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Ecology and management of northern red oak (*Quercus rubra* L. syn. *Q. borealis* F. Michx.) in Europe: a review

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Northern red oak (*Quercus rubra* L. syn. *Q. borealis* F. Michx.) is a valuable broadleaved tree species originating from the eastern half of the USA and Canada. It was introduced to Europe in 1691 and currently covers over 350 000 ha, being found all over the continent, except the coldest part of Scandinavia. It is a fast-growing and valuable broadleaved tree due to its ecological characteristics, good wood properties and high economic value. Northern red oak prefers deep, loose, moderately humid and acid soils, without compact horizons and of at least moderate fertility. It does not grow well on dry, calcareous soils as well as waterlogged or poorly drained soils. It is either naturally regenerated using a group shelterwood system or planted using seedlings of European provenance, collected in certified seed stands. As northern red oak is light-demanding, its management should be 'dynamic' and includes heavy interventions (cleaning–respacing and thinning from above), in order to minimize crown competition between the final crop trees. These should produce large diameter trees for valuable end uses (e.g. veneer, solid furniture, lumber, etc.) within a rotation period generally of 80–100 years. The necessity for pruning (both formative and high) depends on the stand stocking at establishment, the subsequent silvicultural interventions as well as the occurrence of forking. The adaptation potential of northern red oak to predicted climate change, especially drought, seems to be higher than for European native oaks, the importance of the species is expected to increase in the future.

Introduction

Northern red oak (*Quercus rubra* L. syn. *Q. borealis* F. Michx.) is a valuable broadleaved tree species originating from the eastern half of the USA (32–47° N latitude, 62–96° W longitude). It is the northernmost American oak species (so 'baptized' *borealis*) and grows from low elevations up to 1680 m in the southern Appalachians. In its natural range, northern red oak forms either pure or mixed stands, along with both broadleaves (*Quercus* sp., *Fraxinus* sp., *Acer* sp., *Populus* sp., *Carya* sp., *Juglans* sp., *Magnolia* sp., *Celtis* sp., etc.) and conifers (*Pinus* sp., *Thuja* sp.) (Sander, 1965, 1990).

The year of introduction to Europe of this tree species has been traced back to 1691, when northern red oak seeds or seedlings were brought in to France by Roland Barrin de La Galissonière (1646–1737), a prominent navy officer, and planted in Le Petit Trianon (in the vicinity of Versailles Palace) (Goeze, 1916). Since then and especially in the 19th century (Table 1), the species has been used in parks, gardens, arboreta, trials, as well as forest plantations, all over Europe, with the exception of the cold zone of Scandinavia.

Currently, northern red oak covers over 350 000 ha in Europe, with the most important forest areas in Ukraine (192 868 ha – Lavnyy and Savchyn, 2016), France (52 000 ha – Merceron, 2016), Germany (44 550 ha – BMEL, 2014), Poland (15 261 ha – Gazda *et al.*, 2016), Hungary (13 174 ha – Rédei, pers. comm.), Slovenia (11 978 ha – Brus *et al.*, 2016), Bulgaria (9941 ha – EFA, 2016), the Netherlands (8696 ha – Schelhaas, 2014, in Mohren and Kramer, 2016). On a smaller scale, northern red oak can also found in Czech Republic (5586 ha – Uhul 2007, in Urban *et al.*, 2016), Romania (ca. 2500 ha – Şofletea and Curtu, 2007), Slovakia (2193 ha – Šebeň, 2017), Lithuania (1500 ha – NFI, 2014, in Marozas and Straigyte, 2016) and the UK (700–1000 ha; Wilson *et al.*, 2018).

Northern red oak provides a wide range of ecosystem services: soil protection/stabilization and improvement (Haralamb, 1967; Traci, 1960, 1985; Kupka and Dimitrovský, 2011; Nagel, 2015), carbon sequestration, habitat for wildlife (birds, mammals, rare species of insects) (Goßner, 2004; Goßner and Simon, 2005; Nagel, 2015), as shelterbelt, windbreak (plain areas, continental sand dunes), fire belt (pine regions) (Traci, 1985; Anonymous, 2002; Nagel, 2015). As it has a large crown and crimson-coloured leaves, almost entirely marcescent on young trees in the winter, with a high landscape and ornamental value, and good resistance to urban pollution, the species is used in parks, public gardens and is a common street tree (Brus, 2011). Northern red oak may be an alternative to native oaks (pedunculate oak *Quercus robur* L. and sessile oak *Q. petraea* (Mattushka) Liebl.) on sites that are marginal for the latter, or under expected climate change as a 'drought tolerant species', as is considered in the UK (Ray *et al.*, 2010).

In Europe, northern red oak is cultivated especially for its valuable wood, which is denser but of lower quality and durability than that of native oaks (CTBA, 1980; Brus, 2011). It has a specific gravity (12 per cent moisture content) ranging from 550 to 980 kg cu.m^{-1} (Réh and Réh, 1997), the most frequently cited values being 680–720 kg m^{-3} (Dumitriu-Tătăranu and Costea (coord.), 1988; Jourez and Leclercq, 1992; Stoykov and Andonova, 2008; Meier, 2015; Zeidler and Boruvka, 2016). This coarse-grained wood is hard, strong, stiff, with good workability, impregnation and splitting potential (Stănescu, 1979; Lorent and de Wouters, 2001). Consequently it is a versatile timber used for lumber, furniture, veneer (less decorative than the one of native oaks – Mazet, 1988), in construction, for the interior finish of houses (e.g. wall panelling, flooring, parqueting), railroad ties, as mine wood, firewood, etc. (Dumitriu-Tătăranu and Costea (coord.), 1988; Réh and Réh, 1997; Vansteenkiste *et al.*, 2005). As the growth rings are wide and wood is ring-porous, the timber cannot be used in the manufacture of barrels for alcoholic liquids but can be used for oily ones (Haralamb, 1967; Stănescu, 1979; Mazet, 1988).

The price of northern red oak sawlogs in Europe generally ranges between 60 and 100 euro m^{-3} reaching a maximum in western countries such as France and Germany (Table 2). However, regardless of the wood assortment, the price of northern red oak logs is lower (up to 2–3 times less) than that of pedunculate oak or sessile oak.

Taking into account the above issues, the main aim of this paper is to present the essential characteristics of northern red oak in Europe including site requirements, root system, regeneration ecology, invasive potential, shade tolerance, potential for natural pruning, vulnerability to pests, diseases and wildlife, as well as growth and yield of its individual trees or stands. Based on this information, we outline appropriate management of northern red oak in Europe, including establishment and stand regeneration, early tending interventions (release cutting and cleaning–respacing), commercial thinning and pruning (both formative and high), all with the aim of producing high-quality

Table 1 Northern red oak: year of introduction to parks/gardens and forest cultures.

Country	In gardens	Reference	In forest	Reference
Belgium			ca. 1890–1900	Vansteenkiste *et al.* (2005)
Bulgaria	1902–1904	Ganev (1942)		
Denmark	18th century (beginning)	Bornebusch (1945)		
Croatia	1800–1850		1920–1940	
Czech Republic	1890	Kupka (pers. comm.)	Beginning of 20th century	Kupka (pers. comm.)
Germany	1735	Bauer (1953)	ca. 1750	Bauer (1953)
Hungary		Rédei *et al.* (2010)	Mid 19th century	Fekete (1881)
Italy	1812–1818	Reg. Piemonte (2013); Repetti (1828)	1922	Reg. Piemonte (2013)
Poland	End of 18th–beginning of 19th century	Anonymous (2017)	1798	Anonymous (2017)
Romania	End of 19th century	Haralamb (1967)	Beginning of 20th century	Haralamb (1967)
Slovakia	Mid 19th century	Benčať *et al.* (1984)	Beginning of 20th century	Réh and Réh (1997)
Slovenia	1781–1836	Wraber (1951); Dobrilovič and Kravanja (2003)	1889–1898	Wraber (1951); Dobrilovič and Kravanja (2003)
Ukraine	1809	Ivchenko (2002)	1888	Ivchenko (2002)
UK			1720–1740	Wilson *et al.* (2018)

Table 2 Comparative prices of northern red oak, pedunculate oak and sessile oak logs in some European countries.

Country	Average price of…, euro m^{-3}				Source	Observations
	Sawlogs		Veneer logs			
	NRO*	PO**/SO***	NRO	PO/SO		
Czech Republic	60	100	80	120–150	Kupka, pers. comm.	
Slovenia	–	87–176	115–140	291–421	Brus, pers. comm.	Dbh over 50 cm
Hungary	110–150	348	–	–	Rédei, pers. comm.	Upper end diameter over 36 cm
Germany	217	445/437	274	641/683	Vor, pers. comm.	B quality
France	90–120	200–400			Bastien, pers. comm.	Dbh over 65 cm, very good quality

NRO* = northern red oak; PO** = pedunculate oak; SO*** = sessile oak.

wood assortments. A secondary aim of this paper is to compare northern red oak with the same native oaks in Europe in terms such as species characteristics, growth, yield, rotation and silvicultural interventions.

Species characteristics

Site requirements

Climate

In the native range of northern red oak, the mean annual precipitation varies between 760 and 2030 mm, while the mean annual temperature ranges between 4 and 16°C. The frost-free period averages 100 days yr^{-1} in the north and 220 days yr^{-1} in the south (Sander, 1965, 1990).

In Europe, where northern red oak grows generally at altitudes between 250 and 800 m (Rey, 1960; Nagel, 2015), the species shows a wide climatic tolerance, being cultivated in areas with similar mean temperature as in the native range, but much lower mean precipitation, reaching a minimum of 500–550 mm yr^{-1} (Hančinský, 1972; Nagel, 2015; Burkardt, 2017). It seems that its climatic optimum on our continent lies in the *Castanetum* (mean annual temperature m.a.t. 13–17°C; absolute minimum temperature a.m.t. −16°C) and the warm part of *Fagetum* (m.a.t. 7–12°C; a.m.t. −25–(−30)°C) forest vegetation types as defined by Mayr (Haralamb, 1967). It shows a better resistance to drought than *Quercus petraea* and *Q. robur* (Durand *et al*., 1983; Timbal and Dreyer, 1994; Lorent and de Wouters, 2000; Dressel and Jäger, 2002). This drought resistance is due to the fact that northern red oak has lower water consumption and its growth is less affected by water deficit. In addition, northern red oak leaf tissues have a high capacity to tolerate dessiccation, and the leaves show a high stomatal density (higher than both *Q. robur* and *Q. petraea*) (Timbal and Dreyer, 1994). The species tolerates very low temperatures (down to −30, even – 40° C – Bellon *et al*., 1977; Brus, 2011; Jaworski, 2011) during winter as well as spring frosts owing to a specific 'avoidance strategy' of the leaves flushing later than pedunculate oak and sessile oak (Haralamb, 1967; Jacamon, 1987). Northern red oak is sensitive to autumn frosts (Haralamb, 1967), which can cause the forking of non-hardened shoots or branches. This 'undesirable' tendency to forking, as well as forming multiple leading shoots, owing to the occurrence of many buds on terminal shoot, should be taken into account when managing the species (Jacamon, 1987; Savill, 1991, 2013; Hubert, 1994; Hubert and Courraud, 1998). Consequently, northern red oak is best cultivated in regions free from frost (Dumitriu-Tătăranu (coord.), 1960) or formative pruning (shaping) should be used for the correction of this defect when worthwhile. It is affected by early (late autumn), heavy and sticky snow that can lead to trunk or branch breakage, especially when trees are young (Haralamb, 1967; Jaworski, 2011).

Soil

Northern red oak has lower nutrient (nitrogen, phosphorus and potassium – Bauer, 1953; Plaisance, 1978; Dumitriu-Tătăranu and Costea (coord.), 1988; Miltner *et al*., 2016) and water demands (better resistance to soil drought) than native sessile oak and pedunculate oak and therefore can be more vigorous and productive on less fertile sites (Haralamb, 1967; Riepšas and Straigyte, 2008; Brus, 2011). *Q. rubra* can grow on poor, sandy and acid soils, if they are not too dry, as well as on heavy-textured, clay-rich (loamy-clay and clayey) soils. On the latter soils it grows like *Quercus cerris* L. (Turkey oak) and *Q. frainetto* Ten. (Hungarian oak), which are the best adapted oak species to such harsh edaphic conditions (Haralamb, 1967). It does not grow well on dry, calcareous soils, since its growth rate reduces and foliar chlorosis becomes more intense as calcium content increases (Pilar-Landeau, 1984; Timbal and Dewilder, 1994), although its sensitivity to calcium content seems to decrease with age (Broshtilov and Broshtilova, 2013). Waterlogged or poorly drained soils are not recommended for the species, because it cannot tolerate long flooding periods or stagnant water (Haralamb, 1967; Bellon *et al*., 1977; Brus, 2011; EFA, 2011; Jaworski, 2011; Nagel, 2015). In general, northern red oak prefers deep, loose, moderately humid and acid, limestone-free soils, without compact horizon and of at least moderate fertility (Boudru, 1978; Stănescu, 1979; Réh and Réh, 1997; Stănescu *et al*. 1997; Lorent and de Wouters, 2000; Şofletea and Curtu, 2007; Nagel, 2015). Such sites are similar to the ones where northern red oak grows best in its natural range (Sander, 1990).

Root system

Northern red oak has a root system similar to the one of *Q. petraea* and *Q. robur* (Negulescu and Săvulescu, 1957). It is deep, tap-rooted during the early years (can reach over 70 cm depth at 3–5 years of age), then heart-like with many thin lateral roots, shallower than in native oaks (Bauer, 1953; Nagel, 2015). These roots can expand horizontally up to over 15 m from the tree stem (Lyr and Hoffmann, 1967, in Timbal and Kremer, 1994). Consequently, the trees are firmly anchored in the soil, so that windthrow is rare (Timbal and Kremer, 1994; Réh and Réh, 1997). On rich sandy soils, with a shallow water table, it does not develop a tap root but the lateral roots, with many oblique or vertical branches, are well developed (Chiriță *et al.*, 1977). On sandy soils overlying a loam layer, northern red oak develops, at late ages, a deep and wide root system, exceeding the crown projection (Chiriță *et al.*, 1977). Unlike the stem growth, which is polycyclic (discontinous), the growth of roots was found to be continuous throughout the vegetation season (Dickson, 1994; Hubert, 1994).

Regeneration ecology

The first heavy seed crop occurs in stands 20–30 years of age (Stănescu, 1979; Milev *et al.*, 2004). Mast years are more frequent than for *Quercus petraea* and *Q. robur* and have been observed every 2–3 years; years without any seed production are rare (Negulescu and Săvulescu, 1965; Haralamb, 1967; Vor and Lüpke, 2004; Vor, 2005). Northern red oak seeds (acorns) need about 15 months to ripen (biennial seed production) (Supplementary material S1). The acorns are dispersed mostly by gravity (especially under the tree canopy – it was recorded a lack of seedlings beyond 15 m from a seed tree – Major *et al.*, 2013) as they are heavy (275 acorns kg^{-1} on average, ranging from 165 to 565 acorns kg^{-1} – Olson, 1974). The acorns are also dispersed by birds and mammals (i.e. wood mice *Apodemus sylvaticus*, red squirrel *Sciurus vulgaris*, rats *Rattus* sp., wild boar *Sus scrofa* – Merceron, 2016). Most acorns germinate within a distance of 150 m from the seed tree (Bauer, 1953; Nagel, 2015). Long-distance seed dispersal (up to 10 km from the mother trees) happens on a very small scale, and the main vector is the European jay (*Garrulus glandarius*) (Myczko *et al.*, 2014; Anonymous, 2017). It buries acorns before consuming them, somehow preserving the seeds from predation by other animals (Merceron, 2016). When both pedunculate oak and northern red oak acorns are available, the jays prefer pedunculate oak acorns for dispersal. Those of northern red oak, which are heavier, are dispersed mostly by wood mice (Bieberich *et al.*, 2016). In the home range, where the main dispersers of acorns are the rodents (mice, voles, squirrels), jays do not play a major role in seed dispersal as they avoid large red oak acorns (Dey, 1996).

Acorn predation by insects (e.g. *Balaninus* spp., *Valentina grandunella*, *Melisoppus latiferranus*), birds (including jays) and mammals is very common, but acorns of *Q. petraea* and *Q. robur* are generally preferred (e.g. by European jays and wild boar) (Wasik, pers. comm.).

Quercus rubra also regenerates vegetatively in Europe, due to its good sprouting potential (Hubert, 1994) in common with reports from its natural range (Sander, 1990). The sprouting potential is good at young ages, but there have been reports of a decline after 40 years of age (Broshtilov and Broshtilova, 2013). The majority of shoots occur in the lower part of the stool, close to the collar, grow rapidly, are straight and well formed (Broshtilov and Broshtilova, 2013). In the USA, more than 95 per cent of the northern red oaks in new production stands are sprouts, either from advance reproduction (when old stems are damaged during logging) or from sprouts of cut trees (Sander, 1990). In the same area, seedlings and young trees sprout prolifically also when killed by fire (Sander, 1990). Sprouting of northern red oak in Europe, even quite abundant, was observed to be weaker than of native *Q. petraea* and *Q. robur* (Réh and Réh, 1997).

Invasive potential

Since northern red oak regenerates well naturally (by seed) in Europe, it is sometimes considered by official bodies or various authors as a *potentially invasive* or even an 'invasive species' (Table 3).

The invasive potential is site-specific: northern red oak can be invasive on dry, nutrient poor soils (oak/pine forests – Ukraine – Lavnyy and Savchyn, 2016; Austria – Van Loo *et al.*, 2016) or on relatively rich sandy soils (Belgium – Henin and Vandekerkhove, 2016), while on richer soils, it is far less invasive (Henin and Vandekerkhove, 2016).

In the other European countries, northern red oak is not considered to be a threat because its potential to spread is limited due to the ineffective seed dispersal vectors (Major *et al.*, 2013),

Table 3 Invasive potential of northern red oak in some European countries.

Country	Northern red oak considered as…		Observations
	Potentially invasive	Invasive	
Bulgaria	**X** (Petrova *et al.*, 2013, in Petkova *et al.*, 2016)	–	
Czech Republic	–	**X** (Mlíkovský and Stýblo, 2006), in Urban *et al.*, 2016	
Germany	–	**X** (Vor, pers. comm.)	Not considered invasive by forest scientists – Nagel (2015); Vor *et al.* (2015)
Lithuania	–	**X** (Riepšas and Straigyte, 2008)	
Slovenia	**X** (De Groot *et al.*, 2017)	**X** (Zelnik, 2012; Strgulc Krajšek *et al.*, 2016)	
Poland	–	**X** (Tokarska-Guzik *et al.*, 2012)	
Belgium		**X** ('with moderate impact') (Henin, pers. comm.)	

lack of vegetative reproduction by root suckers and a high browsing pressure (Konnert and Spiecker, 2016).

Shade tolerance

Northern red oak is more shade-bearing than *Q. robur* and *Q. petraea* (Savill, 1991, 2013). When young, *Q. rubra* is able to tolerate a light shelter (Lorent and de Wouters, 2000; Vor and Lüpke, 2004; Vor, 2005). The light intensity for an optimum growth is 15–30 per cent of full sunlight, although Kuehne *et al.* (2014) state that *Q. rubra* exhibits a high photosynthetic capacity even under closed canopies. At adult ages, it is a light-demanding species, showing a marked phototropism and develop a lean in search for light. Lack of access to light can lead to crown dieback (Şofletea and Curtu, 2007), therefore the species requires regular and frequent cleaning–respacing and thinning to reduce or even eliminate the competition at crown level (Lorent and de Wouters, 2000). However, a number of factors can stimulate the production of epicormic branches including heavy thinning, lack of light from above, crown dieback or too much competition (Boudru, 1989; Crave, 1991; Jenner, 1993 in Europe; Arend and Scholz, 1969 and Sander, 1990, in the USA).

In general, epicormics are not a major problem of northern red oak (Evans, 1984; Savill, 1991, 2013).

However, trees with long and narrow crowns were observed to produce more epicormic branches than dominant and large-crowned trees (Schulenburg, 1966 – Supplementary material S2). The risk of epicormics on red oak trees with large crowns is lower than for *Q. petraea* and *Q. robur* (Bauer, 1953; Nagel, 2015).

Potential for natural pruning

When free-grown, northern red oak has a short and thick stem, with a very large crown; as a forest tree, it has a straight and long stem, with a small and round crown (Ionescu and Lăzărescu, 1966; Boudru, 1989). Generally, the potential for natural pruning is good when trees are grown in stands with dense canopy cover (i.e. over 80 per cent) (Stănescu, 1979; Crave, 1991; Stănescu *et al.*, 1997). In such stands, the length of pruned height can be as high as 1/2–2/3 of the total height (Traci, 1960; Haralamb, 1967; Hristov, 1992), reaching 10.5 m at 30 years (Eleršek *et al.*, 1994) or 12 m at 40 years (Plaisance, 1978). However, even in dense stands, natural pruning is not perfect as often many dead limbs remain attached to the trunk, so it should be combined with artificial removal of low branches (Hubert and Courraud, 1998). It is also the case in plantations with initial spacing higher than 2 × 2 m, where natural pruning is slow (Hubert, 1994) so artificial pruning becomes necessary (Hubert and Courraud, 1987; Thill, 1994).

Vulnerability to pests, diseases and wildlife

Many fungal pathogens and insect pests have been found in northern red oak stands across Europe, but so far none of them have been reported to cause serious damages to the species (Delatour *et al.*, 1994; Delplanque and Menassieu, 1994; Delkov, 2004; Perić, pers. comm.; Rédei, pers. comm.; Stefančik, pers. comm.). The spectrum of defoliators (to which the species is quite resistant) is the same as for other oak species, i.e. *Operophtera brumata*, *Erannis defoliaria*, *Tortrix viridana*, *Euproctis chrysorrhoea*, *Lymantria dispar*, *Melolontha melolontha* (Videlov and Lambrev, 1986b; Delplanque and Menassieu, 1994; Anonymous, 2017). Wood-boring insects such as *Cerambyx cerdo*, *Scolytus intricatus*, *Agrillus viridis*, *Zeuzera pirina*, *Cossus cossus*, as well as acorn-damaging insects such as *Laspeyresia splendana*, *Curculio glandium*, *Curculio elephas*, have also been found on northern red oak (Negulescu and Săvulescu, 1957; Videlov and Lambrev, 1986b; Delplanque and Menassieu, 1994; Anonymous, 2017).

Leaves and branches of northern red oak are colonized by fungi such as *Ciboria candolleana* and *Taphrina caerulescens*. It seems to be almost immune to *Erysiphe alphitoides* (Haralamb, 1967). The bark is affected by *Stereum rugosum*, *Pezicula cinnamomea*, *Phytophthora cinnamomi*, *Nectria galligena*, and its roots are prone to *Armillaria mellea* and *Collybia fusipes*. The main agents for wood rot are *Laetiporus sulfureus*, *Stereum rugosum*, *Stereum hirsutum*, *Ganoderma* spp., *Inonotus dryadeus* (Videlov and Lambrev, 1986a; Delatour *et al.*, 1994; Rossnev *et al.*, 2004). One should mention that the most important enemy of northern red oak in the natural range, the vascular fungi *Ceratocystis fagacearum*, which produce the so-called 'oak wilt', has not been encountered in Europe thus far.

Last but not least, northern red oak is very often browsed by mammals such as deer and other animals can cause damage such as hares, rabbits, voles and mice (Haralamb, 1967; Ducousso, 1994).

Growth and yield

Growth dynamics

Height growth

Northern red oak trees grow very quickly in height up to 30–40 years of age (Rameau *et al.*, 1989; CRPF, 2007), with a peak at 15–20 years of age, so surpassing all native oak trees including *Q. cerris*, which is regarded as the quickest species in youth among native European oaks (Stănescu *et al.*, 1997; Lorent and de Wouters, 2000; Vansteenkiste *et al.*, 2005). In this respect, *Q. rubra* trees can reach heights of 6 m at 10 years (Stănescu *et al.*, 1997), 8 m at 12 years (Turlakov, 1966), 21 m at 35 years (Hristov, 1992), 30 m at 80 years (Dumitriu-Tătăranu and Costea (coord.), 1988) and 35 m at 100 years (Pilar-Landeau, 1984). The correlation graphs between age and dominant or mean height depict the character of 'fast-growing species' of northern red oak: it can reach mean/dominant heights of 16 m at 20 years, 21 m at 30 years and 24 m at 40 years (Table 4). On best sites, northern red oak's mean/dominant height is 30–36 m at 80–100 years (Supplementary material S3).

Depending on the country and productivity class, the mean heights of northern red oak stands are higher, similar or lower than the ones of pedunculate oak and sessile oak in old stands (70–80 years old, close to the rotation age), as shown in Table 5.

Diameter growth

Diameter growth reaches a maxima at 20–40 years of age (Romania – Dumitriu-Tătăranu, 1984) or 50–60 years of age (Belgium – Boudru, 1978, 1989; France – Lanier *et al.*, 1980). It is about 0.5 cm yr^{-1} on average, but can reach 1 cm yr^{-1} under very favourable site conditions and using an appropriate silviculture (Boudru, 1978; Lorent and de Wouters, 2000; Delkov, 2003). On the best sites and following heavy thinning from above, mean diameters of 40 cm can be reached in 50 years, 55 cm in 80 years (Dumitriu-Tătăranu and Costea (coord.), 1988) and 60 cm in 100 years (Pilar-Landeau, 1984). Exceptional northern red oak trees, of 156 cm d.b.h. (Czech Republic – