application of a *tree silviculture*, based on three principles:

1. Natural or artificial regeneration;
2. Presence of an understorey/secondary storey;
3. Permanent and gradual selection of the best individuals (Bary-Lenger and Nebout 1993).

In general, management of sessile oak for wood production includes different stages or activities as shown in Fig. 5.

Regeneration and stand establishment

Background

Sessile oak is one of the few major tree species regenerated in high forests, coppice-with-standard forests and coppice forests, as "there is no single and unique silvicultural regime valid for oaks" (Bonfils et al. 2015). High forests are regenerated by seed (naturally or artificially by planting or direct seeding) and natural regeneration by seed should be a priority in regenerating sessile oak as is done in countries such as France, Romania, Bulgaria, Croatia, Turkey, Slovenia,

Table 7 Rotation age of sessile oak in different European countries

Country	Rotation age, years	Source and observations
France	130–140[a]…180–190[b] (dynamic silviculture) 105–110[a]…155–165[b] (silviculture involving high thinning completely removing the competitors of final crop trees)	Sardin 2008 [a]Very high fertility, log quality A–B [b]Low fertility, low quality A–B
United Kingdom	Over 120	Savill 1991, 2013
France	120–150	Timbal and Aussenac 1996
France	150–240	Cochet 1971
France	150–200	Bastien 1997
France	160–180 [range (130) 150–240]	Duplat 1992
France	180–200	Lafouge 1990
France	180–250 (even longer)	Sevrin 1996; Chaar and Colin 1999
France	185–205*	Jarret et al. 1996 (*traditional/classical silviculture)
Denmark	120–160	Madsen pers.comm
United Kingdom	120–160 Over 120 130–160	Evans 1984; Kerr and Evans 1993 Savill 1991, 2013 https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131560-sessile-oak-sok/
Austria	(120) 140–160	Hochbichler 1993
Romania	120[a]–140[b] (regenerated by seed for sawlogs); 100[a]–120[b] (regenerated by stump shoots, for sawlogs) 160–180 (stands for veneer production)	MMAP 2022d [a]Vth production class; [b]Ist production class
Switzerland	160 (range 140–180)	Schütz and Badoux 1979; Schütz 1993
Slovenia	Maximum 130	Brus comm.pers
Croatia	120 (high forests); 80 (simple coppice forests)	Regulation on Forest Management (2018)
North Macedonia	120 (high forests); 50 (simple coppice forests)	Ministry of Agriculture, Forestry and Water Management (2019)
Germany	140–240	Vor pers.comm
Germany	300 (Spessart)	Viney and Pardé 1960; Martinot-Lagarde 1970
Poland	120–240 (most common 120–160)	Forest Management Manual 2023
Czech Republic	120–160 (high forest) 40 (range 30–50) (simple coppice)	Podrázský pers.comm Štochlová and Hédl 2018
Serbia	120[a]–130[b] (high forests); 70[c]–90[d] (simple coppice forests)	Medarević et al. 2006 [a]production functions; [b]protection functions; [c]well-preserved stands; [d]protective forests
Ukraine	111–120	Lavnyy pers.comm
Ireland	90–110	Joyce et al. 1998
Turkey	40–50 (simple coppice)	Bariș Özel and Ertekin 2018
Bulgaria	120 (high forest, production classes I–II)-160 (high forests, production classes IV–V); 90–100 (simple coppice forests, production classes I–III); 55–60 (simple coppice forests, production classes IV–V)	https://www.iag.bg/data/docs/nareba_18_inventarizaciq.pdf

In coppice-with-standards, rotation of the sessile oak standards, in general, is 100–130 years (Crowther and Evans 1984; Garfitt 1995, both in Nicolescu et al. 2018; Hochbichler 1993)

Serbia and North Macedonia (Radkov 1948; Radkov and Minkov 1963; Matić 2000; Odabaşı et al. 2004b; Sardin 2008; Lemaire 2010; Kohler et al. 2020; Bončina et al. 2021; MMAP 2022a). As natural regeneration by seed presents difficulties many sessile oak forests in central Europe have been artificially established by planting or direct seeding for example in Germany, Belgium, Czech Republic, Hungary, Austria (Kenk 1984; Boudru 1989b, 1992; Hochbichler 1993; Solymos 1993; Mölder et al. 2019; Kohler et al 2020; Podrázský pers.comm.). This is necessary because, even after a mast year, resulting in high seedling densities, few if any survive without the control of deer and wild boar, light demand and competition (Annighöfer et al. 2015). However, even in Germany, natural regeneration by seed as well as direct seeding are commonly applied in the south and south-west of the country, where this is a long established tradition (Mölder et al. 2019). Modern silvicultural planning for sessile oak forests in Europe favours natural regeneration

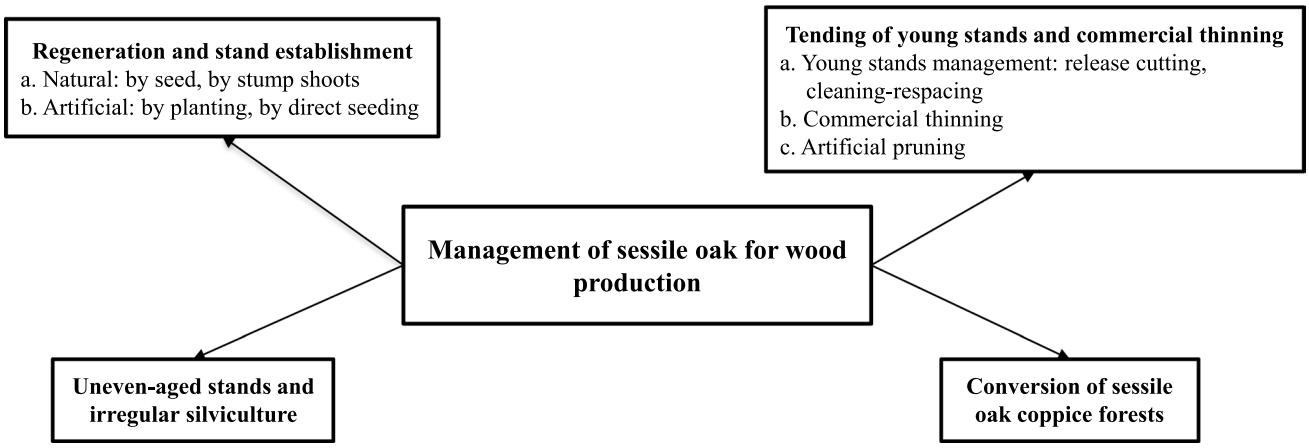

Fig. 5 Conceptual figure of management of sessile oak for wood production

following the principles of close-to-nature silviculture, with the advantages over artificial regeneration including (1) preservation of autochtonous genetic diversity, (2) natural selection from a vast number of individuals, (3) facilitation of the formation of undisturbed root systems (Kohler et al. 2020; Kanjevac et al. 2021), as well as (4) lower costs and (4) vigorous and site-adapted species (Annighöfer et al. 2015).

Natural regeneration by seed

Sessile oak regenerates naturally under the shelter of old stands by using silvicultural systems such as uniform shelterwood cutting, group shelterwood cutting, and irregular shelterwood cutting. Uniform shelterwood cuttings are recommended in countries such as France (Sardin 2008; Lemaire 2010; CNPF 2023; Unisylva 2024a), Germany (Lüpke 2008; Kuehne et al. 2020, both cited by Kohler et al. 2020), Bulgaria (Radkov 1948; Radkov and Minkov 1963), Turkey (Çalışkan et al. 2004; Odabaşı et al. 2004b), Croatia (Matić 2000), North Macedonia (Trajkov pers.comm.), Poland (Klisz pers.comm.). It is particularly important for pure sessile oak stands and begins with a seeding cut, carried out either after a mast year or, preferably, following the establishment of a new cohort/generation under the old stand. The intensity of seeding cutting reaches (30) 40–50% by number of trees (Sardin 2008; CNPF 2023), 30–40% (Boudru 1989b) or even 50% by standing volume (Bary-Lenger and Nebout 1993; Lemaire 2010). This cut is followed by secondary cuttings (1–3 interventions, every 3–5 years, to provide light to the established seedlings), and the final cut removing the last residual old trees (Lorentz and Parade 1883; Boudru 1989b; Bary-Lenger and Nebout 1993; Balleux 2006; Lemaire 2010; CNPF 2023; Unisylva 2024a). This final cut is recommended when seedlings are no taller than 50–70 cm (Bary-Lenger and Nebout 1993) or a maximum of 80 cm in height (Balleux 2006; Sardin 2008). The regeneration period had decreased from 10 to 15 years (centre-west of France, Boppe 1889; Belgium, but preferably 10 years, Bary-Lenger and Nebout 1993) to a maximum of 12 years (Sardin 2008) or even less than 10 years (Serbia: 6–8 years—Kanjevac et al. 2021; Belgium: 6–9 years, Balleux 2006; France: 8 years, Lemaire 2010; 8–10 years, Unisylva 2024a). Sometimes, when the last thinning has not achieved the objectives of stand preparition for regeneration in terms of number of trees per ha or species composition, then so-called preparatory cuttings are applied in the last decade before the seeding cutting (Bary-Lenger and Nebout 1993). The success of regeneration depends on the interventions coupled with the regeneration cuttings: (I) removal of understory woody species and ground vegetation to reduce the competiton for resources, particularly light, before the establishment of a new cohort/seeding cutting, (II) opening of skidding trails, 4 (5) m wide, every (15) 20–30 m, during seeding cutting, to extract the old trees and reduce the potential logging damage, and (iii) opening of silvicultural racks, 2–2.5 m wide, every 5–6 m, during the secondary or final cutting, to enable future tending operations such as release cutting and cleaning-respacing (Bary-Lenger and Nebout 1993; Balleux 2006; Sardin 2008; Lemaire 2010; Unisylva 2024a). Group shelterwood cuttings are used in countries such as Bulgaria (Kostov 2018), Romania (Haralamb 1967; Constantinescu 1973; MMAP 2022a), Turkey (Odabaşı et al. 2004b), Slovakia (Sarvaš et al. 2010), Serbia (Krstić et al. 2005), and Poland (Klisz pers.comm.), especially in mixed stands with sessile oak, as this needs shelter in the early stages of development (seedling, sapling). A similar succession of cuttings (seeding/for opening of gaps, secondary/for enlarging the gaps, and final) were also used. When necessary, preparatory cuttings as in case of uniform shelterwood cuttings are applied. The

recommended size of gaps/openings is variable: 0.1 ha (mixed European beech-oak stands in Germany—Stimm et al. 2022), at least 0.16 ha (Switzerland—Ammann et al. 2024), 0.2 ha (50 m in diameter; Germany, Lüpke 2008), at least 0.2 ha (Kuehne et al. 2020), 1–1.5 × mean stand height (Romania, MMAP 2022a; Denmark, Madsen pers.comm.). The size of canopy opening is crucial for height increment, with seedlings performing best with light conditions at least 50% of open field levels; this was also found with canopy openings at least 0.2 ha in size (Modrow et al. 2020). For instance, in pure sessile oak stands located on south-facing slopes, the recommended diameter of circular gaps is 1 × mean stand height increasing to 1.5 × mean stand height on shaded slopes (MMAP 2022a). In sessile oak-dominated stands, which include other broadleaved species such as European beech, European hornbeam, small-leaved lime and field maple, ellipse-shaped gaps are recommended, with the long axis 1.5 × mean stand height long on the EW direction, and the short axis 0.5–1.0 × mean stand height long. The gaps are enlarged by cuttings advancing from north to the south (MMAP 2022a). However, as pointed out by Kohler et al. (2020), there is no robust evidence on the size and shape of gaps required to provide enough light for survival and growth of a new cohort of sessile oak seedlings. The recommendation that canopy openings between 0.1 ha and 0.3 ha in size would be sufficient to naturally regenerate sessile oak has limited validity because the studies this is based on did not include larger canopy openings for comparison (Kohler et al. 2020). The recommended regeneration period for group shelterwood cuttings is shorter than that for uniform shelterwod cuttings ranging between 5 and 7 years (Purcelean and Ciumac 1965; Haralamb 1967; Dămăceanu 1984). If this period extends to 10 years, the young generation will be taller than 100 cm and can be badly affected during skidding (Dămăceanu 1984). In case of irregular shelterwood cuttings, recommended in countries such as Bulgaria (Kostov 2018), Germany (ML and MU 2018, cited by Kohler et al. 2020), Slovenia (the dominant silvicultural system for the regeneration of sessile oak stands, Bončina et al. 2021), Romania (MMAP 2022a), the gap size ranges from that recommended for group shelterwood cuttings (1–1.5 × mean stand height in Romania, MMAP 2022a) to 0.3–0.5 ha (Germany, ML and MU 2018, cited by Kohler et al. 2020), or up to 0.5 ha, sometimes even 0.5–2.0 ha (Slovenia, Bončina et al. 2021). Within the gap, during seeding cuttings/opening of gaps, all trees are removed after the establishment of a new cohort or the canopy cover is reduced to 50% after a mast year. The residual trees are cut after new cohort establishment, in 1–2 interventions, depending on the regenerated seedlings. Consequently, at gap/opening level, there are 1–3 cuttings, whereas at stand level this reaches 4–8. The regeneration period is extended up to 30 or even 40 years, and the result is an irregularly structured stand (MMAP 2022a).

Regenerating oak naturally in small canopy openings seems to be possible in principle as already shown by the nineteenth century silviculture in the Spessart Mountains. But, owing to the short duration of most studies, this conclusion is only partially based on sufficient/strong evidence and needs to be reassessed in future medium- to long-term studies (Kohler et al. 2020). The interventions applied to uniform shelterwood cuttings in order to increase the success of regeneration e.g., (I) removal of understory woody species as well as ground vegetation before the establishment of a new cohort/seeding cutting, (II) opening of skidding trails, and (III) opening of silvicultural racks, are also necessary in the case of stands treated with group shelterwood cuttings and irregular shelterwood cuttings.

Regeneration by stump shoots

Oak coppice forest has been widespread in Europe for the last 1000 years, meeting social and economic needs in pre-industrial Europe, and these are normally rich in biodiversity and associated with cultural values (Löf 2024). Simple coppices of sessile oak are regenerated by stump shoots on a small-scale in countries such as Austria (Kühmaier et al. 2018), Bulgaria (Markoff et al. 2018; Tsavkov pers.comm.), Croatia (Dubravac et al. 2018), France (Ruch et al. 2018), Slovenia (Krajnc et al. 2018), Czech Republic (Matula et al. 2012; Štochlová and Hédl 2018), Turkey (Bariş Özel and Ertekin 2018) and North Macedonia (Trajkov pers.comm.). In the latter country, over 70% of the area of coppice forest is treated by clear-cutting, followed by regeneration by stump shoots, while the rest of the stands are converted to high forests (Trajkov pers.comm.).

Artificial regeneration

Background on seed origins

A very important issue to address in relation to the artificial regeneration of sessile oak is the origin of seeds. Should they be solely from local seed sources or from other regions, as the latter are better adapted to the changing climate? In this respect we should take into account the warning by Ledig and Kitzmiller (1992, cited by Aitken and Bemmels 2016): “If global warming materializes as projected, natural or artificial regeneration of forests with local seed sources will become increasingly difficult. Planting programs may have to deploy non-local seed sources, imported from further south or from lower elevations…”.

Across its distribution range, sessile oak shows high levels of phenotypic plasticity, enabling the species to adapt to a broad range of environments and, consequently, to display good resilience in response to climate change (Sáenz-Romero et al. 2019). It shows a high level of genetic differentiation for adaptive traits as well as a clinal genetic variation along temperature gradients linked to latitude or altitude (Alberto et al. 2011 and Vitasse et al. 2009, both cited by Sáenz-Romero et al. 2019). Therefore, population level variation must be taken into account when trying to predict the response of oaks to climate change (Sáenz-Romero et al. 2019). In Europe, *Q. petraea* is found in (a) large, contiguous stands, with a high level of diversity most likely due to the maintenance of very large population sizes, gene flow over distances, and interfertility (Goicoechea et al. 2012), or (b) as scattered, fragmented, and heavily altered populations (Eusemann and Liesebach 2021). The extensive, apparently homogenous sessile oak forests are far from uniform at the genetic level. On the contrary, they form highly complex mosaics of remarkably small local neighborhoods (Eusemann and Liesebach 2021). In fragmented populations, sessile oak (an anemophilous and allogamous species) shows remarkable dispersal capabilities, with a mean pollen dispersal distance of 22.6 m (± 17.4 m, range of 3.2–72.8 m) and a mean seed dispersal distance of 8.4 m (± 10 m, range of 0.2–81.9 m). However, it is considered that fragmented stands are much better connected by pollen-mediated gene flow that would be expected by their physical appearance (Eusemann and Liesebach 2021). This gene flow across the landscape maintains a high level of reproductive connectivity between sessile oak fragments. Within-stand gene flow is supplemented by a substantial fraction of external gene flow (10–30% originates from oak stands within a 5 × 5 km area, and 5% of immigrant pollen are dispersed supra-regionally) (Buschbom et al. 2012). This external gene flow safeguards genetic diversity and, thus, resilience to future environmental changes and events (Neale and Kremer 2011, cited by Buschbom et al. 2012). In this respect, assisted migration (also referred to as assisted colonization, managed relocation, assisted translocation), which proposes deliberate displacement of populations and in some cases species, based on climate change predictions, is proposed. This consists of transferring populations to new locations (to the north and at higher elevation than those where they currently grow) with climates to which they are best adapted (Sáenz-Romero et al. 2017). Sessile oak populations transferred from milder to cooler climates should better match new temperature and moisture regimes than local populations, and may improve resilience on drought-prone sites, at the expense of lower growth potential (Aitken and Bemmels 2016; Sáenz-Romero et al. 2017; Mátyás 2021). Growth decreases when populations of sessile oak are transferred either to warmer/drier sites (positive transfer distances), or to cooler/wetter sites (negative values) (Sáenz-Romero et al. 2019). As the competition in artificially established stands will thin them over time, retaining the best adapted individuals, one management solution to increase forest resilience is increasing planting density to allow for greater mortality during establishment (Aitken and Bemmels 2016). The main problem in assisted migration is how to use the incoming provenances/genotypes:(I) alone, as advocated by Mátyás (2021) owing to the slower initial growth of incoming resilient populations, or (II) as composite provenances, mixing seedlings grown from local sources intimately with selected non-local seedlings to increase diversity and resilience, and reduce the risk of plantation or restoration failure (Aitken and Bemmels 2016). Assisted migration can also be used to supplement an existing population on a site where numbers are dwindling (Ducci et al. 2017). Obviously, health risks may arise from assisted transfer/migration, but better resilience may postpone stress-triggered decline and attack by pests and disease (Csóka et al. 2019, cited by Mátyás 2021).

However, as emphasized by Mátyás (2021), "The use of local provenances as a recommended adaptive measure indicates limited relevance for sessile oak", and "… to prefer local origins as a universal measure to mitigate climate change effects has low relevance".

Artificial regeneration by planting

In countries such as Germany, the Czech Republic, Denmark, Poland and Ukraine, sessile oak is mostly established by planting after clear-felling. The acorns used for planting originate from forest genetic resources or seed stands (tested or selected) including the species which covers important areas i.e. 10,951 ha in France (Doucerain 2020), 8626 ha in Romania (Pârnuţă et al. 2012), 4780 ha in Poland (Chałupka et al. 2011), 4505 ha in Bulgaria (Alexandrov and Dobrev 2015), 2503 ha in Slovakia (Sarvaš et al. 2010; Bednárová 2023), 823 ha in Serbia (Andrašev pers.comm.), 353 ha in Turkey (URL1 2024), 220 ha in Ukraine (Los et al. 2014), and 126 ha in Slovenia (Brus pers.comm.). Such stands produce on average 300 kg ha^{-1} of sessile oak acorns, with a range of 10 to 1000 kg ha^{-1} (Enescu 1982). Other valuable sources of sessile oak acorns for plant production are seed orchards (11.0 ha in Poland, Klisz pers.comm.; 1.0 ha in Slovakia, Bednárová 2023; 9 seed orchards in Germany, where it is planned to increase the number to better select individual trees that seem adapted for climate change, Hardtke et al. 2016), as well as plus trees (e.g., 365 in Slovakia, Bednárová 2023; 163 in Ukraine, Lavnyy pers.comm.) (Fig. 6).

Acorns of sessile oak are among the heaviest of all native European tree species with 285–475 seeds kg^{-1}, and a potential germination of 60–85% (Vlase 1982; Iancu 1999). They are collected manually, from the ground, with gravity as the main dispersal agent, but mammals such as red squirrels

Fig. 6 Sessile oak plus tree in Poland (photo W. Gil)

Fig.7 Production of seedlings of sessile oak in the south of Romania (photo V.N. Nicolescu)

Sciurus vulgaris L. or mice *Apodemus* spp. as well as birds such as European jay *Garrulus glandarius* L. or woodpeckers *Picoides* spp. can contribute to dispersal over long distances (kilometers) (Damian 1978; Stimm and Knoke 2004; Sarvaš et al. 2007, 2010; Kurek and Dobrowolska 2016). Acorns are collected in October–November and sown in the nursery either immediately in the autumn (the preferred period, Rubțov 1958; Iancu 1999), or stored under special conditions. They should be stored in well-ventilated places, with a temperature close to 0 °C (Vlase1982) or–3 °C (Joyce et al. 1998) and a moisture content of 40–42% (Vlase 1982) or 42–48% (Joyce et al. 1998). If these conditions are fulfilled, the acorns can be stored for 2 years. If not, the germination potential of sessile oak seeds lasts for only 6 months (Haralamb 1967). The acorns can be sown in the nursery in the autumn if the soil has enough moisture and the seed can germinate until the first frost. Autumm sowing is also preferred due to the higher germination percentage (73–93%) than of spring sowing (71–84%) (Rubțov 1958). Before sowing, the acorns are soaked in a solution of Formalin 1% for 5–10 min to protect them against pathogens. Sowing is made on bare ground, in rills, at a depth of 7–8 cm. In winter this is protected (mulching) using a thick layer (8–10 cm) of straw, leaves, or reed (Vlase 1982; Iancu 1999). Spring sowing (March–April, after soaking the acorns in water for 48 h to return the moisture content to the desired level, Joyce et al. 1998) is made on bare ground and in rills (60 cm × 15 cm × 60 cm, to allow for the mechanized cultivation) at a depth of 4–6 cm. During dry periods, the seed bed is covered with straw or leaves. This is removed once the acorns have germinated (usually after 25–30 days, Haralamb 1967), but is kept between the rills in dry areas. The normal sowing rate is 30–37 acorns m^{-1} of rill (4000 kg ha^{-1}), and the optimum density of seedlings is 20–30 plants m^{-1} (Iancu 1999) or 350 plants m^{-2} (Rubțov 1958). In order to produce a rich root system, the taproot of sessile oak (40–50 (even 100) cm long after the first growing season, Haralamb 1967) is undercut (20 cm below the collar) in the spring of following year (Haralamb 1967; Iancu 1999; Klisz pers.comm.). The use of medium-large acorns of sessile oak, in combination with undercutting the taproot, is an efficient tool to produce taller and thicker seedlings in the nursery (Tilki et al. 2009). Production cycles of sessile oak bare-root seedlings in forest nurseries is very variable: 2 years (1 + 1, minimum collar diameter 6 mm, at least 20 cm height in Romania, Iancu 1999; Abrudan 2006; Fig. 7), 2 years (1 + 1) or 3 years (1 + 2) in Turkey (Ayan pers.comm.), 1 year (minimum collar diameter 2 mm, minimum height 7 cm), 4 years (minimum collar diameter 5 mm, minimum height 35 cm) in Poland (Rozporządzenie 2004), 2 years (1 + 1), 3 years (1 + 2) or even 4 years (1 + 3) in Belgium (Boudru 1992).

Apart from the field/nursery production of sessile oak bare-root seedlings, container/cell grown production of plants is also used in different European countries. Large containers (220–250 cm^3, up to 20 cm depth, with no bottom) have provided the best results for species with big seeds and strong root systems such as sessile oak. They are filled with a mixture of organic substrate and perlite in a volume ratio of 2:1, and liquid fertilizers as well as fungicides are used to increase the height growth and protect seedlings from pest attacks. Containers are watered

regularly, especially during warm summer days. Germination starts mid-April and the 1-year-old seedlings, ready for planting, attain (10) 20–40 cm in height and a root collar diameter of 3–5 mm (Orešković et al. 2006; Jokanović et al. 2024; https://www.lieco.at/en/products/broad-leaves). The price is variable and depends on the type of seedlings and country. In case of bare-root seedlings, the current price per unit is 0.10 € (1-year-old) in Ukraine (Lavnyy pers. comm.), 0.12 € (2-year-old)-0.17 € (3-year-old) in Poland (Analiza 2022), 0.25–0.50 € in Czech Republic (Podrázský pers.comm.), 0.28–0.38 € in North Macedonia (PE National Forests 2023b), 0.36 € in Romania (https://www.rosilva.ro/articole/puieti_forestieri__p_132.htm), 0.36 € in the UK (https://www.rjtreesandhedging.co.uk/sessile-oak-quercus-petraea-p45), 0.50 € (1-year-old, 15–30 cm height) to 2.80 € (4-year-old, 120–150 cm height) in Germany (Vor pers. comm), 1.40–1.55 € in Slovenia (Drevesnica Štivan 2024).

As for container/cell grown sessile oak plants, the price per unit is 0.20 € (1-year-old) in Poland (Analiza 2022), 0.25 € in Ukraine (Lavnyy pers.comm.), 2.10 € in the UK (20–60 cm tall, https://cheviot-trees.co.uk/broadleaves/61-quercus-petraea-sessile-oak.html), 2.20 € in Austria (1-year-old, 20–40 cm tall, https://www.lieco.at/en/products/broad-leaves), even 2.34–3.54 € in the UK (20–40 cm tall, https://www.planfor.co.uk/buy,oak-sessile,2045,EN). The annual production of sessile oak seedlings (both bare-root and container-grown) is very high: 3.06 million (range 0.323–7.85 million between 1992 and 2022) in Croatia (Đodan and Perić, 2022; Đodan et al. 2023), over 3.5 million in France (Girard et al. 2022), 25 million in Poland (state-owned forest nurseries, Analiza 2022). Usually sessile oak plantations are established in rows; the initial stocking is very variable and ranges between 2500 and 15,000 individuals ha^{-1} (Table 8).

In Germany, an alternative to the high-density row planting of sessile oak is cluster planting, comprising 20 to 30 seedlings in either nests (nest planting), with about 0.2 m between trees, or groups (group planting), with 1 m initial spacing between trees (Saha 2024). In the group planting method, circa 20 sessile oak seedlings per group are planted. These trees are surrounded by 8–16 planted shade-tolerant trainer trees (e.g. European beech, European hornbeam, small-leaved lime), in order to accelerate self-pruning of oaks and maintain the desired branch-free bole length (at least 25% of tree height) by preventing the formation of epicormic branches (Skiadaresis et al. 2016; Saha 2024). The distance between group centers ranges between 10 and 13 m, resulting in 60–100 groups ha^{-1} and an initial planting density ranging between 1800 and 4200 seedlings ha^{-1} (Skiadaresis et al. 2016). Ideally, one future crop tree will emerge from each group to ensure the development of the

Table 8 Initial stocking in sessile oak plantations

Country	Initial stocking (plants ha^{-1})/spacing	Source	Observations
United Kingdom	2500 (2 m × 2 m)—restocking 3100 (1.8 m × 1.8 m)—new planting 6000 +	Kerr and Evans 1993 https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131560-sessile-oak-sok/	
Poland	At least 3000	Andrzejczyk et al. 2023	
Belgium	2500 (2 m × 2 m)—3–4-year-old seedlings 3100 (1.8 m × 1.8 m)—4-year-old seedlings 4444 (1.5 m × 1.5 m)—3-year-old seedlings 6400 (1.25 m × 1.25 m)—2-year-old seedlings	Bary-Lenger et al. 1988 Boudru 1992	
Ukraine	4000 (2.5 × 1.0)	Lavnyy pers.comm	
Austria	4000–6000 (2.2 × 0.5–0.7 m)	Hochbichler 1993	50% SOAK50% EB, EH[a]
Romania	5000 (2.0 × 1.0 m)	MMAP 2022c	60–70% SOAK + 30–40% SLL, CA, WC, NM[b] (in groups)
Switzerland	5000–6000	Schütz and Badoux 1979	
Turkey	5000–7000	Ayan pers.comm	
Slovakia	5000–9000 (1.1 m × 1.1 m to 1.4 m × 1.4 m)	Repáč et al. 2017	
Germany	6000–10,000 (seldom 2,500)	Kenk 1993	
	5000–8000	Bartsch et al. 2020	
Ireland	6700 (2.0 m × 0.75 m)	Joyce et al. 1998	
Hungary	6,000–10,000	Solymos 1993	
Czech Republic	10,000 (1 m × 1 m)	Podrázský pers.comm	
Croatia	10,000–15,000	Matić 1994	

[a] *SOAK* sessile oak, *EB* European beech, *EH* European hornbeam

[b] *SLL* small-leaved lime, *CA* common ash, *WC* wild cherry, *NM* Norway maple

target stand composition (Skiadaresis et al. 2016). Sessile oak trees planted in groups have comparable quality and growth to those planted traditionally in rows, group planting ensuring cost savings in the establishment phase and high tree species diversity (Skiadaresis et al. 2016; Mölder et al. 2017; Andrzejczyk et al. 2023; Saha 2024). Another potential solution for artificial regeneration of sessile oak, used especially when natural regeneration fails, is the *transplanting* of naturally regenerated seedlings, established under the protective shelter of the parent stand. After one growing season, the survival rate of 4- and 5-year-old transplants ranged between 34.3% (open canopy, with direct solar radiation in summer) and 67.1% (under shelter and in areas with favourable soil moisture content) (Kanjevac et al. 2023). The cost of row planting per ha is very variable, from about 6000 € in Bulgaria (includes all costs: soil preparation, planting, beating-up, weed control, soil cultivation, up to the third year of plantation, Tsavkov pers.comm.) to 10,000 € in the Czech Republic (Podrázský pers.comm.) or up to 18–20,000 € (including fencing) in Germany (Skiadaresis et al. 2016; Vor pers.comm.). Consequently, compared to other species, the cost of establishing sessile oak by planting (including costs of planting, weed control, protection against browsing and early tending) is high (Spiecker 2021).

Artificial regeneration by direct seeding

Artificial regeneration of sessile oak by direct seeding is used especially locally and on a much smaller scale than the one by planting. It is associated with regeneration of existing oak stands, when acorns are sown under a light canopy, providing shelter and protection from frost in addition to curbing weed growth, which is retained for a short period (up to 5 years) until the plants are well established (Joyce et al. 1998). Two methods of seeding are employed: broadcast seeding (not a viable option because of the subsequent problems with competing vegetation) and drill seeding [drills are opened 1.7–2.0 m apart, 5 cm deep; the acorns are sown in these at a density of 15–20 seeds m^{-1} (7–5 cm apart), covered with mineral soil and firmedin—Joyce et al. 1998], which is more suitable and is the most used. Autumn sowing (October–November) is preferred so there is no need for winter seed storage (Joyce et al. 1998; Łukaszewicz and Gil 2007). The amount of acorns used depends on the seeding method and ranges from 200 kg ha^{-1} in Poland (Lasy Państwowe 2023), 200–1000 kg ha^{-1} in Germany (Bartsch et al. 2020), 300–350 kg ha^{-1} (drill seeding) in Turkey (Huss and Kahveci 2009), 400–550 kg ha^{-1} (seed-drill) in Ireland (Joyce et al. 1998), and 700–800 kg ha^{-1} (broadcast seeding) in Turkey (Huss and Kahveci 2009). Direct seeding of sessile oak was widely used in the Bavarian Spessart and Rheinland-Pfalz regions of Germany (Martinot-Lagarde 1970; Joyce et al. 1998). For instance, the famous Spessart forest is based on a very high number of oak seedlings (50–80,000 ha^{-1}, Kenk 1993) in the phase of establishment, seeded with up to 1000 kg of acorns ha^{-1} of local provenance (Bartsch et al. 2020). However, as emphasized by Löf et al. (2019), issues such as poor seed quality, acorn predation by seed-eating rodents, competing vegetation, and browsing damage can cumulatively contribute to reduced seedling establishment that leads direct seeding being considered unreliable despite being the least costly approach as a large-scale practice of establishing oaks.

Tending of young stands and commercial thinning

Background

Until 1950's, sessile oak's 'traditional' (or 'classical') management included low-intensity release cutting and cleaning-respacing in sapling-thicket stages, followed by light thinning, especially from below and not including the selection and favouring of final crop trees (Bary-Lenger and Nebout 1993; Mölder et al. 2019). The production of very large diameter logs (70–80 cm), with narrow growth rings [maximum 2 (2.5 mm)] was targeted, and this approach led to very long rotations (160–200 years, Bagneris 1873) or even 200–300 years (Boppe 1889). Modern silviculture of sessile oak stands generally includes a generalized practice of release cutting and cleaning-respacing, sometimes at high intensity, followed by high intensity thinning from above, with the most profitable final crop trees selected either at the end of thicket stage or beginning of pole stage (Bary-Lenger and Nebout 1993; Jarret et al. 1996; Mölder et al. 2019). These interventions are controlled using either stand density (number of trees ha^{-1}) at different ages or stocking (basal area, in m^2 ha^{-1}), kept at the same level throughout the whole life of the stand (Jarret 2004; Sardin 2008; Sardin and Mothe 2010). Such a 'dynamic' approach, targeting the production of large diameter logs (70–80 cm at quality classes A and B in France; 60–70 cm in Sweden, Löf et al. 2016), with wider growth rings (up to 4 mm or even more), is intended to allow for shortening the rotation age to 100–120 years (Weaver and Spiecker 1993; Sardin 2008, 2010; Lemaire 2010; Bonfils et al. 2015).

In Germany, sessile oak management is recommended to be split into two phases: (1) oaks should be cautiously tended and thinned to stimulate natural pruning and (2) future crop trees, selected at the beginning of this phase, should be released strongly to stimulate diameter growth of the current branch-free boles, leading to a smaller knotty core (Spiecker 2021).

