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REVIEW ARTICLE

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in Europe: an overview of management practices

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Abstract Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), one of the most commercially important tree species in western North America and one of the most valuable timber trees worldwide, was introduced to Europe in 1827. It became a major species for afforestation in Western Europe after WWII, currently grows in 35 countries on over 0.83 million ha and is one of the most widespread non-native tree species across the continent. A lower sensitivity to drought makes Douglas-fir a potential alternative to the more drought-sensitive Norway spruce so its importance in Europe is expected to increase in the future. It is one of the fastest growing conifer species cultivated in Europe, with the largest reported dimensions of 2.3 m in diameter and 67.5 m in height. Pure stands have high productivity (up to 20 m3 ha-1a-1) and production (over 1000 m3 ha-1). The species is generally regenerated by planting (initial stocking density from less than 1000 seedlings ha-1 to more than 4000 ha-1), using seedlings of European provenance derived from seed orchards or certified seed stands. As the range of end-uses of its wood is very wide, the rotation period of Douglas-fir is highly variable and ranges between 40 and 120 years. When the production of large-sized, knot-free timber is targeted, thinnings are always coupled with pruning up to 6 m. There is an increasing interest in growing Douglas-fir in mixtures and managing stands through

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close-to-nature silviculture, but the species' intermediate shade tolerance means that it is best managed through group selection or shelterwood systems.

Keywords Douglas-fir · Ecological requirements · Growth and yield · Timber · Climate change

Introduction

Since the arrival of black locust (*Robinia pseudoacacia* L.) in 1601, a range of non-native tree species, particularly from North America and Asia, have been introduced to Europe to increase the attractiveness of landscapes, to augment the productivity of native forests, and to improve the profitability of forest management. Currently, 145 non-native or exotic tree species can be found growing in European forests and together cover an area of 8.54 million ha, or 4.0% of the continent's forested area (Brus et al. 2019). One of these species, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is one of the most commercially important tree species in western North America and one of the most important and valuable timber species worldwide (Hermann and Lavender 1999). The native range of Douglas-fir stretches over 3400 km from south to north (latitude 19° to 55° N.), the largest latitudinal spread of any conifer of western North America. It also extends over 1600 km from east to west, covering 14.3 million hectares in the U.S.A. and 4.5 million hectares in Canada (Hermann and Lavender 1990; Fletcher and Samuel 2010). Two geographic varieties are recognised: the coastal variety or green Douglas-fir (*P. menziesii var. menziesii*), and the interior variety (*P. menziesii var. glauca* (Beissn.) Franco) also called Rocky Mountain or blue Douglas-fir.

The species was introduced to Europe by David Douglas in 1827 when the first trees were planted at Scone Palace in Perthshire, Scotland (Haralamb 1967). This was followed by introductions to many European countries, with the first plantations occurring between 1851 and 1900 (van Loo and Dobrowolska 2019a). The coastal variety of Douglas-fir has proved much better adapted to European conditions than the interior variety, having a higher growth rate, being resilient to frost and more resistant to fungal diseases (Bastien et al. 2013; Lavender and Hermann 2014; Petkova et al. 2014; Konnert 2016), so green Douglas-fir is preferred throughout the continent (Konnert and Bastien 2019). In Western Europe, Douglas-fir was widely used in afforestation programs after the Second World War, and such plantings were supported in national and regional subsidy schemes (Bastien et al. 2013; Spiecker 2019). Eighty per cent of these plantations were established in three countries: France (half of all European plantings), Germany and the UK (da Ronch et al. 2016). In France, the area of Douglas-fir was ca. 4000 ha in 1937 (Haralamb 1967), 220,000 ha in 1984 (Bouchon 1984, in Hermann and Lavender 1999), 330,000 ha in 1993 (Bastien 1998) and 411,000 ± 31,000 ha today (https://inventaire-forestier.ign.fr). In Germany, Douglas-fir covered ca. 90,000 ha in the mid-1980's (Braun and Weissleder 1986, in Hermann and Lavender 1999), increasing to 134,000 ha in mid-1990s and 217 600 ha at present (BMEL 2014). Currently, Douglas-fir is grown in 35 European countries and covers over 0.83 million ha, being the second most widespread non-native conifer species in Europe after Sitka spruce (*Picea sitchensis* (Bong.) Carr) (van Loo and Dobrowolska 2019b). In the southern hemisphere, Douglas-fir has been planted in New Zealand (112,000 ha-the second most important introduced tree species in the country-Dungey et al. 2010), Chile (15,000 ha-Bastien et al. 2013), and in Argentina (7500 ha-Bastien et al. 2013).

Currently there is no comprehensive summary of the silviculture and management of Douglas-fir in Europe that can be used to indicate its future role in different countries. Our paper provides a short overview of key factors influencing the management of Douglas-fir and 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, since effects upon wider ecosystem services have been examined by others (e.g., Wohlgemuth et al. 2019, 2021; Thomas et al. 2022).

Douglas-fir characteristics influencing management

Site and climate

European experience indicates that Douglas-fir can grow on a range of soil types apart from heavy soils with pseudogley close to the surface, on dry or heavily waterlogged soils where rooting is restricted, leading to instability, and on calcareous soils. It grows best on deep, well-aerated, moderately acidic (pH 5 – 6), free draining soils of loamy-sand or sandy-loam texture which allow good root development (Rameau et al. 1989; Riou-Nivert 1996; Horgan et al. 2003; Perić et al. 2011; Spellmann et al. 2015; Novák et al. 2018; Eckhart et al. 2019; Savill 2019; Čater 2021).

In continental Europe, Douglas-fir grows best at low to middle altitudes (between 300 and 900 m asl) in oak-dominated and European beech-dominated zones. However, it also grows at lower (200 m asl) and higher elevations (up to 1300 m asl in Slovakia and 1600 m asl in France; Coopérative Forestière Bois Limousin 2016), but with lower yields. The best climatic conditions for growing Douglas-fir in

Europe are in moderate to moist temperate climates, with mean annual temperatures of 7 – 8 ºC (Czech Republic: Mondek and Balaš 2019), 7 – 9 ºC (Romania: Stănescu et al. 1997), 8 – 11 ºC (France: Coopérative Forestière Bois Limousin 2016), 9 – 11 ºC (Slovenia: Čater 2021; Smolnikar et al. 2021). The most important limiting factor for successful cultivation of the species in Europe is the minimum mean annual precipitation, with a critical lower threshold between 600 mm (Czech Republic: Mondek and Balaš 2019; Romania: Haralamb 1967; Slovakia: Slávik pers.comm.) and 750 mm (France: de Champs and Demarq 1996; Bastien 1998). A second limiting factor is the minimum annual precipitation during the growing season, defined as 350 mm (Germany: Spellmann et al. 2015) or 450 mm (Romania: Marcu and Liubimirescu 1979).

An important characteristic of Douglas-fir, in the context of expected climate changes, is a greater tolerance of summer drought than other species on a wide variety of sites and in different climatic conditions (Wohlgemuth et al. 2021), especially in areas with at least 700 mm precipitation and on soils with good water reserves (CRPF 1999; Nicolescu 2019). In western (Germany, Switzerland, Belgium), central (Czech Republic) and eastern (Romania) parts of Europe, Douglas-fir has proved less sensitive to drought than Norway spruce (*Picea abies* (L.) Karst), European silver fir (*Abies alba* Mill.), Scots pine (*Pinus sylvestris* L.), larch (*Larix* spp.), oaks (*Quercus* spp.), European beech (*Fagus sylvatica* L.) (Eilmann and Rigling 2010, 2012; Manise and Vincke 2014; Nicolescu 2019; Spiecker 2019). Thus, coastal Douglas-fir could be a replacement for Norway spruce, providing high productivity and resilience to climate change (Chakraborty et al. 2019; Covre Foltran et al. 2020; Frei et al. 2022). However, Douglas-fir stands in Europe have suffered reduced growth and dieback during extreme drought conditions, especially at lower elevations (Bastien 2019). Thus, new growing areas may be at medium and high altitudes (Schüler and Chakraborty 2021), with optimum sites possibly moving to higher altitudes (over 1000 m asl) (Wohlgemuth et al. 2021). Similar concerns are reported from its native range where water deficit-related stress is predicted to increase in the western United States and consequently Douglas-fir growth will decrease (Restaino et al. 2016).

Growth performance in Europe

Douglas-fir grows to substantial heights, for instance in parts of its native range (e.g., Oregon, USA), a number of trees > 90 m height have been recorded (Sillett et al. 2018). In Europe, although most Douglas-firs are young compared to long-lived specimens in the native range (> 1000 years; Cline et al. 1980; in Weiskittel et al. 2012), impressive heights and diameters have been attained (Table 1).

Mean annual volume increment in even-aged stands in Europe peaks at between 50 and 80 years and diminishes gradually afterwards (Schütz et al. 2015). Increments recorded in different countries range from 10 to 20 $m^3\ ha^{-1}a^{-1}$ (e.g., 14.8 in France, 18.9 in Germany; Kohnle et al. 2019), with still higher increments reported (Thomas et al. 2022). These values are significantly higher compared to European native forest species.The average annual increment of Douglas-fir exceeds that of other conifers by 76% and 47% in France and Germany respectively. In its native range, coastal Douglas-fir produces over 13 $m^3\ ha^{-1}a^{-1}$ on average (Talbert and Marshall 2005), while in New Zealand, the average annual volume increment reaches 16 $m^3\ ha^{-1}a^{-1}$ (http://www.nzffa.org.nz). These growth rates lead to high

Table 1 Maximum heights and diameters of Douglas-fir in different European countries

Height, m	Diameter (cm)	Country	Source	Observations
30		Serbia	Ratknić (1995)	50 years old
40	100	Hungary	Rédei pers.comm	
43.1	38.4	Italy	Scotti (2016)	50 years old
44	80	Ukraine	Lavnyy pers.comm	
51	102	Bulgaria	Petkova et al. (2017)	100 years old
49.7		The Netherlands	http://www.bomeninfo.nl/tall%20trees.htm	National record
57.9		Austria	Jasser (2008)	103 years old, national record
64	80	Czech Republic	Podrázský pers.comm	148 years old; tallest tree in the country
Over 66.5	> 160	Germany	https://ddg-web.de/rekordbaeume.html?VCardId=6735	
67	118	France	Angelier (2007)	124 years old; tallest tree in the country
67.0	150	Slovenia	Hostnik (2021)	
67.5	111	UK	https://www.treeregister.org/champion	Wales, planted in 1921
38.5	233	UK	https://www.treeregister.org/champion	Scotland, planted in 1846

standing volumes that can reach 1000 m^3 ha^{-1} or more at 80 years of age (Table 2).

Timber: quality, uses, prices

Douglas-fir timber is better quality than that of Norway spruce and European silver fir and similar to European larch (Larix decidua L.) (Stănescu 1979; Zeidler et al. 2022). It is moderately hard, stiff, moderately stable, fast to normal drying, resistant to fungi and insect attacks and moderately resistant to rot (Riou-Nivert 1989, 1996; de Champs and Demarq 1996; Molnár 2008; Bastien et al. 2013; Pollet et al. 2013; France Bois Forêt 2016; Kahl et al. 2017; Podrázský et al. 2019). The timber is difficult to impregnate with preservatives, insecticides and fungicides (Liese et al. 1982; Suzuki et al. 1995).

In Europe, the average density of Douglas-fir ranges between 360 kg m^{-3} and 583 kg m^{-3} at 12% moisture content (Table 3). In its native range, it is 480 kg m^{-3} (Interior North: Alden 1997) and 500 kg m^{-3} (Interior West: Alden 1997) with higher densities in coastal areas (540 kg m^{-3}) (Remeš and Zeidler 2014).

The maximum ring width for Douglas-fir timber to be considered the best grade /highest strength class ranges from 4 mm (Poland, The Netherlands) and 6 mm (Austria, Belgium, France, Germany, Great Britain), or even 8 mm in special circumstances (France) (Henin et al. 2019). High growth rates in this species do not appear to result in a reduction in density and associated wood properties (Pollet et al. 2017). Therefore, timber from trees grown at wide spacing in plantations should not be rejected for general use (Melin and Riou-Nivert 1985; in Pollet et al. 2017). However, for structural uses, a ring width of 5 mm to guarantee the best

Table 2 Maximum standing volumes of Douglas-fir stands in different European countries

Total standing volume (m3 ha-1)	Country	Source	Observations
600 – 800	Europe-wide	Bastien et al. (2013)	40 years of age; production depending on site potential
603	Slovenia	Smolnikar et al. (2021)	46 years old
606	Bosnia and Herzegovina	Ibrahimspahić et al. (2006)	46 years old, mean dbh 29.9 cm, mean height 24.1 m
670	Romania	Negulescu and Săvulescu (1957, 1965)	40 years old; Norway spruce standing volume at the same age 310 m3 ha-1
678	Croatia	Klepac (1962)	70 years old, mean dbh 43.5 cm
700 – 750	Italy	La Marca et al. (2016)	45 years old
868	Hungary	Redei pers.comm	50 years old, mean dbh 38.5 cm, mean height 32.2 m
988	Bulgaria	Popov (1991)	80 years old, mean dbh 46 cm, mean height 33 m
1153	Slovenia	Čokl (1965)	62 years old
1166	Bulgaria	Popov (2006, 2009)	82 years old, mean dbh 43 cm, mean height 38 m
1233	Bulgaria	Popov (2006)	71 years old, mean height 33 m

Table 3 Average Douglas-fir density reported in European studies

Average density, kg m-3	Country	Source
360 – 480	Ireland, Scotland	Gil-Moreno et al. (2019)
425	Slovenia	Možina (1960)
440 – 513	Bulgaria	Bluskova (2006)
440–600	Italy	La Porta pers.comm
488	Czech Republic	Remeš and Zeidler (2014)
500	Belgium, France, Germany, Great Britain, Italy, Poland	Henin et al. (2019)
	Slovakia	(Ťavoda 2007; Petráš and Mecko 2008)
	France	France Bois Forêt (2016)
533 – 575	Czech Republic	(Giagli et al. 2019; Podrázský et al. 2019; Zeidler et al. 2022)
540	France	http://www.frenchtimber.com/en/french-species/douglas-fir/
570	The Netherlands	Polman and Militz (1996)
583	Serbia	Šoškić et al. (2007)

mechanical properties should not be exceeded (Nepveu and Blachon 1989; in Pollet et al. 2017). Users of Douglas-fir require ring wood regularity, an aspect of equal importance to average ring width, as irregular ring wood is more prone to distortion (Henin et al. 2019).

Because of its excellent mechanical properties, combined with a relatively low density and dimensional stability, Douglas-fir is particularly well-suited to structural applications such as timber frames, floor and roof trusses, glue-laminated beams, and flooring. As a result, in Western Europe, the price of Douglas-fir timber is on average 25% higher than Norway spruce (Pulkrab et al. 2014). For example, in France in 2020, the average price of Douglas-fir timber (1.0 m^3 standing volume) was 61 € m^{-3} compared with 36 € m^{-3} for Norway spruce of the same volume (https://www.forestiere-cdc.fr/sites/default/files/2021-06/prix-de-vente-des-bois-sur-pied-en-foret-privee-indicateur-2021_0.pdf). Similarly, in Belgium in 2021 – 2022, the price for timber 50 cm diameter was 90 – 110 € m^{-3} for Douglas-fir compared to 60–80 € m^{-3} for Norway spruce (www.experts-forestiers.be/Tableauprixbois.pdf). Prices for Douglas-fir logs for veneer often exceed 110 € m^{-3} and can reach as high as 180 and 250 € m^{-3} (Germany-https://www.forstpraxis.de/douglasie-schwarzwald-rekordmenge-rekorderloes/; https://www.landesforsten.de/wp-content/uploads/2021/03/ergebnisse_submission_nadelholz_2021.pdf) while a record 527 €m^{-3} was registered in Slovenia in 2021 (Gozd in gozdarstvo 2021).

With the attributes of good growth, desirable wood properties, and resistance to drought, Douglas-fir is attractive for the forest industry in many European countries (Spiecker 2019; Covre Foltran et al. 2020; Forest Europe 2020; Frei et al. 2022).

Root system

Douglas-fir is a deep-rooting species, with a tap root down to 1.5 m or to 3.2 m (Köstler et al. 1968; in Thomas et al. 2022) in favourable soils. In such soils, Douglas-fir develops a tap root that grows rapidly to about 50% of its final length in 3 to 5 years, and to 90% in 6 to 8 years (Hermann and Lavender 1990). Main lateral roots develop during the first or second growing season as branches of the tap root grow obliquely into deeper soil layers and provide anchorage (Hermann and Lavender 1990; Mauer and Palátová 2012). On well draining soils, Douglas-fir has better anchorage than spruce (Nicoll et al. 2006) and is less vulnerable to wind (Paşcovschi and Purcelean 1954; de Champs 1988; Mauer and Palátová 2012). However, when grown on shallow or poorly drained soils, plate-like root systems develop. Under such conditions, the species is prone to windthrow (Haralamb 1967; Hermann and Lavender 1990; Hart 1994; Sychra and Mauer 2013; Savill 2019) and more prone than European silver fir but perhaps less than Norway spruce (Haralamb 1967). Therefore, on exposed sites, the planting of Douglas-fir should be avoided as the trees can be uprooted or become badly deformed (Wouters and Lorent 2002; Savill 2019).

Shade tolerance

In its natural range, except in youth when it is reasonably shade tolerant, coastal Douglas-fir is intermediate in shade tolerance (Herman and Lavender 1990) or shade intolerant compared to associate species (Larson 2010). This characteristic is affected by site quality, with decreasing tolerance with increasing soil moisture (Carter and Klinka 1992). European studies generally consider the species as having 'intermediate' tolerance (Niinemets and Valladares 2006) with recruitment being more light-demanding than European silver fir and Norway spruce (Schütz et al. 2015), while mature trees are more shade tolerant than sessile oak (*Quercus petraea* (Matt.) Liebl.), pedunculate oak (*Quercus robur* L.) and Scots pine (Thomas et al. 2022). Seedlings require a minimum of 15% (Mason et al. 2004) or 20 to 40% open sky light intensity for establishment and growth (Mailly and Kimmins 1997; Drever and Lertzman 2003; Herrington 2006; all in Frei et al. 2022). Thus, Douglas-fir is sufficiently shade-tolerant to be planted beneath well-thinned canopies; underplanting is likely to be more successful under a sparse canopy (Stokes et al. 2021).

Regeneration ecology

Douglas-fir trees start to produce seed cones at 30 – 35 years (Şofletea and Curtu 2007; Savill 2019), with the best production occurring from 50 – 60 years. Mast years occur every 2 – 3 years (Romania: Stănescu 1979), 4 – 6 years (UK: Savill 2019), 7 years (Germany: Spellmann et al. 2015) or irregularly (one heavy and one medium crop every 7 years in Ireland; COFORD 2020). Seed production is often higher in years following a dry summer (Van Vredenburch and La Bastide 1968). The seeds are dispersed by wind for distances of 25 – 30 m (Bulgaria, Milenkova 2020) up to 50 to 100 m (Czech Republic: Podrázský pers. comm; France: Boussaid 2008; Germany: Stimm 2004; Lange et al. 2022) or even 100 – 150 m (Switzerland: Wohlgemuth et al. 2019). Consequently, in stands with a high proportion of Douglas-fir, natural regeneration is common e.g., Britain (Jones 1945), Romania (Dumitriu-Tătăranu 1960; Negulescu and Săvulescu 1957), Belgium (Boudru 1989), France (Riou-Nivert 1996; Bastien 1998; CRPF 1999), Czech Republic (Sychra and Mauer 2013), Bulgaria (Popov et al. 2018; Milenkova 2020), Slovakia (Slávik pers. com.), Italy (La Marca and Pozzi 2016). Successful seed germination can be limited by vegetation competition (Malcolm et al. 2001) and favoured by improved light conditions from either silvicultural treatments reducing canopy cover (La Marca and Pozzi 2016), windthrow creating large gaps in the stand (Raida 2018) or the sparse cover of light-demanding species such as Scots pine, silver birch (*Betula pendula* L.) or European larch (Bindewald et al. 2021).

The abundant natural regeneration of Douglas-fir has caused debate about the invasive potential of the species, although recent reports have considered that it is not invasive in Europe (Brus et al. 2019). This categorization was supported by Eberhard and Hasenauer (2018), Bindewald et al. (2021) and Lange et al. (2022) based on the natural spread of the species being site-limited and easy to manage (e.g., Essl 2005; Ammer et al. 2016; Raida 2018; Wohlgemuth et al. 2019). However, in certain countries (e.g., Germany) there continues to be contrasting opinions about the species invasiveness (Thomas et al. 2022).

Douglas-fir vulnerabilities to abiotic and biotic disturbances

As noted, Douglas-fir can be vulnerable to windthrow, especially if grown on soils that result in shallow rooting. In Germany, the species is considered as prone to windthrow as Norway spruce (Albrecht et al. 2010, 2013), attributed to the heavy weight of the large crowns (Boudru 1989; Hart 1994). Dense crowns also favour snow retention (Dobrev 1962), resulting in stem breakage as a result of heavy loading (Govedar et al. 2003). In Denmark, field studies indicated that Douglas-fir was less susceptible to windthrow than Norway spruce (Decker 2018), in line with the results of the tree pulling experiments conducted in Britain between 1960 and 2000 (Nicoll et al. 2006). Wind risk models now available can be used to predict the vulnerability of even-aged Douglas-fir stands, as well as other conifer species (Hale et al. 2015).

Douglas-fir can be damaged by very low winter temperatures as well as early autumn and late spring frosts (Bosnia and Herzegovina: Pintarić 1990; Croatia: Vidaković and Franjić 2004; Czech Republic: Novák et al. 2018; Ireland: Horgan et al. 2003; COFORD 2020; Romania: Drăcea 1923; Pașcovschi and Purcelean 1954; Ionuț 1956; Sweden: Malmqvist 2017), especially on low-lying sites with poor air drainage (Ireland: Horgan et al. 2003; UK: MacDonald et al. 1957; in Savill 2019). Fire is an important disturbance affecting the dynamics of stands in its native range where moderate severe fires allow thicker bark Douglas-fir to survive and regenerate at the expense of thin bark species of lower fire resistance (Hermann and Lavender 1990; Sillett et al. 2018).

Douglas-fir is currently less threatened by pests and pathogens in Europe than are the indigenous Norway spruce and Scots pine (Spellmann et al. 2015). Fungal pathogens *Phaeocryptopus (Adelopus) gaeumannii* Petr. (Swiss needle cast) and *Rhabdocline pseudotsugae* Sidow (Rhabdocline needle cast) can cause yellowing of foliage, reduction in growth, and eventual drop of needles (Georgieva 2009; Podrázský et al. 2019; Roques et al. 2019; Horgan et al. 2003, in COFORD 2020). Douglas-fir may also show root rot caused by *Heterobasidion* spp, the damage being mostly associated with *H. annosums* (Fr.) Bref (Roques et al. 2019). However, it is less susceptible to this fungus than many other conifers (COFORD 2020). Important insect pests of Douglas-fir are the vapourer moth (*Orgyia antiqua* L.), which severly defoliated Douglas-fir stands in Poland in the mid-1970s, and the nun moth (*Lymantria monacha* L.), with local outbreaks in the 1980s and 1990s, especially in central France. The large pine weevil (*Hylobius abietis* L.) can cause severe damage in young plantations (Spellmann et al. 2015; Roques et al. 2018; Wallertz et al. 2014; in COFORD 2020). Roques et al. (2018) noted that `compared to other exotic conifers introduced to Europe, Douglas-fir is still relatively free of biotic damage because its phylogenetic distance to native tree species is preventing rapid switches of most native plants. However, climate change and the worldwide movement of plants for planting is likely to accelerate the arrival of pests from the native range`.

In both its natural range and in Europe, Douglas-fir is widely considered prone to game damages (browsing, fraying, especially by roe deer, red deer and wild boar), affecting the young, smooth, soft bark, resin-rich, up to $1-2$ m height (Rădulescu and Cazacu 1968; Hermann and Lavender 1990; Riou-Nivert 1996; Spellmann et al. 2015; Podrázský et al. 2019; Savill 2019) (Fig. 1).

When bowsing pressure is high, fencing plantations is necessary, as recommended in Bulgaria, Czech Republic, Hungary, Romania, Slovakia, Slovenia, and the UK. The application of chemical repellents (e.g., TRICO) can be effective against hares, and red, roe, fallow and sika deer and is recommended in some countries (Czech Republic: Podrázský pers.comm.; France: CRPF 1999; Slovenia: Brus pers.comm.). Individual protection by treeshelters is not advised other than for small gaps (< 0.2 ha), as they are expensive and can produce slender plants with limited root growth, leading to bent stems after storms or breakage under wet snow (Petersen 2016).

Management of Douglas-fir

Even-aged stands

In Europe, Douglas-fir is generally established by using seedlings from a range of sources: these include certified seed stands (over 2200 stands covering about 4800 ha in the EU) and seed orchards (69 orchards, with 390 ha) as well as seed imports from its natural range (Konnert and

Fig. 1 Wild boar damage on Douglas-fir (photo T. Vor)

Bastien 2019). All Douglas-fir provenances recommended for Europe are of the coastal variety and originate from the part of its native range between 40º and 50º N latitude, west of the Cascade Range and below 600 m altitude, e.g., northern Oregon and western Washington states in the USA as well as the Vancouver region in British Columbia, Canada (Isaac-Renton et al. 2014; Chakraborty et al. 2015; Konnert and Bastien 2019).

Plant production, spacing and early establishment

Planting stock of Douglas-fir is produced in bare-root and containerized nurseries in Europe and in its native range (Aldhous and Mason 1994). Production begins with seed pre-treatment involving stratification by chilling for three or more weeks at 3 – 5 ºC and sowing either in October – November (Marcu and Liubimirescu 1979) or in late March (Podrázský et al. 2019; Savill 2019). Bare-root seedlings are generally produced as 2 – 3 year-old stock around 30 – 60 cm height and a minimum root collar diameter of 5 mm with a fibrous rooting system; undercutting is recommended to stimulate root production and improve root:shoot balance (Marcu and Liubimirescu 1979; Boudru 1992; Aldhous and Mason 1994; de Champs and Demarq 1996; CRPF 1999; Anonymous 1999; Horgan et al. 2003). Containerised seedlings are normally grown on a 12–24-month cycle, with watering and shading regimes in greenhouses often adjusted to try and improve quality (Curtis et al. 2007; Turner and Mitchell 2003; Talbert and Marshall 2005).

Douglas-fir is mostly planted in spring (Austria and Germany: Eberhard et al. 2021; Czech Republic: Podrázský et al. 2019; Ireland: Horgan et al. 2003; Romania: Ionescu 1963, Marcu and Liubimirescu 1979; Sweden: Malmqvist et al. 2017). Survival rates of 70% – 80% or more can be obtained under good conditions, although failure rates tend to be higher than with some other conifers (Kohnle et al. 2019). Investigations of physiological factors causing post-planting failures revealed that Douglas-fir seedlings were more sensitive to root desiccation and stresses caused by rough handling than many other conifer species (McKay and Milner 2000). Cold storage is used in some regions to extend planting seasons (Aldhous and Mason 1994; O'Reilly et al. 1999). Autumn planting is not recommended as Douglas-fir seedlings are often damaged by game species (red deer, roe deer) (Marcu and Liubimirescu 1979).

The initial stand density used in Douglas-fir plantations will affect the long-term stabilityof the trees as well as stand productivity and timber quality (Klädtke et al. 2012; Kohnle et al. 2021; both in Eberhard et al. 2021). A lower initial stand density improves tree stability and promotes social differentiation (several authors, in Eberhard et al. 2021). Historically, the initial density recommended for Douglas-fir plantations was high, but this was reduced sharply from the mid-20th century onwards (i.e., in France from 2500 to 3000 plants ha^{-1} in 1950 – 1955 to 1100 – 1300 plants ha^{-1} at the end of 1980's; Lanier 1986; de Champs 1988; Riou-Nivert 1989; Giraud and Champaux 1997; Bastien 1998). Currently, the initial stand density of Douglas-fir plantations in Europe ranges from 600 plants ha^{-1} to over 4000 plants ha^{-1} with most countries using somewhere between 1000 and 2000 stems ha^{-1} (Table 4).

The initial densities of Douglas-fir plantations in Europe are similar to those in its native range (750 – 1500 plants ha^{-1}-Cafferata 1986, in Hermann and Lavender 1990; 1100 plants ha^{-1}-Talbert and Marshall 2005) and in New Zealand (1250 – 1650 plants ha^{-1}-http://www.nzffa.org.nz).

Planting in pits is recommended as being the most suitable for all planting stock, preventing the root system from deformation (Ionescu 1963; Mauer and Houšková 2014, in Podrázský et al. 2019). Alternatively, soil cultivation has improveds urvival and early growth, particularly in more northern countries where cold soil temperatures may limit new root growth (Sharpe et al. 1990; Wallertz and Malmqvist 2013). Early growth and rate of establishment is enhanced when competition from herbaceous and woody weeds is controlled (Rose and Rosner 2005).

Table 4 Initial density and spacing recommended for Douglas-fir plantations in a range of European countries

Initial density (plants ha-1)	Initial spacing (m)	Country	Observations	Source
600 – 800	4×4, 3×4	Belgium		Wouters and Lorent (2002)
600 – 800 (1000)	5×2.5, 4×4, 4×2.5	France	Adapted to small estates or dynamic forest owners	Riou-Nivert (2020)
1000 – 1200		France	Dynamic silviculture, with only one intervention before mean height of 12 m	Riou-Nivert (2020)
1000 – 1500		Italy	Only one thinning until rotation age	La Porta pers.comm
1000 – 2000		1. Europe-wide	1. Offer optimal balance between quality, stability, total volume growth and diameter growth rate	1. Kohnle et al. (2019)
		2. Germany	2. To avoid growth rings wider than 8 mm	2. Kohnle (2008)
		3. Germany		3. Klädtke et al. (2012)
1100 – 2500	2×2, 3×3	Serbia		Jovanović and Stojanović (1982)
1200 – 1500		France	First intervention when mean height reaches 16 m	Riou-Nivert (2020)
1500 – 2000		Austria	Sawtimber and veneer production	Schönauer (2008)
Max. 1600		Germany		Knook and Hanewinkel (2019)
1700 – 2500	2×2, 2.5×2, 3×2	Hungary		Rédei pers.comm
1700 – 3500	2.0 – 3.0×1.5 – 2.0	Bulgaria		Petkova pers.comm
2000 – 2500		Belgium		Perin et al. (2014)
		Italy	Two thinning until rotation age	La Porta pers.comm
2500	2×2	1. Romania	Fill the gaps of natural regenerations	1. MAPPM (2000a)
		2. Ireland		2. Horgan et al. (2003)
		3. United Kingdom		3. Mason pers.comm
3000		Czech Republic		Podrázský et al. (2019)
4400	1.5×1.5	Romania	Plantations 50% Douglas-fir 50% broadleaves	MAPPM (2000a)

Young stand management

In many countries where the initial stand density is often no more than 2000 plants ha^{-1}, management of young stands does not generally involve cleaning or respacing. However, these measures become necessary when pioneer, light-demanding and fast-growing species such as silver birch, trembling aspen (*Populus tremula* L.), and goat willow (*Salix capraea* L.) become naturally established and compete with young Douglas-fir trees (Liubimirescu 1973). In very dense natural regenerations of European beech (together with hornbeam *Carpinus betulus* L., sessile oak *Quercus petraea* (Matt.) Liebl., small-leaved lime *Tilia cordata* Mill.) where Douglas-fir is planted to fill-in gaps, there is a need to protect and promote the conifer as it grows slowly in the first 4 – 5 years and can be suppressed by native species (Liubimirescu 1973; Marcu and Liubimirescu 1979; Eberhard and Hasenauer 2018; Kohnle et al. 2019). Consequently, woody weeds should be removed from around Douglas-fir seedlings in the first 2 – 3 years (Rose and Rosner 2005), especially on rich soil, followed by the first cleaning when height is about 2 m and ca. 2000 trees ha^{-1} remain. This intervention is followed by a respacing when the average height is 5 – 7 m, and ca. 1000 trees ha^{-1} remain (Podrázský et al. 2019). In mixed stands, Douglas-fir should be at least 20% – 30% (Podrázský et al. 2019) of the remaining trees with undesirable species such as hornbeam or poorly formed Douglas-fir trees removed (Liubimirescu 1973).

In denser stands, such as in the Czech Republic and Romania, where the species is mixed with Norway spruce or European beech, the first intervention is carried out when the average height is 4 – 5 m and the density has been reduced to 2000 plants ha^{-1}, of which Douglas-fir is 20% – 30%.The second respacing follows when average height reaches 10 m and the density is reduced to ca. 1500 trees ha^{-1} (Podrázský et al. 2019). If a necessary cleaning or respacing is delayed, the trees can be slender and prone to toppling after release due to poorly developed crowns and roots (Eberhard et al. 2021).

Thinning and pruning

Thinning should start early, ideally before 20 years of age (de Champs and Demarq 1996; Riou-Nivert 1996, 2020;

Kohnle 2008). Delayed early thinning can result in stand instability and make Douglas-fir susceptible to windthrow (Wilson and Baker 2001). The first thinning should be heavy, removing 20% – 25% of trees (Romania: Liubimirescu 1973) up to 30% – 35% (France: CRPF 1999) to fully utilize the growth potential of the species. During subsequent stand development, 3 – 5 thinnings may be carried out depending on the rotation length (CRPF 1999); the thinning cycle varies: from 5 years (Belgium: Wouters and Lorent 2002; Romania: Liubimirescu 1973), up to 10 years (Serbia: Andrašev pers.comm.). The volume removed per thinning may be as high as 60 m^3 ha^{-1} or even higher in dense stands (Germany: Vor pers.comm.).

A range of thinning regimes have been proposed for Douglas-fir stands but most involve an initial line thinning to allow machine access (CRPF 1999; Horgan et al. 2003) followed by a mixture of selective thinning types. While thinning from below or intermediate (both from above and from below) was frequently practiced in the past (e.g., Czech Republic: Podrázský pers.comm; Romania: Liubimirescu 1973), recent decades have seen increased use of thinning from above in several countries, including Germany (Weise et al. 2001; Kohnle 2008; Kohnle et al. 2019). In some countries, before the second thinning when the mean diameter is about 15 cm, the (potential) final crop trees to be favoured during subsequent operations are selected and permanently marked. The criteria for selection are vigour, stem quality and spacing (Klädtke and Abetz 2010, in Kohnle et al. 2019). The final number of crop trees will vary with the intensity of silviculture being used, thus in Belgium it is around 150 – 200 trees ha^{-1} in traditional silviculture, increasing to 250 – 300 trees ha^{-1} with more intensive management (Wouters and Lorent 2002). It will also decrease as the target diameter increases (Kohnle et al. 2019).

In the last two decades, several regimes for even-aged Douglas-fir silviculture have been proposed which vary according to the initial stand density, the frequency of thinning, the incidence of pruning, and the target wood products. For example, in France, a range of options has been devised for private Douglas-fir forests (Riou-Nivert 2020). Thus, when an initial low density (600 – 800 plants ha^{-1}) is used, the objective is to produce large diameter stems (200 trees ha^{-1} over 50 cm dbh) in 50 – 60 years with the wood destined for carpentry and timber frames. This regime involves 3 – 4 thinnings, starting when the mean height is 16 – 18 m and includes pruning up to 6 m. At the other extreme is the high-density option with an initial density of 1500 – 1600 trees ha^{-1} aiming for 40 – 45 cm dbh trees with fine branches and narrow growth rings in 40 – 45 years. This includes only 1 – 2 thinnings and no pruning with the first thinning taking place when mean height is ca. 20 m.

Branching and consequent knot abundance and size are very important features affecting the grading of roundwood, veneer and timber (Drewett 2015; Henin et al. 2019). There is consensus that self pruning of Douglas-fir is slow, even in dense stands (Fig. 2) (e.g., Hermann and Lavender 1990; Hubert and Courraud 1998; Lowell et al. 2014; Drewett 2015; Savill 2019), so unpruned Douglas-fir can be very knotty (Haralamb 1967; Savill 2019; Smolnikar et al. 2021).

Therefore, pruning is widely regarded as essential to increase log quality when targeting the production of highly valuable wood products, e.g., France (Hubert and Courraud 1998), Germany (Kohnle et al. 2019, 2021), the Czech Republic (Novák et al. 2018; Mondek and Balaš 2019) and Switzerland (Schütz et al. 2015). The selling price for well-pruned logs could easily be 80 euros more per m^3 than for unpruned logs (Schütz et al. 2015). If the number of branches is affected by provenance choice (Fletcher and Samuel 2010), the diameter of branches depends on stand density (Drewett 2015; Smolnikar et al. 2021). As noted by Hein et al. (2008), even at densities exceeding 1200 trees ha^{-1}, artificial pruning may be necessary to produce high quality logs.

The main characteristics of successful pruning operations include only pruning the final crop trees where the production of high quality wood assortments is the goal (Marcu and Liubimirescu 1979). Depending on the country and

Fig. 2 Slow natural pruning of 50-year-old Douglas-fir in Slovenia (photo R. Brus)

silvicultural regime used, the final number of crop trees to prune per hectare is variable: i.e., in France from 100 trees (pruning height up to 8 – 10 m) to 200 – 400 trees (up to 6 m) (Hubert and Courraud 1998; CNPF 2016), in the Czech Republic 200 trees (Podrázský et al. 2019) or 200 – 360 trees in Romania (Liubimirescu1973; Liubimirescu et al. 1977). Usually, the final pruning height is between 5 and 10 m (Eberhard et al. 2021) with two interventions (Horgan et al. 2003; Riou-Nivert 2020). In practice, pruning height is strongly correlated with the target diameter: 5 m (diameter 60 cm), 10 m (diameter 80 cm) and (seldom) 15 m (diameter 100 cm) (Kohnle 2008). The diameter of trees chosen for pruning should be between 10 and 15 cm as it is too early to select final crop trees ˂ 10 cm, and no more than 15 cm because there will not be enough clearwood produced to increase the log value when the tree is harvested. In other words, pruning occurs before the trees reach one third of their final diameter (Nițescu and Achimescu 1979; Siepmann 1981; Schütz 1990; CRPF 1999).

The most frequently proposed pruning season is the end of winter-beginning of spring (Querengässer 1956, from IDT 1961; Haralamb 1967; Marcu and Liubimirescu 1979) to allow for the healing of pruning wounds. Pruning green branches up to 25% – 30% of live crown in one operation and retaining a minimum green crown of 50% leads to only negligible losses in volume growth; the wounds heal quickly and the taper is improved (Lanier 1986; Boudru 1989; CRPF 1999; MAPPM 2000b). The branches to remove should be ≤ 3 cm in diameter (Wouters and Lorent 2002).

Rotation length

Douglas-fir stands are managed with rotation ages between 40 and 80 years (Table 5), although longer rotations are found in parts of Eastern Europe**.** In its native range in Canada, the rotation age for pure coastal Douglas-fir stands was 50 – 80 years four decades ago (Scott 1981; in Hermann and Lavender 1990), and currently 40 – 60 years in industrial forests in the U.S.A. (Lowell et al. 2014). In New Zealand, the rotation age of Douglas-fir plantations is 40–50 years (without thinning—www.douglasfir.co.nz/net/) but may be 60 years when the majority of trees are harvested for lumber (www.nzffa.org.nz/farm-forestry-model/).

Large pruned trees with diameters > 60 cm are valued for the production of solid furniture, decorative panels, peeled veneer as well as for exterior uses (CRPF 2010). Shorter rotations (less than 50 years) are generally not favoured as smaller logs have high proportions of juvenile wood and less favorable mechanical properties than mature wood (Barett and Kellog 1991; Lausberg et al. 1995; Vikram et al. 2011; Drewett 2015; all cited by Pollet et al. 2017). Long rotations in combination with large diameters are favorable management options to reduce the amount of juvenile wood and provide a more homogenous wood material (Henin et al. 2019). Slower radial growth usually benefits technological wood properties (e.g., reduced proportion of juvenile wood, branch diameters) (Henin et al. 2019), but long rotation are associated with higher risks, i.e., storm damage increases progressively with stand height (CRPF 2010; Kohnle et al. 2021). When reaching rotation age, European stands of Douglas-fir have traditionally been harvested through clear-felling, followed by replanting on the site as in the Czech Republic (Podrázský pers.comm.), Croatia (Đodan pers.com.), Hungary (Rédei pers.comm.), Ukraine (Lavnyy pers.comm.), UK (Mason pers.comm.). However, there has been increasing interest in adopting alternative silvicultural approaches characteristic of closer-to-nature forestry (Larsen et al. 2022).

Mixtures

In the context of a wider use of biodiversity-friendly practices such as closer-to-nature-forestry as part of the EU Biodiversity Strategy for 2030 (European Commission 2020), the use of Douglas-fir in mixed stands with native tree species is of major importance (Kohnle et al. 2021). This mixture with greater biodiversity than pure stands can (1) increase resistance and resilience to biotic agents detrimental to stand health, and (2) link stands of the exotic Douglas-fir to the native forest community, an aspect of particular importance within the concept of close-to-nature forest management (Kohnle et al. 2019).

The patterns of planting Douglas-fir to create mixed stands vary across Europe. These include establishing groups in a matrix of other species as in the Czech Republic (Novák et al. 2018; Slodičák et al. 2014; both in Podrázský et al. 2019) and in Romania, when the species is used in filling gaps in natural broadleaf regeneration (MAPPM 2000a). Group planting to form mixtures is also advocated as means of avoiding any negative environmental impacts from Douglas-fir (Ammer and Utschick 2004; in Thomas et al. 2022). Planting in rows can also be used to create mixtures but there should be a maximum of 4 m between rows to avoid the development of thick branches (Kohnle 2008). Current Romanian technical norms also recommend planting Douglas-fir in rows 1.5 m apart when the species is used in mixture with European beech (MAPPM 2000a).

Douglas-fir has been grown in mixtures with a wide range of mostly native conifers and broadleaf species. These include Norway spruce (Bulgaria, the Czech Republic, Germany, Slovenia), Sitka spruce (Ireland, UK), European silver fir (the Czech Republic, France, Slovenia), Scots pine (Bulgaria, Germany), black pine (*Pinus nigra* J.F. Arnold) (Bulgaria), European larch (Bulgaria, UK), hybrid larch (*Larix x eurolepis*) (Ireland), Japanese larch (*Larix kaempferi* (Lamb.) Carr) (Ireland, UK), western hemlock (*Tsuga*

Table 5 Stand rotation ages and target diameters of Douglas-fir in different European countries

Country	Rotation age, years	Target diameter, cm	Source
France	1. 40 (in monocultures)		1. van Loo and Dobrowolska (2019b)
	2. Minimum 40, maximum 60 – 80		2. Bastien (1998)
	3. 40 – 50 (initial planting density 1000 – 1200, 1200 – 1500 or 1500 – 1600 seedlings ha-1)	3. 40 (mean diameter)	3. Riou-Nivert (2020)
	4. 40 – 80		4. Riou-Nivert (1996)
	5. 50 – 60 (initial planting density 600 – 800 seedlings ha-1)	5. Minimum 50 (mean diameter)	5. Riou-Nivert (2020)
	6. 50 – 70		6. CRPF (1999)
	7. 65 – 75		7. Giraud and Champaux (1997)
	8. 66 – 74		8. Angelier (2007)
		9. From 40 – 50 cm on, even 55 – 60 cm in stands of good quality	9. CRPF (2010)
United Kingdom	1. Ca. 50; except where a premium is paid for larger logs produced on longer rotation		1. Mason pers.comm
	2. 50–65 (absolute rotation age)		2. Savill (2019)
Romania	50 (absolute rotation age)		Bakoș (1968)
	75 – 80 (veneer, sawnwood)		Liubimirescu (1973)
Portugal	50 – 60		Fontes et al. (2003)
Ireland	50 – 65		Horgan et al. (2003)
Belgium	50 – 80		Wouters and Lorent (2002)
	70 – 80		Boudru (1989)
Croatia	60		Đodan pers.comm
Germany (Baden-Württemberg)	1. 60 + (in mixed stands)		1. van Loo and Dobrowolska (2019b)
	2. 60 – 80	2. Target diameter 50 +	2. Spellmann et al. (2015)
	3. 80 – 120	3. Target diameter 70 +	3. Spellmann et al. (2015)
		4. 70 – 80 (when mean age is 80 – 90 years)	4. Șimon et al. (2014)
Bosnia and Herzegovina	60 – 120, depending on site quality		Cvjetkovic pers.comm
Czech Republic	80 +		Podrázský pers.comm
Serbia	80 – 100		Andrašev pers.comm
Ukraine	81 – 90		Lavnyy pers.comm
Bulgaria	100 – 120		Petkova pers.comm

heterophylla (Raf.) Sarg.) (Ireland, UK), European beech (Czech Republic, France, Germany, Romania, Serbia, Switzerland, Ireland), Italian alder (*Alnus cordata* Loisel.) (Italy) (Čokl 1965; Petkova 1989; Alexandrov et al. 2000; MAPPM 2000a; Wilson and Cameron 2015; Petkova et al. 2017; Keane et al. 2018; COFORD 2020; Nicolescu et al. 2021; Royal Forestry Society 2021; Andrašev pers.comm.; Đodan pers.comm.; La Porta pers.comm.; Podrázský pers. comm.; Vor pers.comm.).In the Czech Republic, the share of the species in mixtures is about 20% – 40%, evenly distributed over the area (Podrázský et al. 2019). A similar share of Douglas-fir (30% on average) was used in mixed plantations in Austria and Germany (Eberhard et al. 2021). In both Denmark (Larsen and Nielsen 2007) and in the UK (Haufe et al. 2021), forest development guidelines have been proposed to help the development of mixtures of Douglas-fir with broadleaves and conifers.

European beech is considered particularly suitable for mixing with Douglas-fir (MAPPM 2000a; Thomas et al. 2015; Ammer et al. 2016). In such mixtures, Douglas-fir is stabilized against climatic impacts while the climate sensitivity of European beech is increased (Thurm et al. 2016). Douglas-fir growth recovery after drought was shortened and extended for European beech (Thurm et al. 2016). In addition, the productivity of Douglas-fir-European beech stands regularly showed higher productivity compared with that predicted from the species performance in pure stands, largely attributed to the Douglas-fir (Thurm et al. 2016; Lu et al. 2018), with a share up to 33% (Thomas et al. 2015). Another species that may be used in a mixture with

Douglas-fir is Norway spruce. The proportion of Douglas-fir should be only 30% in such mixed stands, a compromise which might offer environmental and social adaptability and help to maintain the productivity of current Norway spruce sites (Fuchs et al. 2022). Douglas-fir may also be used as a nurse species since experiments in Ireland have shown that when it is grown in mixture with Sitka spruce on marginal sites, the latter species has higher productivity than if grown in pure stands (Keane et al. 2018). In its natural range, mixtures of Douglas-fir and red alder (*Alnus rubra* Bong.) resulted in long-term productivity gains for seven decades on nitrogen deficient soils (Binkley 2003).

Irregular silviculture

As Douglas-fir's ecological characteristics are considered `well adapted to irregular silviculture` (Royal Forestry Society 2021), alternative systems to clear-cutting are being carried out in different European countries. These include: group shelterwood cuttings (Bulgaria: Petkova pers.comm; France: Riou-Nivert 2020; Slovakia: Slávik pers.comm.); single-tree selection cutting (Bosnia and Herzegovina: Cvjetkovic pers.comm.; Germany: Vor pers.comm.; Slovakia: Slávik pers.comm.), group selection cutting (UK: Schütz and Pommerening 2013); and irregular shelterwood cuttings (France: Bastien 1998; Riou-Nivert 2020; UK: Malcolm et al. 2001; Mason et al. 2004). With irregular shelterwood cuttings, the recommended gap size for satisfactory natural regeneration and seedling growth is at least 0.1 ha, with a gap diameter: top height ratio of 1.5 – 2.0 (Malcolm et al. 2001).

As noted above, Douglas-fir can be regenerated naturally under the shelter of old, even-aged stands using silvicultural systems such as group shelterwood cutting; if the residual stand is removed (5 to 15 years between the seedling cut and the final cut as proposed in France, Riou-Nivert 2020), the newly established regeneration grows without any competition from above, and subsequent growth dynamics are expected to be similar to the regeneration process in its native range (Kohnle et al. 2019). However, insufficient opening of the canopy may result in poor rooting and crown development (Eberhard et al. 2021). The species also regenerates under canopy shelter with lengthy regeneration periods (over 40 years in Bulgaria—Petkova pers.comm.), more typical of shade-tolerant species (Kohnle et al. 2019). This is the pattern in uneven-aged stands using single-tree selection cutting, group-selection cutting or irregular high forest cutting harvesting individual trees reaching the target diameter. The application of single-tree selection cutting is possible only if the basal area is relatively low (about 27 m^2 ha^{-1}) (Schütz et al. 2015). Under these conditions, young trees, tolerant of shade, are protected against late frost and temperature extremes (Slávik pers.comm.; Vor pers.comm.).

In its natural range in North America, there is increasing adoption of 'ecological silviculture' in public and some private forests, an approach which attempts to follow the natural disturbance regime in Douglas-fir and western hemlock forests to ensure provision of a wide range of environmental services (Palik et al. 2021). Particular features of this approach include the allowance for an extended establishment period (up to 30 years), variable density thinning to develop stand heterogeneity, and harvesting regimes which ensure retention of deadwood and other structural legacies (Larsen et al. 2022). Several of these have yet to be explored in European silvicultural practices with Douglas-fir, especially the use of variable density thinning to create spatial variations within stands which positively affects the restoration of desired ecosystem features after periods of even-aged management (Puettmann et al. 2016).

Conclusion

This paper has outlined the qualitities that have led to the use of Douglas-fir, considered as `one of the most successful species introduced in the history of European forestry` (Podrázský et al. 2013), on a relatively large scale in Europe. It is a very productive species, with valuable timber for various important end-uses. It can form both pure and mixed stands, including mixtures with various native species such as European beech.

In addition, the species generally affects the environment less than Norway spruce or numerous pine species. It has a lower negative impact on the biodiversity of soil flora and has a more favorable role on soil formation especially when mixed with broadleaved species such as European beech (Thomas et al. 2022).

The important position of this species in European forestry is strengthened in the context of anticipated climate change, which favors a species better adapted to drought than Norway spruce, the most important conifer species in Europe. Nevertheless, climate change as well as globalization may have implications for the management of Douglas-fir, for example if biotic pests from its native range are introduced and become adapted to Douglas-fir in Europe. Under anticipated climate change, a major problem will be to identify provenances best adapted to future climatic conditions (Eilmann et al. 2013; Isaac-Renton et al. 2014, Hintsteiner et al. 2018; Konnert et al. 2018; Spiecker 2019; all in Smolnikar et al. 2021). This could require the use of new seed sources and provenances from its natural range, adapted to drier conditions such as those from southern Oregon and northern California (Konnert and Bastien 2019; Marchi and Cocozza 2021; Schüler and Chakraborty 2021).

However, public perception of Douglas-fir in European countries varies appreciably from widespread acceptance in western countries to negative views (even restrictions on its use) in eastern countries. In this context, we echo the very realistic conclusion by Spiecker (2019) and Spiecker and Schuler (2019), '… *the reputation of Douglas-fir and the question of the continued growth of this species in Europe is loaded with hope, prejudice, reservation, and scepticism. The current debates among numerous stakeholders often vary from enthusiastic to emotional, and can benefit from an evidence-based, sound scientific knowledge'*. We hope that this paper can help to inform such debates.

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