Young stand management

Management of young sessile oak stands is based on two principles: (i) the presence of an understory, subordinate to the sessile oak overstory, composed of one or more broadleaves (e.g., European hornbeam, European beech, field maple, small-leaved lime), to protect the soil and help natural pruning of oaks, and (ii) a permanent and gradual selection of the most promising/best individuals of sessile oak, maintaining their dominant position (Bary-Lenger and Nebout 1993; MMAP 2022b). It should also take into account the fact that owing to the low potential of natural elimination the naturally regenerated sessile oak stands if kept too dense (sometimes over 30,000 stems ha^{-1}), are prone to mass snow bending or breakage in the sapling and thicket stages (Ciumac 1967; Petrescu 1971; Kenk 1993; Schütz 1993; MMAP 2022b). However, the resistance of sessile oak trees to snow damage is also dependent on genetic factors such as provenance, the faculty of young trees to hold foliage during the winter (marcescence) being under genetic control (Schütz 1993). In this respect, soon after the establishment of a new sessile oak stand, weeding is necessary to protect the seedlings against competition from aggressive ground vegetation. As soon as the sessile oak stands reach the sapling stage, negative selection continues with the application of release cuttings, not necessary in pure stands but in the mixed ones, if other species of trees and shrubs interfere with the growth and development of sessile oak trees (Sevrin 1997; Bartsch et al. 2020; Unisylva 2024a). Release cuttings target the balance between natural pruning of sessile oak (*enough* competition) to achieve good stem quality and *too much* competition from other species able to outcompete it. If necessary competing tree species such as goat willow *Salix capraea* L., trembling aspen *Populus tremula* L, silver birch *Betula pendula* L., European beech, other very competitive plant species [e.g., blackberries such as *Rubus fruticosus* L., *Rubus hirtus* Waldst. & Kit., bracken *Pteridium aquilinum* (L.) Kuhn, elderberry *Sambucus* spp.], or of badly shaped, damaged or wolf trees should be removed (Sevrin 1997; Vlad et al. 1997; Vacek et al. 2009; Bartsch et al. 2020; MMAP 2022b). Tree species able to form the understory in sessile oak stands such as European hornbeam are preserved but in a dominated condition (Schütz and Badoux 1979; MMAP 2022b). In young naturally regenerated sessile oak stands with maximum mean heights of 3 m, 3–4, even 5–6 frequent and light intensity release cuttings are recommended in countries such as France (Buffet 1978, 1980; Dubois 1988) or Belgium (Boudru 1989a; Bary-Lenger and Nebout 1993). The cycle between the initial release cuttings is 1 year and is continued for 3 years (Bary-Lenger and Nebout 1993). In Romania, the release cuttings (generally 2 interventions) have a cycle of 1–3 years, the shortest in very productive stands, the residual canopy cover after each intervention being at least 80% (MMAP 2022b).

Cleaning-respacing, removing non-desired tree species such as pioneers (e.g., trembling aspen, goat willow, silver birch) as well as wolf, forked or poorly-shaped sessile oak trees while preserving the understory of European hornbeam or European beech, are performed in the thicket stage (Ciumac 1965; Diaci 2006; Vacek et al. 2009; MMAP 2022b). Across Europe there are several ways of application of cleaning-respacing: (I) negative selection and from below, with 3000–4000 stems ha^{-1} at the end of thicket stage, as in Poland (Lasy Państwowe 2023), (II) negative selection and from above as in Czech Republic (Vacek et al. 2009) and Slovenia (Brus pers.comm.), (III) mostly negative, but also positive selection and mixed intervention (from above and from below), reducing the canopy cover after cleaning-respacing to 80% (75% in highly productive stands, with a rich understorey) as in Romania (stand density after

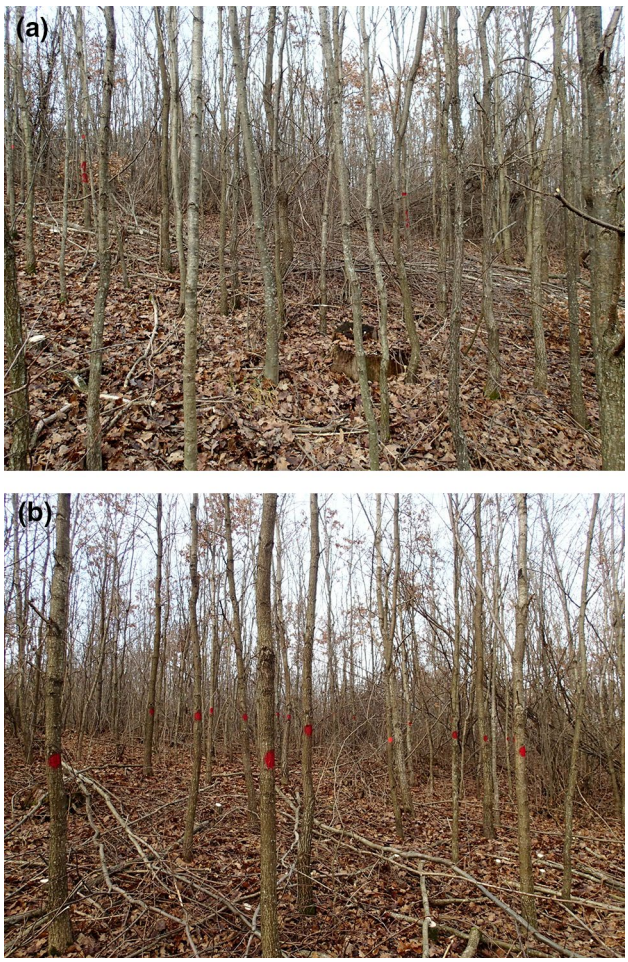

Fig. 8 Sessile oak stand before (**a**) and after (**b**) cleaning-respacingin Romania (photo V.N. Nicolescu)

cleaning-respacing 2500–3600 trees ha^{-1}, MMAP 2022b, Fig. 8a and 8b) or in Belgium (Boudru 1989a).

The approach of using a positive plus negative selection (as `collective education`) in thickets is also recommended by Schütz (1993), in order to homogenize the stand in a quantitative and qualitative way by favouring the trees with continuous and non-forked trunks. In France and Ireland, where the recommended cleaning-respacings are positive selections and from above, part of the so-called 'dynamic silviculture', the stand density is reduced to 3600 trees ha^{-1} when dominant height is 6–7 m, and to 1900–2100 stems ha^{-1} at the end of thicket stage (dominant height 10–11 m) (Jarret et al. 1996; Joyce et al. 1998; Jarret 2004; Sardin 2008; Sardin and Mothe 2010). Stand density is also proposed to be reduced by cleaning-respacing even to 1100–1600 trees ha^{-1} in the case of the most dynamic silviculture proposed by Lemaire (2010). The number of cleaning-respacings range between 1 (pure sessile oak stands, Joyce et al. 1998), 2–3 (Stănescu and Târziu 1973; Buffet 1978; Helliwell 1984; Anonymous 1986, 2000; Sardin 2008) and 3–4 (Bary-Lenger and Nebout 1993). Cleaning-respacing cycle ranges from 3 to 5 years in Romania (Constantinescu 1976; Anonymous 1986, 2000; MMAP 2022b) to 5–7 in Belgium (Bary-Lenger and Nebout 1993). The 'dynamic silviculture' approach also includes the *preselection and marking of potential final crop trees*, at the end of the thicket stage (when mean height is 6–8 m) (COFORD 2002; Allegrini 2010). The choice of these trees is based on the *vigour* (the thickest and tallest, from Kraft classes I and II)—*quality* (vertical-grown, straight, with large and balanced crowns, without forks, wounds or other defects)—*distribution (spacing)* (as evenly spaced as possible) criteria (Sevrin 1997; Wouters et al. 2000; Baar et al. 2004; Baar 2005; Allegrini 2010; Deleuze and Renaud 2010). As emphasized by Bonfils et al. (2015), the tree vigour criterion is of increasing importance in a constantly changing and stressful environment. Consequently, potential final trees will be selected with more weight given to their vigour than to the quality or distribution (spacing) criteria. Obviously, given the relatively young age of selected trees, not all their quality and quantity potential has been fully expressed; therefore it is necessary that the last cleaning-respacing and future thinning will focus on these trees in order to keep their preferential status (Allegrini 2010). The number of potential final crop trees should be (2) 3 (seldom 4) times the one at the rotation age (Schober 1991; Sevrin 1997; Wouters et al. 2000; Baar et al. 2004; Colin et al. 2010; Deleuze and Renaud 2010; Andrzejczyk et al. 2023) or, more exactly, 60–100 trees ha^{-1} (Löf et al. 2016), 100–200 trees ha^{-1} (Sardin 2008), 300–400 trees ha^{-1} (https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131560-sessile-oak-sok/) or 320–400 trees ha^{-1} (Andrzejczyk et al. 2023). In case of the most dynamic sessile oak 'tree silviculture' (France, Lemaire 2010), 70 potential final crop trees (on average 12 m apart) are designated at the end of thicket stage (dominant height 9–12 m), and a heavy intervention from above (détourage in French), targeting the 'free-growth' state at crown level of these valuable trees, combined with their artificial pruning up to 6 m height, is performed. The evolution of ideas on release cutting and cleaning-respacing is, however, in accordance with the old adage: `Release cutting and cleaning-respacing must be applied whenever and wherever they are necessary, without thinking about the wood production that can be obtained` (Bagneris 1876).

Commercial thinning

Thinning, by reducing the inter-individual competition, reduces the natural mortality of trees and susceptibility of stands to secondary pests and pathogens, and appears to be a suitable option for adapting existing sessile oak stands to climate change (Steckel et al. 2020; Černý et al. 2024b). In sessile oak silviculture, the main objective of thinning is the production of straight trees, pruned up at least 6 m height, without epicormic branches and with as uniform as possible growth rings, regardless their width (Schütz 1993). In sessile oak stands, the positive selection and thinning from above (crown thinning) was the method proposed at the end of nineteenth century (Broilliard 1881) and has been recommended throughout the twentieth century (e.g. in Switzerland, Fron 1923; Romania, Ciumac 1965; Germany, Kenk 1978), especially in two-storied sessile oak stands with shade-tolerant species. In crown thinning, (1) 2–3 most competitive trees affecting the final crop trees are removed, to release the crowns of the best individuals (Joyce et al. 1998; Apfel et al. 2016; Nicolescu et al. 2018) (Fig. 9).

Fig. 9 High thinning in sessile oak stand (photo V.N. Nicolescu)

Currently, this thinning method is applied across Europe, in France (from Bagneris 1878 to Jolyet 1916, from Jarret 1996 to Lemaire 2010), Belgium (Bary-Lenger and Nebout 1993; Baar 2010), the Czech Republic (Dobrovolný and Macháček 2012), Germany (Spiecker 1991; Stimm et al. 2022), Ireland (Joyce et al. 1998), Switzerland (Schütz and Badoux 1979), Sweden (Löf et al. 2016), Slovakia (Apfel et al. 2016) and Turkey (Huss and Kahveci 2009), ensuring the optimal crown development and diameter growth of stems. In particular situations (e.g., dry conditions, where understorey species may not survive), thinning from below is recommended (Turkey, Odabaşı et al. 2004a). The recommended thinning type is intermediate (mixed) in North Macedonia (Trajkov pers.comm.), Ukraine (Lavnyy pers. comm.) and Romania (MMAP 2022b). In general, the designation of 'genuine' future crop trees using the `potential` final crop trees selected during the thicket stage, based on the same criteria i.e. vigour-quality-distribution (spacing) should be accomplished during the first thinning when dominant height is (12) 13–15 m (Bastien 1997; Sevrin 1997; Joyce et al. 1998; Wouters et al 2000; Baar 2005; Sardin 2008; Allegrini 2010; Lemaire 2010). There are also recommendations for selecting such valuable trees at the second thinning, when the dominant height is 16–18 m (Colin et al. 2010), 16–19 m (Jarret 1996), 17 m (Kenk 1984), 17–20 m (Jarret et al. 1996), 18 m (Oswald 1982; Duplat 1992; Jarret 2004) or even 20 m (Oswald 1981; Lafouge 1990; ONF 1991). Depending on stand age, selection of final crop trees is recommended to be done at age 25–28 years (Baar 2005), 30–40 years (Löf et al. 2016; MMAP 2022b), 35–40 years (Apfel et al. 2016), at maximum 50–60 years (Duplat 1992; Bary-Lenger and Nebout 1993), or around 60 years (Sevrin 1997). The proposed age was much longer in the past e.g., 60–80 years (Lanier 1986, 1994), 60–90 years (Martinot-Lagarde 1973) or 70–75 years (Lorne 1956, 1959). The number of final crop trees is variable and ranges between (40) 50 and 200 individuals ha^{-1}, the majority of recommended stand densities at rotation age being a maximum of 100 individuals ha^{-1} (Table 9).

However, this number of sessile oak final crop trees per ha^{-1} depends on the target diameter at rotation age. For instance, it is 90–110 trees ha^{-1} when the target diameter is 50 cm, 60–80 trees ha^{-1} when the required diameter is 60 cm and 50–60 trees ha^{-1} when a diameter of 70 cm is the aim at rotation age (Kerr and Haufe 2011). The mean distance between future crop trees is selected depending on their diameter at breast height (dbh): 12 m (dbh 60 cm), 16 m (dbh 80 cm) (Spiecker 2021) or 11–12 m, when the target diameter is between 60 and 70 cm (Wouters et al. 2000). Usually, the mean distance between these trees is circa 14–15 m (50 trees ha^{-1}), 13–14 m (60 trees ha^{-1}), 12–13 m (70 trees ha^{-1}) or 11–12 m (80 trees ha^{-1}) (Sardin 2008; Kerr and Haufe 2011). However, as the distance between final crop trees cannot be perfectly constant, it is recommended to have a minimum distance between these trees of 50 to 70% of the mean distance at rotation age (Oswald 1981; Allegrini 2010; Lemaire 2010), e.g. at least 5 m (Sevrin 1997). The intensity of thinning in sessile oak stands across Europe is also very variable: 15–20% of growing stock (pure sessile oak stands in Slovakia—Apfel et al. 2016), up to 20% of growing stock (North Macedonia – Trajkov pers.comm.), 6% (age 80 years) to 15% (age 21–30 years) of growing stock in Romania (MMAP 2022b), 15% (sessile oak, European beech mixture, share of sessile oak over 60%) to 25% (sessile oak, European beech mixture, with the proportion of European beech over 60%) (Slovakia, Farkaš and Saniga 2015; Apfel et al. 2016), maximum 20%–25% (France—CNPF 2023). In Germany, thinning intensity should not be higher than 30 m^3 ha^{-1} $intervention^{-1}$, to achieve high valuable timber (veneer quality, target diameter 80+ cm) (Vor pers. comm.). In France, the recommended minimum volume to remove through each crown thinning is 35 m^3 ha^{-1} (Jarret et al. 1996). An important issue to take into account when applying heavy thinning is that before the age of 100 years, sessile oak reacts to such thinning vigorously but this decreases significantly after this age (Jarret et al. 1996), reducing totally after age 120 years (Martinot-Lagarde 1970). Thinning cycles are very variable as well: 4–8 years (young stands) to 8–12 years (older stands) (Belgium, Boudru 1989a), from 5 years (good sites) to 10 years (low quality sites) (the Czech Republic—Vacek et al. 2009), from 5 years (age 35–40 a) to 10 years (age 100–100 a) (Slovakia, Farkaš and Saniga 2015; Apfel et al. 2016), from 5 to 10 years (Ukraine—Lavnyy pers.comm.), from 6 to 10 years (France, Jarret et al. 1996; Lemaire 2010), 6–8 years (pole stage) to 8–10 (12) years (high forest stage) (Romania, MMAP 2022b), 8–12 years (France, CNPF 2023), 10 years (Croatia—Matić et al. 2003), and 10–20 years (North Macedonia –Trajkov pers.comm.). In "very dynamic" silviculture (Lemaire 2010), thinning switches back from 'tree silviculture', including 1–2 heavy cleaning-respacing, targeting the 'free-growth' state at crown level of potential final crop trees, to `stand silviculture`, including heavy crown thinning, started when dominant height reaches 16 m (Lemaire 2010; Sardin 2010). Such crown thinning has an intensity of 5 m^2 ha^{-1} per intervention and a cycle between 6 years (dominant height 12–16 m), 8 years (dominant height 16–22 m), 12 years (dominant height 22–26 m), and 15 years (over 26 m) (Lemaire 2010). As thinning target the promotion of final crop trees, which are selected based primarily on the vigour criteria, defined by the presence of a large and balanced crown, one should remember that there is a strong correlation between diameter at breast height ($d_{1.3}$) and crown diameter: the larger the tree crown, the larger

Table 9 Number of final crop trees in different European countries

Country	Number of final crop (trees ha^{-1})	Source	Observations
Belgium	40–80	Balleux 2005	
France	50	Sardin 2008*; Lemaire 2010; Sardin and Mothe 2010	*Silviculture with free-growth of final crop trees of sessile oak
Czech Republic	50–60	Košulič 2010, in Dobrovolný and Macháček 2012	
Sweden	50–70	Löf et al. 2016	
France	50–100	Sardin 2008	Dynamic silviculture
France	55*–80**	Jarret 2004	*Rich sites, **Less fertile sites
France	60*	Sevrin 1996, 1997	*Dynamic silviculture
France	60–70	Jarret 2004	
Germany	60–70	Skiadaresis et al. 2016	
Austria	60–70	Weinfurter 2004	
France	From 60–70* to 90–100**	ONF 1997	*Very rich sites; ** Poor sites
France	60–80	Unisylva 2024a	
United Kingdom	60–90	Evans 1984; Kerr and Evans 1993	
France	60–100	Lafouge 1990; Jarret et al. 1996	
Germany		Vor pers.comm	
Turkey	(60) 70–100	Odabaşı and Çalışkan 1990	
Austria	65	Hochbichler 1993	
France	70	Bouchon and Trencia 1990	
Belgium	70–90	Baar et al. 2004	
France		Oswald 1982; Sevrin 1997; Sardin 2008	Traditional/classical silviculture
Belgium	70–100	Bary-Lenger and Nebout 1993	
France	70–140	Oswald 1981	
France	(70) 80–100	Duplat 1992	
Austria	80–100	Hochbichler 1993	
Switzerland		Schütz 1993	
Germany		Kenk 1978, 1984	
Poland		Andrzejczyk et al. 2023	
Romania	90–100	Anonymous 2000, MMAP 2022b	
France	100	CRPF Bourgogne 2012	
Ireland		Joyce et al. 1998, Horgan et al. 2003	
United Kingdom		https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131560-sessile-oak-sok/	
Slovakia	100–150	Apfel et al. 2016	
Czech Republic	100–200	Vacek et al. 2009	
Poland	150–200	Klisz pers.comm	

the $d_{1.3}$, hence the importance of creating crowns as large as possible on final crop trees (Spiecker 2021). In this respect, the correlation between diameter at breast height ($d_{1.3}$) and crown diameter (d_c) is considered to be as follows (Spiecker 2021):

$$d_c = 0.20 + 0.209d_{1.3} - 0.015a \quad (1)$$

where, a is age, in years.

This correlation was also expressed by Dagnelie et al. (1985) in Belgium (Table 10).

In addition, trees with large crowns have lower risk of epicormic branches, even in stands without an understorey (Savill 1991, 2013; Jarret et al. 1996; Joyce et al. 1998). As mentioned, thinnings are controlled using either stand density (number of trees ha^{-1}) at different ages, culminating with the number of final crop trees at rotation age (Table 7), or stocking (basal area, in m^2 ha^{-1}), kept at the same level throughout the whole life of the stand. In the latter case, the value of this "critical" basal area after each thinning is recommended to range between 14 and 18 m^2 ha^{-1} (France, Sardin 2008; Sardin and Mothe 2010). A higher target basal

Table 10 Correlation between diameter at breast height and mean crown diameter in sessile oak trees

Diameter at breast height ($d_{1.50}$) (cm)	Mean crown diameter (cm)
18	347
33	614
49	882
65	1124
81	1353

area of 23–25 m^2 ha^{-1} (on average) after each intervention was proposed in the UK by Kerr and Haufe (2011). One very important issue to take into account in the management of sessile oak-dominated stands is, as already mentioned, the scrupulous protection of an existing understorey of shade-tolerant forest species such as European hornbeam, European beech, field maple, and small-leaved lime, in order to help the natural shedding of lower branches and control the occurrence and growth of epicormic branches. Among these species, European beech can create two major problems to sessile oak: during the regeneration phase, when its seedlings/saplings, along with those of European hornbeam, tend to overgrow and subsequently outcompete sessile oak seedlings/saplings owing to their greater competitive strength (Maleki et al. 2020), as well as during the pole and high forest stages, when European beech requires a special attention during thinning as a potential major competitor to sessile oak in the upper storey (Bastien 1997; Kohler et al. 2020). Consequently, the vitality of sessile oak in mixed stands can be maintained only through heavy thinning from above in order to establish and maintain beneficial forest structures favouring oak trees (Eaton et al. 2016; Maleki et al. 2020). Under future warmer and drier climates the competitive relationship between sessile oak and European beech is expected to change: the competitiveness of beech might decrease while oak is expected to adapt better to climate changes (Maleki et al. 2020). If this understorey does not exist, it is recommended to be introduced by planting, not with the sessile oak but later: (I) when the dominant height of sessile oak is maximum 6 m (Jarret et al. 1996), (II) in sapling or thicket stands (Schütz and Badoux 1979), (III) after the first thinning, when dominant height is 13–15 m (Joyce et al. 1998), or (IV) when the stand age is over 40 years (Duplat 1992). The presence of an additional understorey of shade-tolerant species is fundamental in a more dynamic silviculture of sessile oak employing heavy thinning from above, which opens the canopy, providing more light to the lower part of stems so making these more prone to epicormic growth (Stimm et al. 2022).

Pruning

Pruning green branches in sessile oak does not create problems such as discolouration or rot. The maximum size such branches which can be pruned safely is 2 cm in slow-growing oaks and 4 cm in the fast-growing ones (Atay 1986). However, this operation, considered "expensive and exceptional" (Boudru 1989a) and "rarely cost-effective, especially over long rotations" (Joyce et al. 1998) is seldom used in the practice of sessile oak silviculture, with some exceptions:

- When the target is the production of quality sawlogs, formative pruning is essential to ensure single leaders and to remove larger side branches. This should start soon after establishment and continue until a single straight stem is achieved. Subsequent management, if growing in a mixed stand, may require follow-up pruning to maintain stem quality to a minimum of 6 m height (https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131560-sessile-oak-sok/).
- When a "tree silviculture" is employed, 70 final crop trees ha^{-1}, selected at 9–12 m dominant height, are high pruned up to 6 m (Lemaire 2010).
- When a free-growth regime, an important producer of epicormic branches, is used, this requires artificial pruning removing such branches in stands targeting the production of high-quality timber (Kerr 1996; Attochi 2013).

The removal of epicormic branches should be carried out in summer, preferably not immediately but following the reduction of epicormic growth vigour i.e. 4–5 a after their occurrence, when the crowns of sessile oaks are rebalanced through lateral/horizontal growth or when an understorey of shade-tolerant species has `arrived` (Sevrin 1997). Annual removal of epicormics, starting immediately after their occurrence, although possible and preferable, is not economically viable. Formative, as well as high pruning can be also carried out before the onset of a new growing season, with clean cuts, protecting the branch swelling, without leaving any stubs or harming the thin bark (Boudru 1989a). The main positive effect of pruning sessile oak trees, if practiced, is shortening the time of knot occlusion (even more than two-time shorter than for the knots of unpruned trees) and reduction of the unsound knot zone (Mederski et al. 2019).

Uneven-aged stands and irregular silviculture

The application of irregular high forest cuttings in sessile oak forests assumes the existence of an irregular structure, which includes trees of various diameters, heights and ages, resulting from a thorough stand inventory. Such stand structure, with a target basal area of 14–18 m^2 ha^{-1} before

intervention, allows for the application of all kinds on works depending on the stage of development: release cutting in the seedling stage, cleaning-respacing in the sapling-thicket stages, thinning during the pole stage, as well as extraction of old, 'ripe' trees (65–70 cm in diameter, regardless the quality class, Unisylva 2024b; target diameters of logs of 50–60 cm in quality class C, 70–80 cm in class B, and 80–90 cm in class A, AFI 2009) by a 'selection cutting'. The target basal area of the stand after cutting decreases generally to 12–14 m^2 ha^{-1}, with a rotation of selection cuttings of (7) 8–12 years and a basal area of trees to remove of 5–7 m^2 ha^{-1} $intervention^{-1}$ (i.e. 15–20% of standing volume) (AFI 2009; CNPF 2023; Unisylva 2024b).

In coppice-with standards, where sessile oak is used solely as a standard tree, the species is well-adapted as it coppices well, the rare crowns of standards are not shading the coppice storey which finds the space and light necessary for growth. All standards together should cumulatively add up to a canopy cover lower than 30% (CNPF 2023), and are managed with a rotation age, in general, of 100–130 years (but also of 60–80 years as in Germany, Becker et al. 2018, 100–120 years in Austria, Kühmaier et al. 2018, or 100–150 years in Belgium, Bary-Lenger and Nebout 1993). The only operation carried out on sessile oak standards is the removal of epicormic branches, occurring along the stems which receive a surplus of light after the coppice is cut (Bagneris 1878; Broilliard 1881; Lorentz and Parade 1883). The epicormics are removed either before the beginning of a new growing season or during the summer, a maximum of 2–3 years after the coppice cut. This intervention, which is costly and not always effective, is performed 2–3 times, with a rotation of several years, until the coppice storey grows up and protects the stems of standards [Drăcea 1942; Guinier (ed) 1947; Nicolescu et al. 2018].

Conversion of sessile oak coppice forests

Since the beginning of the nineteenth century (1824–1825, in Forêt d'Amance, Ningre and Doussot 1993, and Forêt de Senonches, Bary-Lenger and Nebout 1993), in France (public forests), many pure or mixed sessile oak coppice and coppice-with-standards stands have been converted to high forest (Ducousso and Bordacs 2004). The process has been carried out in two ways (Nicolescu et al. 2018):

- Directly by (a) ageing up to (50) 60–80 years, even 100 years, as in Bulgaria (Markoff et al. 2018; Kostov et al. 2019), followed by regeneration cuttings (uniform or group shelterwood), using the normal succession of cuts (seeding-secondary-final) (Bary-Lenger and Nebout 1993), or (b) by replacement/restoration, including clear-felling, followed by planting.
- Indirectly by replacing first the simple coppice with coppice-with-standards, where standards, after 60 years of age, start producing seeds for the transition towards high forest.

This conversion process is ongoing in countries such as Austria (Kühmaier et al. 2018), Belgium (Vandekerkhove et al. 2018), Bulgaria (Markoff et al. 2018), the Czech Republic (Matula et al. 2012; Štochlová and Hédl 2018), North Macedonia (Trajkov et al. 2019), Serbia (Krstić and Petrović 2018), Slovakia (Fehér 2018), Ireland (Joyce et al. 1998), and Turkey (OGM 2005; Bariş Özel and Ertekin 2018; Kaya et al. 2023). In this respect one should mention that, although the majority of European coppice-with-standard forests are converted to high forest, there are two major exceptions (France, Ruch et al. 2018, and Italy, Mairota et al. 2018), where this silvicultural system still plays a very important role, especially in privately-owned forests.

Economics of sessile oak management

As stressed by Bary-Lenger and Nebout (1993), mass wood production of sessile oak is not interesting in financial terms and its silviculture should focus on production of large and high-quality wood, for high value end-uses (e.g., veneer, solid furniture, barrels). In this respect, high forest stands should be prioritized as they produce large-sized logs and the price of sessile oak wood is higher the larger the log diameter (Bary-Lenger and Nebout 1993).

Sessile oak high forests (both regular and irregular) are commercially viable only on the most productive sites. For instance, in sessile oak stands growing on sites with different productivities, with a rotation age of 150 years and a thinning cycle of 10 years, the financial results are as follows (Bary-Lenger and Nebout 1993):

Mean annual volume increment 8 m^3 ha^{-1}: internal rate of return (IRR) 2% (high-quality wood production) vs. 1.6% (industrial wood production);
Mean annual volume increment 6 m^3 ha^{-1}: IRR 1.4% (high-quality wood) vs. 1.2% (industrial wood);
Mean annual volume increment 4 m^3 ha^{-1}: IRR 0.7% (high-quality wood) vs. 0.6% (industrial wood).

In conclusion, sessile oak silviculture is justified economically only in high forests growing on rich, productive sites, which can ensure the production of large diameter and high-quality logs (Bary-Lenger and Nebout1993).

Conclusion

Sessile oak is a long-living forest species, able to adapt to a variety of ecological/site conditions in Europe, and growing at altitudes ranging from sea level to 2200 m despite being known as "the oak of the mountains". It shows high resistance to storms, is drought tolerant and heat stress resistant, regenerates readily from seed and coppices easily, so can be used in high forests, coppice-with-standards and coppice forests. Sessile oak is well-adapted to dynamic silvicultural management, including heavy thinning from above, to favour final crop trees. Its management, requiring active human intervention, is intensive and expensive, requires long rotations (usually over 120 years), and produces valuable timber of various end-uses. In the context of ongoing and predicted climate change, the natural range of sessile oak is predicted to expand and it is expected to become the most important broadleaved species for the future natural vegetation in Europe as a component of climate-resilient mixed-species forests.

Acknowledgements This paper is an output of a joint work of university staff members and researchers in Forestry from different European countries. The authors acknowledge helpful suggestions from the reviewers and the editor.

References

Aas G (2014) Sessile oak (*Quercus petraea*): systematics, morphology und ecology. LWF Wissen 75:6–13 **(in German)**

Abrudan IV (2006) Afforestations. Editura Universității Transilvania, Brașov, p 200 **(in Romanian)**

AFI (2009) Treatment of irregular high forest. Convention France Bois Forêt/AFI 2009, Association Futaie Irrégulière, Besançon, p 144 **(in French)**

Aitken SN, Bemmels LB (2016) Time to get moving: assisted gene flow of forest trees. Evolutionary Applications, 271–290. https://doi.org/10.1111/eva.12293

Albert M, Nagel J, Schmidt M, Nagel R-V, Spellmann H (2021) A new generation of yield tables for oak, beech, spruce, Douglas fir and pine [data set]. https://doi.org/10.5281/zenodo.6343907 **(in German)**

Alexandrov A, Dobrev R (2015) The state of forest genetic resources in Bulgaria. Scholar's Press, Sofia, p 92

Allegrini C (2010) Choosing the future crop trees. Forêts de France 531:33−34 **(in French)**

Ammann P, Junod P, Brüllhardt M (2024) Rejuvenation of light-demanding species: what size of gap? La Forêt 4(24):28–31 **(in French)**

Analiza (2022) Analysis of nursery production in PGL LP for 2022. National Silviculture Conference 26.04.2023, PowerPoint Presentation, data of State Forest Enterprise **(in Polish)**

Andrzejczyk T (2009) Pedunculate and sessile oak. Silviculture. PWRiL, Warszawa, p 302 **(in Polish)**

Andrzejczyk T, Liziniewicz M, Bolibok L (2023) Growth and quality of 16-year-old sessile oak (*Quercus petraea* (Matt.) Liebl.) planted in traditional and alternative row planting patterns. Forestry. https://doi.org/10.1093/forestry/cpad059

Annighöfer P, Beckschäfer P, Vor T, Ammer C (2015) Regeneration patterns of European oak species (*Quercus petraea* (Matt.) Liebl., *Quercus robur* L.) in dependence of environment and neighborhood. PLoS ONE 10(8):e0134935. https://doi.org/10.1371/journal.pone.0134935

Anonymous (1956) Tending of stands. Technical guidelines. Editura tehnică, Bucureşti, p 90 **(in Romanian)**

Anonymous (1986) Technical norms for stand tending 2. Centrul de material didactic şi propagandă agricolă, Bucureşti, p 166 **(in Romanian)**

Anonymous (1987) Regulatory and reference materials for the forest measurement in Ukraine and Moldova. Urozhaj, Kyiv, p 560 **(in Russian)**

Anonymous (1997) Qualitative classification. Hardwood roundwood. Part 1: Oak and beech. Norme européenne/norme française NF EN 1316-1. AFNOR, Paris, p 8 **(in French)**

Anonymous (2000) Technical norms for tending operations 2. Ministerul Apelor, Pădurilor şi Protecţiei Mediului, Bucureşti, p 164 **(in Romanian)**

Antonesco P (1911) Oak and its culture in Romania. Bulletin de la Société Centrale Forestière de Belgique, F. van Buggenhoudt, Editeur, Bruxelles, p 15 **(in French)**

Apfel E, Dendys P, Farkaš J, Jasík M, Mathe P, Saniga M, Štrupl L (2016) Handbook for close to nature forest management in Natura 2000 territories and the possibilities of its financial support. State Nature Conservancy of the Slovak Republic, Banská Bystrica, p 99 **(in Slovak)**

Assyov B, Petrova A (eds) (2012) Conspectus of the Bulgarian Vascular Flora. In: Distribution maps and floristic elements, 4th edn. Bulgarian Biodiversity Foundation, Sofia, p 490 **(in Bulgarian)**

Ata C (2021) Trees and shrubs used in landscape design in Turkey (Broadleaved species). Yeditepe University, Istanbul, p 400 **(in Turkish)**

Atay İ (1986) A tending measure that increases its importance: "Pruning." İstanbul Üniversitesi Orman Fakültesi Dergisi Seri b 36(1):21–30 **(in Turkish)**

Attochi G (2013) Pruning effects on the production of new epicormic branches: a case study in young stands of pedunculate oak (*Quercus robur* L.). In: Proceedings of the 4th scientific conference on hardwood processing 2013, 7th–9th October 2013, Florence, Italy, pp 44–49

Baar F (2005) Towards the targeted annual harvest of a few very high quality target trees to ensure forest revenues. Forêt Wallonne 77:19–36 **(in French)**

Baar F (2010) Tree marking in irregular hardwood or sofwood forest. Direction Générale Opérationnelle de l'Agriculture, des Ressources Naturelles et de l'Environnement, Service publique de Wallonnie, Jambes, p 60 **(in French)**

Baar F, Snoeck B, Balleux P, Claessens H (2004) Silviculture of "target" trees or future crop trees. Forêt Wallonne 68. Cahier Tech 27:2–8 **(in French)**

Babić V, Govedar Z, Galić Z, Milenković M, Vukin M, Stajić S, Kanjevac B (2021) Effects of the light regime on natural regeneration of sessile oak (*Quercus petraea* Matt. Liebl.) forests in Fruska Gora National park, Serbia. Fresenius Environ Bull 30(07A):8834–8842

Bagneris S (1873) Manual of silviculture. Berger-Levrault & C[ie], Libraires-Éditeurs, Paris et Nancy, p 311 **(in French)**

Bagneris G (1876) Manual of Silviculture. Chief Commissioner's Office Press, Nagpur, p 188

Bagneris G (1878) Elements of Silviculture. 2ème édition. Imprimerie Berger-Levrault et Cie, Nancy, p 325 **(in French)**

Balleux P (2005) Sessile oak and pedunculate oak, two distinct ecologies. Silva Belgica 5: I-IV **(in French)**

Balleux P (2006) Natural regeneration of native oaks. Silva Belgica, Sylviculture—fiche technique no. 14, 113(2):I–XII **(in French)**

Bariș Özel H, Ertekin M (2018) Turkey. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 348–351

Bartsch N, Lüpke B. von, Röhrig E (2020) Silviculture on ecological basis. 8th Edition. UTB, Ulmer, Stuttgart, p 676 **(in German)**

Bary-Lenger A, Evrard R, Gathy P (1988) The forest. In: Ecology-management-economy-conservation. Troisième Edition. Editions du Perron, Liège, p 619 **(in French)**

Bary-Lenger A, Nebout J-P (1993) Pedunculate and sessile oaks in France and in Belgium. Ecology-Economy-History-Silviculture. Editions du Perron, Alleur-Liège, p 604 **(in French)**

Bastien Y (1997) Silviculture of sessile and pedunculate oaks. Ecole Nationale du Génie Rural, des Eaux et des Forêts, Centre de Nancy, p 18 **(in French)**

Baylot J, Vautherin P (1992) Classification of hardwood roundwoods. CTBA, Paris, p 76 **(in French)**

Becker G, Unrau A, Pyttel P, Dohrenbusch A, Suhomel (2018) Germany. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 249–255

Bednárová D (2023) Final report "Control of forest reproductive material" of Forest reproductive material control centers for the year 2023. National Forest Centre, Zvolen, p 21 **(in Slovak)**

Bencheva S, Doychev D (2018) Biotic and abiotic damages on the sample trees and stands. In: Pavlova E, Pavlov D, Genova-Doncheva M, Bencheva S, Doychev D, Koleva-Lizama I, Kuzmanova R, Kadinov G (eds) Monitoring of forest ecosystems. Biological indicators. Region 4B. South slopes of Middle Balkan Mts., Srednagora Mt., Vitosha Mt. (east and north slopes), Rila Mt. (north and east slopes) and Plana Mt. PSSE, Sofia, pp 73–97 **(in Bulgarian)**

Bergès L, Nepveu G, Franc A (2008) Effects of ecological factors on radial growth and wood density components of sessile oak (*Quercus petraea* Liebl.) in Northern France. For Ecol Manag 255:567–579. https://doi.org/10.1016/j.foreco.2007.09.027

Blaskova G (2004) Wood science. UF Publishing House, Sofia, p 287 (**in Bulgarian**)

Bogdanov K (1975) Possibilities for increasing productivity of forests in the region of Eastern Staraplanina. Ph.D. thesis, Higher Institute of Forestry, Sofia, p 243 **(in Bulgarian)**

Boland TP (2024) The world of oaks-diversity, cultural history, and conservation. In: Martens et al (eds) The international oak symposium: science-based management for dynamic oak forests. Gen. Tech. Rep. SRS-278. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station, p 3

Bončina A, Rozman A, Dakskobler I, Klopčič M, Babij V, Poljanec A (2021) Forest vegetation types of Slovenia: vegetation, stand and management characteristics. Biotehniška fakulteta, Univerze v Ljubljani in Zavod za gozdove Slovenije, Ljubljana, p 576 **(in Slovenian)**

Bonfils P, Rigling A, Brändli UB, Brang P, Forster B, Engesser R, Gugerli F, Junod P, Müller R, Günthardt-Goerg MS (2015) Oak in the face of climate change. Future prospects for a species. Note for the practitioner. Institut fédéral de recherches WSL, Birmensdorf, 55, Aôut, p 12 **(in French)**

Boppe L (1889) Treatise of silviculture. Berger-Levrault et Cie, Libraires-Éditeurs, Paris et Nancy, p 444 **(in French)**

Boratyńska K (1979) Sessile oak (*Quercus petraea* (Mat.) Liebl.) in northeastern Poland. Arboretum Kórnickie XXIV:69–86 **(in Polish)**

Bose AK, Scherrer D, Camarero JJ, Ziche D, Babst F, Bigler C et al (2021) Climate sensitivity and drought seasonality determine post-drought growth recovery of *Quercus petraea* and *Quercus robur* in Europe. Sci Total Environ 784:147222. https://doi.org/10.1016/j.scitotenv.2021.147222

Bouchon J, Trencia J (1990) Silviculture and production of oak. Revue Forestière Française XLII 2:246–253 (**in French**)

Boudru M (1989a) Forest and silviculture: applied silviculture. Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, p 248 **(in French)**

Boudru M (1989b) Forest and silviculture: silvicultural systems. Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, p 356 **(in French)**

Boudru M (1992) Forest and silviculture: afforestation and reforestation. Les presses agronomiques de Gembloux, A.S.B.L., Gembloux, p 348 **(in French)**

Bozhinov H (1999) Structure and dynamics of the forestland. In: Sustainable management of the forests in Bulgaria. Criteria and Indicators, Delova Sedmica JSC, Sofia, pp 13–21 **(in Bulgarian)**

Bréda N, Cochard H, Dreyer E, Granier A (1993a) Field comparison of transpiration, stomatal conductance and vulnerability to cavitation of *Quercus petraea* and *Quercus robur* under water stress. Ann for Sci 50(6):571–582. https://doi.org/10.1051/forest:19930606

Bréda N, Cochard H, Dreyer E, Granier A (1993b) Seasonal evaluation of water transfer in a mature oak stand (*Quercus petraea* (Matt.) Liebl.) submitted to drought. Can J for Res 23:1136–1143

Broilliard C (1881) Management of forests in France for the use of private owners. Berger-Levrault& C[ie], Libraires-Éditeurs, Paris, p 470 **(in French)**

Brus R (2011) Dendrology for Foresters. Univerza v Ljubljani, Biotehniška fakulteta, Ljubljana, p 408 **(in Slovenian)**

Buffet M (1978) Regeneration of sessile oak in public forest. In: Exposés, Symposium feuillus précieux, Nancy-Champenoux, 11–15 sept. 1978, INRA, Documents no. 78/08, pp 168–177 **(in French)**

Buffet M (1980) Regeneration of sessile oak. Office National des Forêts, Paris, Bulletin technique 12:3-30 **(in French)**

Buschbom J, Gimmerthal S, Kirschner P, Michalczyk IM, Sebbenn A, Schueler S, Schlünzen KH, Degen B (2012) Spatial composition of pollen-mediated gene flow in sessile oak. Forstarchiv 83:12–18. https://doi.org/10.4432/0300-4112-83-12

Bußler H (2014) Beetles and large butterflies on sessile oak. LWF Wissen 75:89–93 (**in German**)

Caudullo G, Welk E, San-Miguel-Ayanz J (2017) Chorological maps for the main European woody species. Data Brief 12:662–666. https://doi.org/10.1016/j.dib.2017.05.007

Cavaignac S (2007) Identification and classification of criteria determining the quality of oak logs (*Quercus petraea* Liebl. and *Quercus robur* L.) based on the study of their sale price and the estimation of user preference. Ph.D. Thesis. Laboratoire d'Etude des Ressources Forêt-Bois, UMR INRA-ENGREF, Equipe de Recherches sur la Qualité des Bois, Champenoux, p 288 **(in French)**

Çanakçı ZE (2011) Effects of seed sowing density and seed sowing depth on some seedling morphological traits of the Iranian oak. Yüksek Lisans Tezi, Artvin Çoruh Üniversitesi Fen Bilimleri Enstitüsü, Artvin, p 45 **(in Turkish)**

Çalışkan A, Özalp G, Karadağ M (2004) Regeneration of oak in mixed stands of black pine-oak-fir-beech in the Karabük-Büyükdüz Research Forest. Çevreve Orman Bakanlığı, Batı Karadeniz Ormancılık Araştırma Enstitüsü Müdürlüğü, Teknik Bülten No: 10, Bolu, p 59 **(in Turkish)**

Cedro A (2007) Tree-ring chronologies of downy oak (*Quercus pubescens*), pedunculate oak (*Q. robur*) and sessile oak (*Q. petraea*) in the Bielinek Nature Reserve: comparison of the climatic determinants of tree-ring width. Geochronom J Methods Appl Absol Chronol 26(1):39–45. https://doi.org/10.2478/v10003-007-0005-2

Černý J, Špulák O, Sýkora P, Novosadová K, Kadlec J, Kománek M (2024a) The significance of European beech in Central Europe in the period of climate change: an overview of current knowledge. Zprábvy Lesnické Hovýzkumu 69(1):74–88 (**in Czech**)

Černý J, Špulák O, Kománek M, Žižková E, Sýkora P (2024b) Sessile oak (*Quercus petraea* [Matt.] Liebl.) and its adaptation strategies in the context of global climate change: a review. Cent Eur for J 70:1–18. https://doi.org/10.2478/forj-2024-0012

Chaar H, Colin F (1999) Impact of late frost on height growth in young sessile oak regenerations. Ann for Sci 56:417–429

Chałupka W, Barzdajn W, Blonkowski S, Burczyk J, Fonder W, Grądzki T, Gryzło Z, Kacprzak P, Kowalczyk J, Kozioł C (2011) Program of conserving forest genetic resources and breeding of trees in Poland for the years 2011–2035. CILP, Warsaw, p 141 **(in Polish)**

Ciceu A, Bălăcenoiu F, de Groot M, Chakraborty D, Avtzis D, Barta M, Blaser S, Bracalini M, Castagneyrol B, Chernova UA, Çota E, Csóka G, Dautbasic M, Glavendekic M, Gninenko YI, Hoch G, Hradil K, Husemann M, Meshkova V, Mujezinovic O, Mutun S, Panzavolta T, Paulin M, Riba-Flinch JM, Simov N, Sotirovski K, Vasilciuc S, Zúbrik M, Schueler S (2024) The ongoing range expansion of the invasive oak lace bug across Europe: current occurrence and potential distribution under climate change. Sci Total Environ 949:174950. https://doi.org/10.1016/j.scitotenv.2024.174950

Ciumac G (1959) Tending of stands. In: Negulescu EG, Ciumac G (eds) Silviculture, Editura Agro-Silvică de Stat, Bucureşti, pp 479–597 **(in Romanian)**

Ciumac Gh (1965) Aspects regarding the tending of mixed stands of oaks with other broadleaved trees. Revista Pădurilor 4:176–178 (**in Romanian**)

Ciumac Gh (1967) Contributions to the study of the natural regeneration of sessile oak stands, sessile oak-pedunculate oak stands and hilly mixed stands of broadleaves. Centrul de documentare tehnică pentru economia forestieră, Bucureşti, p 115 **(in Romanian)**

CNPF (2023) Regional forest management plan. Centre-Val de Loire. Centre Régional de la Propriété Forestière Île-de-France, Centre-Val de Loire, Orléans, p 149 **(in French)**

COFORD (2002) Silviculture of broadleaves. COFORD, Dublin, p 6

Colin F, Fontaine F, Verger S, François D (2010) Epicormic branches and other epicormics of sessile oak. Establishment on trunks, dynamics and silvicultural control. RDV Tech Hors-Série 5:45–55 (**in French**)

Constantinescu N (1973) Regeneration of stands, 2nd edn. Editura Ceres, Bucureşti, p 667 **(in Romanian)**

Constantinescu N (1976) Tending of stands. Volume II. Editura Ceres, Bucureşti, p 402 **(in Romanian)**

Croatian Forests Ltd (2023) Price of main forest products. https://www.hrsume.hr/wp-content/uploads/2023/01/cjenik_glavnih_sumskih_proizvoda_1.1.2023.pdf

CRPF Bourgogne (2012) Sessile oak, pedunculate oak. Centre Regional de la Propriété Forestière de Bourgogne, Nevers, p 4 **(in French)**

Čufar K (2006) Wood Anatomy. Univerza v Ljubljani, Biotehniška fakulteta, Ljubljana, p 186 **(in Slovenian)**

Dagnelie P, Palm R, Rondeux J, Thill A (1985) Volume tables for trees and stands. Les Presses Agronomiques de Gembloux, Gembloux, p 148 **(in French)**

Damian I (1978) Afforestations. Editura Didactică şi Pedagogică, București, p 374 **(in Romanian)**

Dămăceanu C (1984) Research on the improvement of the methods of natural regeneration of sessile oak stands and of hilly mixed sessile oak-broadleaves stands, correlated with the mechanized wood harvesting. Ministerul Silviculturii, Institutul de Cercetări şi Amenajări Silvice, Centrul de material didactic şi propagandă agricolă, Bucureşti, p 79 **(in Romanian)**

Deleuze C, Renaud JP (2010) Silviculture of sessile oak and pedunculate oak. Response of young stands to respacing. ONF, RDV Tech Hors-Série 5:56–65 (**in French**)

Delkov N (1992) Dendrology. Martilen, Sofia, p 366 **(in Bulgarian)**

Del Alamo-Sanza M, Nevares I (2019) Wine aging technologies. Beverages 5(1):24. https://doi.org/10.3390/beverages5010024

Diaci J (2006) Silviculture. Univerza v Ljubljani, Biotehniška fakulteta, Ljubljana, p 348 **(in Slovenian)**

Dincă I (1983) Forest resources of Europe. Editura Ceres, Bucureşti, p 482 **(in Romanian)**

Dobrovolný L, Macháček J (2012) Production potential and quality of sessile oak (*Quercus petraea* Liebl.) in different types of mixtures. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis LX(6):57–66

Đodan M, Perić S (2022) Expert supervision and overview of production of forest planting material in the Republic of Croatia during 2021. Radovi 48(1):48–56 (**in Croatian**)

Đodan M, Bogdanić R, Gradečki Poštenjak M, Perić S (2023) Production of broadleaves planting material in the Republic of Croatia from 2017 to 2021. Šumarski List 147(11–12):555–564 (**in Croatian**)

Doniță N, Popescu A, Păucă-Comănescu M, Mihăilescu S, Biriș IA (2005) Habitats of Romania. Editura Tehnică Silvică, București p 496 **(in Romanian)**

Doucerain M (2020) Sessile oak: what provenances for the future? AgroParisTech, Centre de Nancy, p 55 **(in French)**

Drăcea M (1923) Silviculture. Handout. Şcoala Politehnică, Bucureşti, p 1024 **(in Romanian)**

Drăcea MD (1942) Silviculture handbook. Volume I Regeneration methods and Silvicultural systems. Editura Politehnicei, Bucureşti, p 786 **(in Romanian)**

Drevesnica Štivan (2024) Price list—own production. https://www.drevesnicastivan.si/storage/doc/202309/cenik-2023-24.pdf

Dubois JM (1988) Modern techniques for the regeneration of sessile and pedunculate oaks. Information-Forêt, Afocel-Armef 4:287–302 (**in French**)

Dubravac T, Đodan M, Barčić D, Županić M (2018) Croatia. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 213–218

Ducci F, Proietti R, De Dato G, Monteverdi MC, Belletti P, Calvo E, Ayan S (2017) Marginal populations, an experiment on assisted gene flow in oaks. In: International forestry and environment symposium "climate change and tree migration", Trabzon, Turkey, 07–10 November 2017

Ducousso A, Bordacs S (2004) EUFORGEN Technical Guidelines for genetic conservation and use of pedunculate and sessile oaks (*Quercus robur* and *Q. petraea*). International Plant Genetic Resources Institute, Rome, p 6

Duplat P (1992) Tending of young naturally regenerated stands of sessile oak (*Quercus petraea* Liebl.). Current practices. Research to be undertaken. Office National des Forêts, Paris, Bulletin technique 23:3–36 **(in French)**

Dyderski MK, Paź-Dyderska S, Jagodziński AM, Puchałka R (2025) Shifts in native tree species distributions in Europe under climate change. J Environ Manag 373:123504. https://doi.org/10.1016/j.jenvman.2024.123504

Eaton E, Caudullo G, Oliveira S, de Rigo D (2016) *Quercus robur* and *Quercus petraea* in Europe: distribution, habitat, usage and threats. In: San-Miguel-Ayanz J, de Rigo D, Caudullo G, Houston Durrant T, Mauri A (eds) European Atlas of forest tree species. Publication Office of the European Union, Luxembourg, p e01c6df

Ehmcke G, Grosser D (2014) The wood of oak—characteristics and use. LWF Wissen 75:53–64 **(in German**)

Ellenberg H, Leuschner C (2010) Vegetation of Central Europe and the Alps, 6th edn. Eugen Ulmer, Stuttgart, p 1334 **(in German)**

Enchev E (1972) A contribution to the study of physical and mechanical properties of Quercus petraea wood. Gorskostopanska nauka, 9(2): 53–64 **(in Bulgarian)**

Enescu V (1982) Production of forest seeds genetically improved. Editura Ceres, București, p 323 **(in Romanian)**

Eusemann P, Liesebach H (2021) Small-scale genetic structure and mating patterns in an extensive sessile oak forest (*Quercus petraea* (Matt.) Liebl.). Ecol Evol 11:7796–7809. https://doi.org/10.1002/ece3.7613

Evans J (1983) Controlling the epicormics: state-of-the-art in Britain. Revue Forestière Française XXXV(5):369–375 (**in French**)

Evans J (1984) Silviculture of broadleaved woodland. Forestry Commission Bulletin 62, HMSO, London, p 232

Evans J (1988) Natural regeneration of broadleaves. Forestry Commission Bulletin 78, HMSO, London, p 46

Farkaš J, Saniga M (2015) Handbook for forest owners. Cultivating oak stands (knowledge versus practical experience), 1st edn. Technical University in Zvolen, Zvolen, p 61 **(in Slovak)**

Fehér A (2018) Slovakia. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 321–322

Filipovici J, Amzică A (1956) Wood technology. EdituraTehnică, București p 283 **(in Romanian)**

Filipovski G (1997) Soils of the Republic of Macedonia. Volume III. Class of Cambic soils of A-(B)-C and of Eluvial-illuvial soils of A-E-B-C profile types. Macedonian Academy of Sciences and Arts, Skopje, p 519 **(in Macedonian)**

Filipovski G, Rizovski R, Ristevski P (1996) Characteristics of climate-vegetation-soil zones (regions) in the Republic of Macedonia. Macedonian Academy of Sciences and Arts, Skopje, p 177 **(in Macedonian)**

Flies R (1993) Opening address. In: Kremer A, Savill PS, Steiner KC (eds) Genetics of oaks, Proceedings of the first meeting of the IUFRO Working Party S2.02-22, Arboretum National des Barres, France, 2–6 September 1991. Annales des Sciences Forestières, vol 50, no Suppl. 1, pp 19s–20s

Forest Research (2024) Forestry Statistics 2024. Chapter 1: Woodland Area & Planning. Forest Research, Roslin, Midlothian, p 60

Fosso LC, Karahalil U (2023) Spatial area distribution of oaks according to different selected parameters in Türkiye. Turk J for Res 10:130–139. https://doi.org/10.17568/ogmoad.1286914

Fron A (1923) Silviculture. Librairie J.-B. Baillière et Fils, Paris, p 334 **(in French)**

Gačić D, Krstić M, Laketić M (2006) Effect of big game on sessile oak forests in the National park "Đerdap." Šumarstvo (Belgrade) 1–2:21–33 (**in Serbian**)

Ganchev I, Bondev I (1966) Genus 220(3) Oak—*Quercus* L. In: Jordanov D (ed) Flora of the People's Republic of Bulgaria, vol 3. Bulgarian Academy of Sciences, Sofia, pp105–145 **(in Bulgarian)**

Gasparini P, Di Cosmo L, Floris A, De Laurentis D (2022) Italian national forest inventory—methods and results of the third survey, 1st edn. Springer Tracts in Forest Engineering, p 576. https://doi.org/10.1007/978-3-030-98678-0

Gauthey A, Kahmen A, Limousin J-M, Vilagrosa A, Didion-Gency M, Mas E, Milano A, Tunas A, Grossiord C (2024) High heat tolerance, evaporative cooling, and stomatal decoupling regulate canopy temperature and their safety margins in three European oak species. Glob Change Biol 30:e17439. https://doi.org/10.1111/gcb.17439

Genç M (2004) Silvicultural techniques. Süleyman Demirel Üniversitesi Orman Fakültesi, Yayın No: 46, Isparta, p 357 **(in Turkish)**

Genç M (2012) Basic principles of silviculture. Süleyman Demirel Üniversitesi, Yayın No: 44, Isparta, p 351 **(in Turkish)**

Giefing DF, Karaszewski Z, Szakiel M, Bembenek M, Mederski PS, Gierszewska M (2014) Influence of wood defects in oak on grading. For Lett 107:10–15

Gil-Pelegrín E, Peguero-Pina JJ, Sancho-Knapik D (2017) Oaks and people: a long journey together. In: Oaks physiological ecology. Exploring the functional diversity of genus *Quercus* L. Springer, New York, pp 1–11

Girard Q, Ducousso A, de Gramont CB, Louvet JM, Reynet P, Musch B, Kremer A (2022) Provenance variation and seed sourcing for sessile oak (*Quercus petraea* (Matt.) Liebl.) in France. Ann for Sci 79:27. https://doi.org/10.1186/s13595-022-01140-0

Giurgiu V, Drăghiciu D (2004) Mathematical-auxological models and production tables for stands. Editura Ceres, București, p 607 **(in Romanian)**

Gößwein S, Lobinger G (2014) Organisms relevant to forest protection on sessile oak. LWF Wissen, 75: 80–88 **(in German)**

Goicoechea P, Petit RJ, Kremer A (2012) Detecting the footprints of ecological speciation in oaks with linked markers. Heredity 109(6):361–371. https://doi.org/10.1038/hdy.2012.51

Gosling RH, Jackson RW, Elliot M, Nichols CP (2024) Oak declines: reviewing the evidence for causes, management implications and research gaps. Ecol Solut Evid 5(4):e12395. https://doi.org/10.1002/2688-8319.12395

Gozd in Gozdarstvo (2024) https://www.gozd-les.com/novice/2024/rezultati-18-drazbe-lesa-slovenj-gradcu-2024

Green report (2023) Report on the Forest Sector of the Slovak Republic. 2022 Green Report. Ministry of Agriculture and Regional Development of the Slovak Republic, Bratislava, p 76

Gribbe S, Enderle L, Weigel R, Hertel D, Leuschner C, Muffler L (2024) Recent growth decline and shifts in climatic growth constraints suggest climate vulnerability of beech, Douglas fir, pine and oak in Northern Germany. For Ecol Manag 566:122022. https://doi.org/10.1016/j.foreco.2024.122022

Guinier P (1947) Forestry technique. La Maison Rustique, Paris, p 316 **(in French)**

Güngördü M (1999) Plant geography of the Marmara Region. İstanbul Üniversitesi, Yayın No: 4176, Edebiyat Fakültesi Yayın No: 3416, İstanbul, p 94 **(in Turkish)**

Haane A (2020) Fructification of oak and beech in Bavaria from 1965 to 2003. Master Thesis, Technical University Munich, p 75 **(in German)**

Halaj J, Petráš R (1998) Yield tables of the main tree species, 1st edn. Slovak Academic Press, Bratislava, p 325 **(in Slovak)**

Haralamb A (1967) Culture of forest species, 3rd edn. Editura Agro-Silvică, Bucureşti, p 755 **(in Romanian)**

Hardtke A, Meißner M, SteinerW JA (2016) New start of breeding pedunculate and sessile oak. AFZ-DerWald 6:42–44 (**in German**)

Hauck M, Schneider T, Bahlinger S, Fischbach J, Oswald G, Csapek G, Dulamsuren C (2025) Heat tolerance of temperate tree species from Central Europe. For Ecol Manag 580:122541. https://doi.org/10.1016/j.foreco.2025.122541

Helliwell DR (1984) Economics of woodland management. Packard Publishing Ltd., Chichester, p 64

Hemery G, Simblet S (2014) The New Sylva. A discourse of forest & orchard trees for the twenty-first century. Bloombsbury, London-New Delhi-New York-Sydney, p 390

Hochbichler E (1993) Methods of oak silviculture in Austria. Ann Sci for 50(6):583–591

Horgan T, Keane M, McCarthy R, Lally M, Thompson D (2003) A guide to forest tree species selection and silviculture in Ireland. COFORD, Dublin, p 256

Húdoková H, Petrik P, Petek-Petrik A, Konôpková A, Leštianka A, Střelcová K, Kmet J, Kurjak D (2022) Heat-stress response of photosystem II in five ecologically important tree species of European temperate forests. Biologia 77:671–680. https://doi.org/10.1007/s11756-021-00958-9

Huss J, Kahveci O (2009) Close-to nature forest management in Turkiye. OGEM-VAK, Ankara, p 532 **(in Turkish)**

Iancu I (1999) Manual of forest ranger. Theory and practice. Tipografia Pegasus, București, p 622 **(in Romanian)**

IGN (2024) Reminder. Edition 2023. National forest inventory. Institut national de l'information géographique et forestière, Paris, p 37 **(in French)**

Jacamon M (1987) Dendrology guide. Volume II Broadleaves. Ecole Nationale du Génie Rural, des Eaux et des Forêts, Nancy, p 256 **(in French)**

Jarman R, Kofman PD (2018) Coppice in Brief. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 22–28

Jarret P (1996) The key silvicultural stages for producing quality wood in state forests: two species, two silvicultural objectives, two silvicultures. Forêt-Entrep 112:36–37 (**in French**)

Jarret P (2004) Atlantic oak forests. Office National des Forêts, Paris, p 335 **(in French)**

Jarret P, Duplat P, Hoyau A, Kiefer E (1996) Silviculture of sessile oak. ONF Bull Tech 31:21–28 (**in French**)

Jokanović D, Nikolić Jokanović V, Živanović K, Ilić M, Antanasijević N, Jovanović F (2024) Variability of morpho-anatomical traits of one year-old *Quercus* sp. container seedlings. Reforesta 18:22–33. https://doi.org/10.21750/REFOR.18.02.118

Jolyet A (1916) Practical treatise of silviculture, 2nd edn. Librairie J.-B. Baillière et Fils, Paris, p 724 **(in French)**

Jovanović B (2000) Dendrology. Textbook. Šumarski fakultet, Beograd, p 536 **(in Serbian)**

Joyce PM, Huss J, McCarthy R, Pfeifer A, Hendrick E (1998) Growing broadleaves. Silvicultural guidelines for ash, sycamore, wild cherry, beech and oak in Ireland. COFORD, Dublin, p 144

Kabrick JM, Vickers LA (2024) Site factors, disturbances, and the distribution of oaks. In: Martens C, Clark S, Schweitzer C (eds) The international oak symposium: science-based management for dynamic oak forests. Gen. Tech. Rep. SRS-278. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, p 26

Kadunc A (2010) Quality, value characteristics and productivity of pedunculate and sessile oak stands in Slovenia. Gozdarski Vestnik 68(4):217–226, 239–240 **(in Slovenian)**

Kanjevac B, Dobrosavljević J, Babić V (2017) Contribution to study of the yield abundance and quality of sessile oak acorn in north-eastern Serbia. Šumarstvo (Belgrade) 1–2:65–76 (**in Serbian**)

Kanjevac B, Krstić M, Babić V, Govedar Z (2021) Regeneration dynamics and development of seedlings in sessile oak forests in relation to the light availability and competing vegetation. Forests 12:384. https://doi.org/10.3390/f12040384

Kanjevac B, Krstić M, Babić V (2023) Artificial regeneration of sessile oak forests by planting natural young stock. Šumarstvo (Belgrade) 1–2:55–67 (**in Serbian**)

Karadžić D, Milijašević T (2005) The most frequent parasitic and saprophytic fungi on sessile oak in Serbia and their contribution to tree dieback. Šumarstvo (Belgrade) 3:71–84 (**in Serbian**)

Kaya İ, Özdemir M, Şahin A, Yıldırım N (2023) Evaluation of silvicultural interventions in sessile oak (*Quercus petraea* (Matt.) Liebl.) stands intended to be converted into high forests according to optimal forest structure: Yıldız Mountains. Ormancılık Araştırma Dergisi 10: 26–32. https://doi.org/10.17568/ogmoad.1274574 **(in Turkish)**

Kenk G (1978) Rejuvenation and tending of valuable oak stands in Baden-Württemberg. In: Exposés, Symposium feuillus précieux, Nancy-Champenoux, 11–15 sept. 1978. INRA Documents no. 78/08: 231–250 **(in German)**

Kenk G (1984) Production of quality oak and its improvement in Baden-Württemberg. Revue Forestière Française XXXVI (no. spécial): 26–33 **(in French)**

Kenk GK (1993) New perspectives in German oak silviculture. Ann Sci for 50(6):563–570

Kerr G (1996) The effect of heavy or 'free growth'thinning on oak (*Quercus petraea* and *Q. robur*). Forestry 69(4):303–317

Kerr G, Evans J (1993) Growing broadleaves for timber. Forestry Commission Handbook 9, HMSO, London, p 95

Kerr G, Haufe J (2011) Thinning Practice. A Silvicultural Guide. Forestry Commission, version 1.0, January 2011, p 54

Keše R (2016) Comparison of selected properties of oak sapwood and heartwood. B.Sc. work, Biotehniška fakulteta, Univerza v Ljubljani, Ljubljana, p 54 **(in Slovenian)**

Kleinschmit J (1993) Intraspecific variation of growth and adaptive traits in European oak species. In: Kremer A, Savill PS, Steiner KC (eds) Genetics of oaks. Proceedings of the first meeting of the IUFRO Working Party S2.02–22. Arboretum National des Barres, France, 2–6 September 1991, Annales des Sciences Forestières, vol 50, no Suppl. 1, pp 166s–185s

Kohler M, Pyttel P, Kuehne C, Modrow T, Bauhus J (2020) On the knowns and unknowns of natural regeneration of silviculturally managed sessile oak (*Quercus petraea* (Matt.) Liebl.) forests—a literature review. Ann for Sci 77:101. https://doi.org/10.1007/s13595-020-00998-2

Konic J, Heiling C, Haeler E, Chakraborty D, Lapin K, Schueler S (2024) The potential of non-native tree species to provide major ecosystem services in Austrian forests. Front Plant Sci 15:1402601. https://doi.org/10.3389/fpls.2024.1402601

Kostov G (2018) Contemporary close-to-nature forest management methods. Project No. BG05SFOP001-2.006-0039-CO1 "Increasing the capacity of the employees of the Executive Forestry Agency to perform control functions in forest management", co-financed by the European Union through the European Social Fund. https://www.iag.bg/data/docs/TEMA_8_post_sechi.pdf (p 25) **(in Bulgarian)**

Kostov G, Alexandrov N, Kolev K (2019) Regional silvicultural systems for management of oak coppice forests in West Bulgaria. Nauka Za Gorata/For Sci 1:3–26 (**in Bulgarian**)

Krahl-Urban J (1959) The Oaks. Verlag Paul Parey, Hamburg-Berlin, p 288 **(in German)**

Krajnc N, Mihelič M, Poje A (2018) Slovenia. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 323–325

Krstić M, Smailagić J, Nikolić J (2001) Climatic characteristics of the sessile oak forests (*Quercetum montanum serbicum* Čer. et Jov.) belt in Serbia. In: Naydenova T, Raev I (eds) Proceedings of

the 3rd Balcan Scientific Conference "Study, conservation and utilisation of the forest resources", 2–6 October 2001. Bulgarian Academy of Science, Forest Research Institute, Sofia, Bulgaria, pp 67–74

Krstić M, Stojanović LJ, Petrović A (2005) Proposal of silvicultural operations in mixed forests of sessile oak and hornbeam in the region of Majdanpek. Šumarstvo (Belgrade) 3:53–69 (**in Serbian**)

Krstić M, Petrović N (2018) Serbia. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 318–320

Kubov M, Fleischer P Jr, Rozkošný J, Kurjak D, Konôpková A, Galko J, Húdoková H, Lalík M, Rell S, Pittner J, Fleischer P (2020) Drought or severe drought? Hemiparasitic yellow mistletoe (*Loranthus europaeus*) amplifies drought stress in sessile oak trees (*Quercus petraea*) by altering water status and physiological responses. Water 12:2985. https://doi.org/10.3390/w12112985

Kuehne C, Pyttel P, Modrow T, Kohnle U, Bauhus J (2020) Seedling development and regeneration success after 10 years following group selection harvesting in a sessile oak (*Quercus petraea* [Mattuschka] Liebl.) stand. Ann for Sci 77:71. https://doi.org/10.1007/s13595-020-00972-y

Kurek P, Dobrowolska D (2016) Acorns dispersal by jays *Garrulus glandarius* onto clear-cuts and under the forest canopy. Sylwan 160(6):512–518 (**in Polish**)

Kühmaier M, Hochbichler E, Stampfer K, Mills J, Buckley P (2018) Austria. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 194–198

Lafouge R (1990) Comparative silviculture of sessile oak and pedunculate oak in forests managed by Office National des Forêts. Revue Forestière Française XLII 2:269–275 (**in French**)

Lanier L (1986) Summary of silviculture. Ecole Nationale du Génie Rural, des Eaux et des Forêts, Nancy, p 468 **(in French)**

Lanier L (1994) Summary of silviculture. Ecole Nationale du Génie Rural, des Eaux et des Forêts, Nancy, p 477 **(in French)**

Lasy Państwowe (2023) Silvicultural principles. DGLP, Warszawa, p 60 **(in Polish)**

Lemaire J (2010) Oak in a different way. Producing quality oak in less than 100 years in regular high forests. IDF, Paris, p 176 **(in French)**

Leonardsson J, Löf M, Götmark F (2015) Exclosures can favour natural regeneration of oak after conservation-oriented thinning in mixed forests in Sweden: a 10-year study. For Ecol Manag 354:1–9. https://doi.org/10.1016/j.foreco.2015.07.004

Leopold LB (1953) Round river: from the journals of Aldo Leopold. Oxford University Press, New York, p 173

Lorentz B, Parade A (1883) Basic course of Silviculture, 6th edn. Octave Dion, Éditeur, Paris, p 720 **(in French)**

Lorne R (1956) In search of quality and large diameter in oak high forests. Revue Forestière Française 11:754–768 (**in French**)

Lorne R (1959) Quantitative study on thinning in quality oak stands. Revue Forestière Française 11:746–768 (**in French**)

Los SA, Tereshchenko LI, Gayda YI et al. (2014) State of forest genetic resources in Ukraine. Planeta-Print, Kharkiv, p 138 **(in Ukrainian)**

Łukaszewicz J, Gil W (2007) History and present of afforestation and reforestation by seeding. Sylwan 3:11–22 (**in Polish**)

Löf M (2024) Challenges for management of rich *Quercus* forests in Europe. In: Martens C, Clark S, Schweitzer C (eds) The international oak symposium: science-based management for dynamic oak forests. Gen. Tech. Rep. SRS-278. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, pp 9–10

Löf M, Brunet J, Filyushkina A, Lindblath M, Skovsgaard JP, Felton A (2016) Management of oak forests: striking a balance between timber production, biodiversity and cultural services. Int J Biodivers Sci 12(1–2):59–73. https://doi.org/10.1080/21513732.2015.1120780

Löf M, Castro J, Engman M, Leverkus AB, Madsen P, Reque JA, Villalobos A, Gardiner ES (2019) Tamm review: direct seeding to restore oak (*Quercus* spp.) forests and woodlands. For Ecol Manag 448:474–489. https://doi.org/10.1016/j.foreco.2019.06.032

Lupăștean D (2023) Agrilus spp. (Col., Buprestidae) and their relationship with oak decline in Romania. Bucovina Forestieră, 23(2): 169–181. https://doi.org/10.4316/bf.2023.016 **(in Romanian)**

Lyubenova A, Baranowska M, Menkis A, Davydenko K, Nowakowska J, Borowik P, Oszako T (2024) Prospects for oak cultivation in Europe under changing environmental conditions and increasing pressure from harmful organisms. Forests 15:2164. https://doi.org/10.3390/f15122164

Magagnotti N, Schweier J, Spinelli R, Tolosana E, Jyhlä P, Sopushynskyy I, Otepka P, Nestorovski P, Costa M, Rodriguez A, Rossney D, Ruch P, Tsioras P, Stampfer K, Mihelič M, Krajnc N, Mine V, Mederski P, McEwan A (2018) Coppice products. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 78–85

Mairota P, Neri F, Travaglini D, Picchio R, Terzuolo PG, Piussi P, Marchi E (2018) Italy. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 269–282

Maleki K, Zeller L, Pretzsch H (2020) Oak often needs to be promoted in mixed beech-oak stands - the structural processes behind competition and silvicultural management in mixed stands of European beech and sessile oak. iForest 13:80–88. https://doi.org/10.3832/ifor3172-013

Markoff I, Popov G, Pyttel P (2018) Bulgaria. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 209–213

Marcu O (2005) Forest Pathology. Editura Silvodel, Brașov, p 332 **(in Romanian)**

Marcu O, Simon D (1995) Forest Entomology. Editura Ceres, București, p 284 **(in Romanian)**

Margaletić J (2003) Rodent damage and protection. In: Matić S (ed) Common beech in Croatia. Academy of Forestry Sciences, Zagreb, pp 574–584

Martinot-Lagarde P (1970) Management of quality sessile oak in West Germany. Revue Forestière Française XXI I(2):115–130 (**in French**)

Martinot-Lagarde P (1973) Crop trees. ONF Bull Tech 4:23–33 (**in French**)

Matić S (1994) Contribution to the understanding of the number of plants and the quantity of seeds for effective regeneration and reforestation. Šumarski List 138(3–4):71–79 (**in Croatian**)

Matić S (2000) Oak forests (*Quercus* sp.) in Croatia. Glasnik Za Šumske Pokuse: Annales Experimentis Silvarum Culturae Provehendis 37:5–14

Matić S, Anić I, Oršanić M (2003) Silvicultural practices in beech forests. In: Matić S (ed) Common beech in Croatia, Academy of Forestry Sciences, Zagreb, pp 340–369

Matula R, Svátek M, Kůrová J, Úradníček L, Kadavý J, Kneifl M (2012) The sprouting ability of the main tree species in Central European coppices: implications for coppice restoration. Eur J for Res 131:1501–1511. https://doi.org/10.1007/s10342-012-0618-5

Mátyás C (2021) Adaptive pattern of phenotypic plasticity and inherent growth reveal the potential for assisted transfer in sessile oak (*Quercus petraea* L.). For Ecol Manag 482:118832. https://doi.org/10.1016/j.foreco.2020.118832

Mederski PS, Szczawiński D, Giefing DF, Naparty K, Brunka M (2019) Knot soundness and occlusion time after the artificial pruning of oak. Lesne Prace Badawcze/For Res Pap 80(1):5–11. https://doi.org/10.2478/frp-2019-0001

Medina M, Reyes-Martín MP, Levy L et al (2024) Ex situ germination of European acorns: data from 93 batches of 12 Quercus species. Ann for Sci 81:50. https://doi.org/10.1186/s13595-024-01267-2

Meeran K, Grabner M, Schott K, Wächter E, van Loo M, Watzinger A (2025) Tree size and site environment affects sessile oak growth and intrinsic water-use efficiency response to wet-dry years. For Ecol Manag 577:11413. https://doi.org/10.1016/j.foreco.2024.122413

Meşe Ö, Öner MN, Ayan S (2023) General evaluation of some sessile oak (*Quercus petraea* (Mattuschka) Liebl.) seed stands in Türkiye. Ormancılık Araştırma Dergisi 10:41–49. https://doi.org/10.17568/ogmoad.1278204. (**in Turkish**)

Michiels HG (2014) The sites of sessile oak. LWF Wissen 75:25–29 (**in German**)

MMAP (2022a) Good practice guide on the choice and application of silvicultural systems. In: Monitorul oficial al României anul 190 (XXXIV), nr. 994 bis, 13 octombrie 2022, pp 10–70 **(in Romanian)**

MMAP (2022b) Good practice guide on tending operations. In: Monitorul oficial al României, Anul 190 (XXXIV)—nr. 989 bis, 12 octombrie 2022, pp 5–75 **(in Romanian)**

MMAP (2022c) Good practice guide on species compositions, schemes and technologies for reforestation and afforestation of degraded lands. In: Monitorul oficial al României, Anul 190 (XXXIV)—nr. 1000 bis, 14 octombrie 2022, pp 5–382 **(in Romanian)**

MMAP (2022d) Good practice guide on forest management planning. In: Monitorul oficial al României, Anul 190 (XXXIV)—nr. 999 bis, 14 octombrie 2022, pp 21–455 **(in Romanian)**

Modrow T, Kuehne C, Saha S, Bauhus J, Pyttel PL (2020) Photosynthetic performance, height growth, and dominance of naturally regenerated sessile oak (*Quercus petraea* [Mattuschka] Liebl.) seedlings in small-scale canopy openings of varying sizes. Eur J for Res 139(1):41–52. https://doi.org/10.1007/s10342-019-01238-7

Mölder A, Nagel RV, Meyer P, Schmidt M, Rumpf H, Spellmann H (2017) Historical retrospective of 19th century oak regeneration in the Spessart Mountains (Germany)—the importance of former silvicultural techniques for today's oak management. Forstarchiv 88(3):67–78 (**in German**)

Mölder A, Sennhenn-Reulen H, Fischer C, Rumpf H, Schönfelder E, Stockmann J, Nagel RV (2019) Success factors for high-quality oak forest (*Quercus robur*, *Q. petraea*) regeneration. For Ecosyst 6:49. https://doi.org/10.1186/s40663-019-0206-y

MZe (2022) Report on the state of forests and forestry in the Czech Republic in 2021. Ministry of Agriculture, Prague, p 135 **(in Czech)**

Nacevski M, Iliev B, Nestorovski B, Bahchevandjiev K, Jakimovska Popovska V, Aziri B (2015) Wood density of autochthonous and allochthonous woody species in the Republic of Macedonia. In: Proceedings of the second international scientific conference "wood technology & product design", 2015, Ohrid, Republic of Macedonia. UKIM Faculty of Design and Technologies of Furniture and Interior, pp 191–197

Negulescu EG, Stănescu V (1964) Dendrology, silviculture and forest protection. Volume I. Editura Didactică şi Pedagogică, Bucureşti, p 500 **(in Romanian)**

Negulescu E, Săvulescu Al (1957) Dendrology. Editura Agro-Silvică de Stat, București, p 457 **(in Romanian)**

Negulescu EG, Săvulescu Al (1965) Dendrology, 2nd edn. Editura Agro-Silvică, Bucureşti, p 511 **(in Romanian)**

Nicolescu VN, Carvalho J, Hochbichler E, Bruckman VJ, Piqué M, Hernea C, Viana ŠP, Ertekin M, Đodan M, Dubravac T, Vandekerkhove K, Kofman PD, Rossney D, Unrau A (2018) Silvicultural guidelines for European Coppice forests. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 46–63

Nicolescu VN, Şimon DC, Goia AM, Goanță CB (2022) Mortality and growth in a sessile oak [*Quercus petraea* (Matt.) Liebl.]-dominated young stand managed through silvicultural operations of different types and intensities. SilvaWorld 1(1):1–15. https://doi.org/10.29329/silva.2022.462.01

Niinemets U, Valladares F (2006) Tolerance to shade, drought, and waterlogging of temperate northern hemisphere trees and shrubs. Ecol Monogr 76(4):521–547

Ningre F, Doussot R (1993) The French forest resource in sessile and pedunculate oaks. Analysis and historical explanation. Ann Sci for 50:593–606 (**in French**)

Nord-Larsen T, Østergaard MJ, Riis-Nielsen T, Thomsen IM, Bentsen NS, Jørgensen BB (2023) Forest Statistics 2022. Department of Geosciences and Natural Resource Management, University of Copenhagen, Frederiksberg C. https://static-curis.ku.dk/portal/files/376995779/Rapport_Skovstatistik_2022_web.pdf **(in Danish)**

NW-FVA (2022) High increases of damage in oak stands. Waldschutz-info 07, p 4 **(in German)**

Nyamjav B (2022) Adaptability responses to drought stress in the oak species *Quercus petraea* growing on dry sites. J for Sci 68(11):459–472. https://doi.org/10.17221/123/2022-JFS

Odabaşı T, Çalışkan A (1990) A new approach to tending operations in Turkish forestry. İstanbul Üniversitesi Orman Fakültesi Dergisi, Seri B 40(2):53–64 (**in Turkish**)

Odabaşı T, Çalışkan A, Bozkuş F (2004a) Forest tending. İstanbul Üniversitesi Orman Fakültesi Yayınları, İ.Ü. Yayın No. 4458, O.F. Yayın No. 474, İstanbul, p 191 **(in Turkish)**

Odabaşı T, Çalışkan A, Bozkuş F (2004b) Silvicultural techniques (Silviculture II)). İstanbul Üniversitesi Orman Fakültesi Yayınları, İ.Ü. Yayın No. 4459, O.F. Yayın No. 475, İstanbul, p 314 **(in Turkish)**

OGM (2005) Action plan for the conversion of coppice forests into high forests (2006–2015). Orman Genel Müdürlüğü (ogm.gov.tr). https://www.ogm.gov.tr/tr/e-kutuphanesitesi/Pages/yayinlar.aspx **(in Turkish)**

Ogris N, Hauptman T, Levanič T, Jurc D (2009) The mistletoe (*Loranthus europaeus*) affected the sessile oak on a poor site on Dularjev breg near Zidani Most. Gozdarski inštitut Slovenije, Ljubljana, p 11 **(in Slovenian)**

ONF (1991) Heritage for the future, the oaks of Bellême and Reno-Valdieu. Office National des Forêts, Paris, p 32 **(in French)**

ONF (1997) Regular oak high forest in the Centre region. Office National des Forêts, Direction Régionale Centre, Orléans, p 40 **(in French)**

Oprea AM (2022) Research on the influence of local factors on the quality and commercial value of wood in oak species from Western Romania. Abstract. PhD thesis. Universitatea de Științe Agricole și Medicină Veterinară a Banatului "Regele Mihai I al României", Timișoara, p 14 **(in Romanian)**

Orešković Z, Dokuš A, Harapin M, Jakovljević T, Maradin R (2006) Growing of seedlings of common oak (*Quercus robur* L.) and sessile-flowered oak (*Quercus petraea* (Matt.) Liebl) in different types of containers. Radovi 9:75–86 (**in Croatian**)

Oswald H (1981) Main results of the oak experimental sites of the National Forest Research Center. Revue Forestière Française

no. spécial "Sylvicultures en futaies feuillues", pp 519–528 **(in French)**

Oswald H (1982) Silviculture of oak and beech high forests in France. In: Malcolm DC, Evans J, Edwards PN (eds) Broadleaves in Britain. The Institute of Chartered Foresters, Edinburgh, pp 31–39

Oszako T (2000) Oak declines in Europe's forests—History, causes and hypothesis. In: Oszako T, Delatour C (eds) Recent Advances on Oak Health in Europe, Proceedings of the International Scientific Conference, Warsaw, Poland, 22–24 November 1999, Forest Research Institute: Warsaw, pp. 11–40.

Öztürk S (2013) Identification and diagnostic manual for Turkish oaks. Ormanve Su İşleri Bakanlığı, Orman Genel Müdürlüğü Yayınları, Ankara, p 368 **(in Turkish)**

Pardé J (1978) Silvicultural norms for sessile oak forests. Revue Forestière Française 1:11–17 **(in French)**

Pârnuţă G, Budeanu M, Stuparu E, Scărlătescu V, Chesnoiu EN, Tudoroiu M, Filat M, Nica MS, Teodosiu M, Lorenţ A, Daia M, Dinu C (2012) National catalogue of basic materials for the production of forest reproductive materials in Romania. Editura Silvică, Bucuresti, p 304 **(in Romanian)**

Pagan J (1999) Forest dendrology. Technická univerzita, Zvolen, p 379 **(in Slovak)**

Pașcovschi S, Leandru V (1958) Forest types in the Romanian People's Republic. Editura Silvică de Stat, București, p 459 **(in Romanian)**

PE National Forests (2023a) Price list for determining the prices of the main forest products. Skopje. http://www.mkdsumi.com.mk/admin/documents/cenovnik_za_utvrduvane_na_cenite_na_glavnite_sumproizvodi_na_jp_nacionalni_sumi_po_skopje.pdf **(in Macedonian)**

PE National Forests (2023b) Price list for determining the prices of the seedling material, Skopje. http://www.mkdsumi.com.mk/admin/documents/cenovnik_za_sumski_dekorativen_materijal.pdf **(in Macedonian)**

Pesendorfer MB, Bogdziewicz M, Szymkowiak J, Borowski Z, Kantorowicz W, Espelta JM et al (2020) Investigating the relationship between climate, stand age, and temporal trends in masting behavior of European forest trees. Glob Change Biol 26:1654–1667. https://doi.org/10.1111/gcb.14945

Petráš R, Mecko J, Krupová D, Pažitný A (2021) Aboveground biomass basic density of hardwoods tree species. Wood Res 65(6):1001–1011. https://doi.org/10.37763/wr.1336-4561/65.6.10011012

Petrescu L (1971) Guide for stand tending. Editura Ceres, Bucureşti, p 410 **(in Romanian)**

Petrík P, Petek-Petrík A, Lamarque LJ, Link RM, Waite P-A, Ruehr NK, Schuldt B, Maire V (2024) Linking stomatal size and density to water use efficiency and leaf carbon isotope ratio in juvenile and mature trees. Physiol Plant 176:e14619. https://doi.org/10.1111/ppl.14619

Poskin A (1926) Treatise on Silviculture. Jules Duculot, Editeur, Gembloux, Librairie Agricole de la Maison Rustique, Paris, p 439 **(in French)**

Poskin A (1949) Treatise on Silviculture. 3rd edition. Bibliothéque Agronomique Belge no. 5, Jules Duculot, Gembloux, Librairie Agricole de la Maison Rustique, Paris, p 530 **(in French)**

Puchalski T, Prusinkiewicz Z (1990) Ecological basis of forest habitat science. PWRiL, Warszawa, p 618 **(in Polish)**

Puhek A (2023) Review of oak (*Quercus* spp.) decline in Europe and Slovenia. MSc Thesis, Biotehniška fakulteta, Ljubljana, p 60 **(in Slovenian)**

Purcelean Ş, Ciumac G (1965) Research on the natural regeneration of sessile oak and pedunculate oak in the mixed oak-broadleaves forests of the Târnavelor Plateau. Ministerul Economiei Forestiere, Institutul de cercetări forestiere, Centrul de documentare forestieră, Bucureşti, p 65 **(in Romanian)**

Rabarijaona A, Ponton S, Bert D, Ducousso A, Richard B, Levillain J, Brendel O (2022) Provenance differences in water-use efficiency among sessile oak populations grown in a mesic common garden. Front for Glob Change 5:914199. https://doi.org/10.3389/ffgc.2022.914199

Radkov I (1948) Biological peculiarities of the oak understory. In: Proceedings of the Central Forest Research Institute, Zemizdat, Sofia, vol 4, pp 77–110 **(in Bulgarian)**

Radkov I, Minkov J (1963) Oak forests in Bulgaria. State Publishing House, Varna, p 261 **(in Bulgarian)**

Rameau JC, Mansion D, Dumé G (1989) French forest Flora. 1. Plains and hills. Institut pour le development forestier, Paris, ENGREF, Nancy, p 1789 **(in French)**

Rauš Đ, Trinajstić I, Vukelić J, Medvedović J (1992) Plants of Croatian forests. In: Rauš Đ (editor-in-chief) Forests of Croatia, Faculty of Forestry, Zagreb, pp 33–77 **(in Croatian)**

Repáč I, Parobeková Z, Sendecký M (2017) Reforestation in Slovakia: history, current practice and perspectives. Reforesta 3:53–88. https://doi.org/10.21750/REFOR.3.07.31

Robert C, Géneré B (2010) Valorizing oak production: demanding markets, appropriate silviculture. RDV Tech Hors-Série 5:29–35 **(in French)**

Rodríguez-Calcerrada J, Sancho-Knapik D, Martin-St Paul NK, Limousin JM, McDowell NG, Gil-Pelegrín E (2017) Drought induced oak decline—factors involved, physiological dysfunctions, and potential attenuation by forestry practices. In: Oaks physiological ecology. Exploring the functional diversity of genus *Quercus* L., Springer, New York, pp 419–451

Rozporządzenie (2004) Regulation of the Minister of Environment dated 18.02.2004 on detailed requirements to be met by forest reproductive material. Journal of Laws No. 31 **(in Polish)**

Rubțov Șt (1958) Cultivation of woody species in nurseries (forestry and decorative). Editura Agro-Silvică de Stat, București, p 447 **(in Romanian)**

Ruch P, Mills J, Buckley P (2018) France. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 243–248

Sáenz-Romero C, Lamy JB, Ducousso A, Musch B, Ehrenmann F, Delzon S, Cavers S, Chałupka W, Dağdaş S, Kehlet Hansen J, Lee SJ, Liesebach M, Rau HM, Psomas A, Schneck V, Steiner W, Zimmermann NE, Kremer A (2017) Adaptive and plastic responses of *Quercus petraea* populations to climate across Europe. Glob Change Biol 23(7):2831–2847. https://doi.org/10.1111/gcb.13576

Sáenz-Romero C, Kremer A, Nagy L, Ducousso A, Kóczán-Horváth A, Kehlet Hansen J, Mátyás C (2019) Common garden comparisons confirm inherited differences in sensitivity to climate change between forest tree species. PeerJ 7:1–28. https://doi.org/10.7717/peerj.6213

Saha S (2024) Low-density tree planting: scope of oak cluster planting to create mixed forests. In: Martens C, Clark S, Schweitzer C (eds) The international oak symposium: science-based management for dynamic oak forests. Gen. Tech. Rep. SRS-278. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, p 12

Sardin T (2008) Continental oak forests. Office National des Forêts, Fontainebleau, p 455 **(in French)**

Sardin T (2010) The guide to continental oak forests. Common points and differences with the silviculture of the Atlantic oak forests. RDV Tech Hors-Série 5:14–20 **(in French)**

Sardin T, Mothe F (2010) Economic comparison of silvicultural routes in continental sessile oak forests. RDV Tech Hors-Série 5:21–28 **(in French)**

Sarvaš M, Hoffmann J, Sušková M, Chválová K, Longauer R, Takáčová E, Tučeková A (2007) Forest reproductive material and forest cultivation I. National Forest Centre, Zvolen, p 194 **(in Slovak)**

Sarvaš M, Bruchánik R, Hoffmann J, Chválová K, Ježovič V (2010) Basic characteristics of forest trees—ecological requirements, morphology, forest seed production and nursery, management of gene bases. National Forest Centre, Zvolen, p 82 **(in Slovak)**

Savill PS (1991) The silviculture of trees used in British forestry. CAB International, Wallingford, p 143

Savill P (2013) The silviculture of trees used in British forestry, 2nd edn. CAB International, Wallingford and Boston, p 280

Savill PS, Kanowski PJ (1993) Tree improvement programs for European oaks: goals and strategies. In: Kremer A, Savill PS, Steiner KC (eds) Genetics of oaks. Proceedings of the first meeting of the IUFRO Working Party S2.02–22, Arboretum National des Barres, France, 2–6 September 1991. Annales des Sciences Forestières, vol 50, no Suppl. 1, pp 368s–383s

Schober R (1991) Thinning from above and future crop trees. Revue Forestière Française 5:385–402 (**in French**)

Schütz JPh, Badoux E (1979) Production of young oak stands in relation to the site. Mémoires, Institut fédéral de Recherches Forestières 55(1), Birmensdorf, p 176 **(in French)**

Schütz JPh (1993) High-quality oak silviculture in Switzerland: concepts of education and treatment in ecologically marginal conditions. Ann Sci for 50:553–562 (**in French**)

Schweitzer C (2024) Amazing American *Quercus* communities under threat. In: Martens C, Clark S, Schweitzer C (eds) The international oak symposium: science-based management for dynamic oak forests. Gen. Tech. Rep. SRS-278. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, pp 15–16

Sedlar I (2009) Causes of sessile oak dieback in the local unit Adlešiči. Ljubljana, Univerza v Ljubljani, Biotehniška fakulteta, Oddelek za gozdarstvo in obnovljive gozdne, p 53 **(in Slovenian)**

Sever K, Vukmirović A, Hodak L, Bogdan S, Katičić Bogdan I, Krstonošić D, Škvorc Ž (2022) Functional adaptation of natural sessile oak and common beech saplings in different habitat conditions. Šumarski List 146(7–8):293–307 (**in Croatian**)

Sevrin E (1996) The key silvicultural stages for producing quality wood. In private forests: methods adapted to stands and people. Forêt-Entreprise 112:38–39 (**in French**)

Sevrin E (1997) Sessile and pedunculate oaks. Institut pour développement forestier, Paris, p 97 **(in French)**

Skiadaresis G, Saha S, Bauhus J (2016) Oak group planting produces a higher number of future crop trees, with better spatial distribution than row planting. Forests 7:289. https://doi.org/10.3390/f7110289

Skudnik M, Grah A, Mali B et al (2021) State and changes of Slovenian forests between 2000 and 2028—results of large-scale monitoring of forests and forest ecosystems. Gozdarski inštitut Slovenije, Silva Slovenica, Ljubljana, p 88 **(in Slovenian)**

Solymos R (1993) Improvement and silviculture of oaks in Hungary. Ann Sci for 50(6):607–614

Sork VL (2024) How can oaks survive and thrive in future climates? In: Martens C, Clark S, Schweitzer C (eds) The international oak symposium: science-based management for dynamic oak forests. Gen. Tech. Rep. SRS-278. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, p 18

Spiecker H (1991) Controlling the diameter growth and the natural pruning of Sessile and Pedunculate oaks *(Quercus petraea* (Matt.) Liebl.) and *Quercus robur* L.). Schriftenreihe der Landesforstverwaltung Baden-Württemberg Band 72, Stuttgart, p 133 **(in German)**

Spiecker H (2021) Production of valuable oak wood in Europe. Ann for Res 64(1):5–12. https://doi.org/10.15287/afr.2021.2207

Stănescu V (1979) Dendrology. Editura Didactică și Pedagogică, București, p 470 **(in Romanian)**

Stănescu V, Târziu D (1973) Tending of stands. Systematic silvicultural operations. In: Negulescu EG, Stănescu V, Florescu II, Târziu D (eds) Silviculture, technical and practical backgrounds 2. Editura Ceres, Bucureşti, pp 71–163 **(in Romanian)**

Stănescu V, Șofletea N, Popescu O (1997) Woody Forest Flora of Romania. Editura Ceres, București, p 451 **(in Romanian)**

Steckel M, Moser WK, del Rio M, Pretzsch H (2020) Implications of reduced stand density on tree growth and drought susceptibility: a study of three species under varying climate. Forests 11(6):627. https://doi.org/10.3390/f11060627

Stimm B, Knoke T (2004) Jayseeds: Literature review on silvicultural and economic aspects. Forst und Holz 59:531–534 (**in German**)

Stimm K, Uhl E, Pretzsch H (2022) Chances and limitations of mixed oak regeneration under continuous canopy cover—evidence from long-term observations. Forests 13:2052. https://doi.org/10.3390/f13122052

Stocka T (1997) Factors affecting the health of oak and beech seeds. Las Polski 11(10):23 (**in Polish**)

Štochlová P, Hédl R (2018) Czech Republic. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 218–225

Streiff R, Ducousso A, Lexer C, Steinkellner H, Gloessl J, Kremer A (1999) Pollen dispersal inferred from paternity analysis in a mixed oak stand of *Quercus robur* L. and *Q. petraea* Matt. Liebl. Mol Ecol 8:831–841. https://doi.org/10.1111/mec.12766

Szymkiewicz B (2001) Sessile oak. In: Tables of volume and growth of stands of major forest tree species. PWRiL, Warszawa, pp 122–141 **(in Polish)**

Şahin A (2020) Management principles and yield of sessile oak (*Quercus petraea* (Mattuschka) Liebl.) stands in Marmara Region. Doctoral thesis, İstanbul Üniversitesi-Cerrahpaşa, Lisansüstü Eğitim Enstitüsü, İstanbul, p 384 **(in Turkish)**

Șofletea N, Curtu L (2007) Dendrology. Editura Universității "Transilvania", Brașov, p 418 **(in Romanian)**

Tilki F, Yuksek FT, Guner S (2009) The effect of undercutting on growth and morphology of 1+0 Bareroot Sessile Oak seedlings in relation to acorn size. Aust J Basic Appl Sci 3(4):3900–3905

Timbal J, Aussenac G (1996) An overview of ecology and silviculture of indigenous oaks in France. In: Dreyer E, Spiecker H (eds) Ecology and physiology of oaks in a changing environment. Selected papers from an International Symposium (Nancy, September 1994), Annales des Sciences Forestières, vol 53, no 2–3, pp 649–661

Thomas FM, Gausling T (2000) Morphological and physiological responses of oak seedlings (*Quercus petraea* and *Q. robur*) to moderate drought. Ann for Sci 57(4):325–333. https://doi.org/10.1051/forest:2000123

Thomas FM, Blank R, Hartmann G (2002) Abiotic and biotic factors and their interactions as causes of oak decline in Central Europe. Forest Pathol 32(4–5):277–307

Tkaczyk M (2023) Worldwide review of bacterial diseases of oaks (*Quercus* sp.) and their potential threat to trees in Central Europe. Forestry 96(4):425–433. https://doi.org/10.1093/forestry/cpac048

Tomescu R, Olenici N, Nețoiu C, Bălăcenoiu F, Buzatu A (2018) Invasion of the oak lace bug *Corythucha arcuata* (Say.) in Romania: a first extended reporting. Ann for Res 61(2):161–170. https://doi.org/10.15287/afr.2018.1187

Tomić Z, Lj R (2011) Survey of syntaxa of forest and shrub vegetation of Serbia. Folia Biol Geol (Ljubljana) 52(1–2):111–140

Trajkov P, Dubravac T, Tanovski V, Nestorovski LJ, Sotirovski K, Trajanov Z (2019) Coppice forest management planning and the regeneration potential of pure and mixed oak coppice forests in

North Macedonia. South-East Eur for 10(2):165–172. https://doi.org/10.15177/seefor.19-20
Trouvé R, Bontemps JD, Collet C, Seynave I, Lebourgeois F (2017) Radial growth resilience of sessile oak after drought is affected by site water status, stand density, and social status. Trees 31:517–529. https://doi.org/10.1007/s00468-016-1479-1
Ugrenović A, Potočić Z (1963) Forestry encyclopedia, 1st edn. Miroslav Krleža Lexicographical Institute, Zagreb, pp 547–557 **(in Croatian)**
Unisylva (2024a) Tending a natural regeneration of oaks. Unisylva, Limoges, Fiche technique no. 7, p 4 **(in French)**
Unisylva (2024b) Managing irregular oak stands. Unisylva, Limoges, Fiche technique no. 9, p 5 **(in French)**
URL1 (2024) https://www.ortohum.gov.tr
Úradníček L (2004) Forest Dendrology II/Angiospermae. Mendel University, Brno, p 170 **(in Czech)**
Ürgenç S (1998) Afforestation techniques. İstanbul Üniversitesi Orman FakültesiYayın No. 441/3994, İstanbul, p 600 **(in Turkish)**
Vacek S, Podrázský V, Remeš J et al (2009) Silviculture III—practical measures in silviculture. Kostelec nad Černými lesy, Lesnická práce, p 860 **(in Czech)**
Vacek S, Vacek Z, Ulbrichová I, Bulušek D, Prokůpková A, Král J, Vančura K (2019) Biodiversity dynamics of differently managed lowland forests left to spontaneous development in Central Europe. Austrian J for Sci 136(3):249–282
Vandekerkhove K, Vanbeveren SPP, Ceulemans R, Lecomte H, Marchal D, Mills J, Buckley P (2018) Belgium. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 199–206
Vavrčík H, Gryc V (2012) Analysis of the annual ring structure and wood density relations in English oak and sessile oak. Wood Res 57:573–580
von Lüpke B (2008) Effects of different harvest types on the natural regeneration of a sessile oak–European beech mixed stand. The trial "Mastlager" of the Forest Research Institute Rheinland-Palatinate in the forest district Eppenbrunn (Fischbach in former times). Forstarchiv 79:4–15 **(in German)**
Viney R, Pardé J (1960) For the quality oak folder. Revue Forestière Française 1:44–54 **(in French)**
Višnjić C, Vojniković S, Balić B (2018) Bosnia and Herzegovina. In: Unrau A, Becker G, Spinelli R, Lazdina D, Magagnotti N, Nicolescu VN, Buckley P, Bartlett D, Kofman PD (eds) Coppice forests in Europe. Albert Ludwig University, Freiburg i.Br., pp 207–208
Vlad I, Chiriţă C, Doniţă N, Petrescu L (1997) Ecosystem-based silviculture. Editura Academiei Române, Bucureşti, p 292 **(in Romanian)**
Vucelja M, Bjedov L, Margaletić J (2012) Pedunculate oak's (*Quercus robur* L.) acorn pests in clonal seed orchard Gajić. In: 56 Seminar abiljnezaštite, Glasilo biljne zaštite, Zagreb, pp 40–40 **(in Croatian)**
Vlase I (1982) Conservation of forest seeds. Editura Ceres, București, p 278 **(in Romanian)**
Weaver GT, Spiecker H (1993) Silviculture of high-quality oaks: questions and future research needs. Ann Sci for 50(6):531–534
Weinfurter P (2004) Forestry Handbook. Österreichische Bundesforte AG, Purkersdorf, p 110 **(in German)**
WCM InfoGozd (2024) Prices of forest products from private forests on the Slovenian market in February 2024. GozdarskiinštitutSlovenije. https://wcm.gozdis.si/sl/podatki/cene/podatki/2021100414342192/cene-gozdnih-lesnih-sortimentov/ **(in Slovenian)**
Worrell C, Nixon CJ (1991) Factors affecting the natural regeneration of oak in Upland Britain. Forestry Commission Occasional Paper 31, Forestry Commission, Edinburgh, p 28
Wouters Ph, Notelaers V, Balleux P (2000) Selecting the future crop trees. Silva Belgica 107 (1), Fiche no. 2 Sylviculture: I–VI **(in French)**
Yaltırık F (1984) Identification Manual for Turkish Oaks. Orman Genel Müdürlüğü Yayını, Yenilik Basımevi, İstanbul, p 64 **(in Turkish)**
Yaltırık F, Efe A (1994) Dendrology. İstanbul Üniversitesi Yayın No: 3836, Orman Fakültesi Yayın No: 431, İstanbul Üniversitesi Basımevive Film Merkezi, İstanbul, p 382 **(in Turkish)**
Zadworny M, Jagodziński AM, Łakomy P, Ufnalski K, Oleksyn J (2014) The silent shareholder in deterioration of oak growth: common planting practices affect the long-term response of oaks to periodic drought. Forest Ecol Manag 318:133–141. https://doi.org/10.1016/j.foreco.2014.01.017
Zafirov N, Kostov G (2019) Main stress factors in coppice oak forests in Western Bulgaria. Silva Balcanica 20:37–51
Zaręba R (1993) Sessile oak and its importance in current conditions. Las Polski 17:8–10 **(in Polish)**
Zarzyński P (2019) Number of natural monuments and monumental trees in Poland based on the General Directorate for Environmental Protection inventory from the years 2014–2015. Sylwan 163(3):248–257 **(in Polish)**

Web references

https://cheviot-trees.co.uk/broadleaves/61-quercus-petraea-sessile-oak.html. Accessed 02 Feb 2025
https://mbveneer.com/veneercatalogpage/spessart-oak-wood-veneer/. Accessed 12 Jan 2025
https://roifn.ro/site/rezultate-ifn-2/. Accessed 15 Nov 2024
https://srbijasume.rs/kupci/cenovnici-kupci/. Accessed 1 Apr 2024
https://talaricohardwoods.com/spessart-forest/. Accessed 03 Jan 2025
https://ur-biowooeb.cirad.fr/. Accessed 18 Nov 2024
(2023) https://www.bdl.lasy.gov.pl/portal/. Accessed 14 Aug 2024
https://www.forestresearch.gov.uk/tools-and-resources/tree-species-database/131560-sessile-oak-sok/. Accessed 11 Jan 2025
https://www.iag.bg/data/docs/nareba_18_inventarizaciq.pdf (accessed on 15.05.2024)
https://www.lieco.at/en/products/broad-leaves. Accessed 28 Jan 2025
https://www.monumentaltrees.com/en/trees/sessileoak/records. Accessed 20 Dec 2024
https://www.onf.fr/vivre-la-foret/raconte-moi-la-foret/comprendre-la-foret/explorer-la-nature-en-foret/%2B/1ca7::le-chene-sessile.html. Accessed 22 Dec 2024
https://www.planfor.co.uk/buy,oak-sessile,2045,EN. Accessed 12 Jan 2025
https://www.rjtreesandhedging.co.uk/sessile-oak-quercus-petraea-p45. Accessed 28 Jan 2025
https://www.rosilva.ro/rnp/preturi_vanzare_m_l_p_2024__p_1697.htm. Accessed 20 Jan 2025
https://www.rosilva.ro/articole/puieti_forestieri__p_132.htm. Accessed 27 Dec 2024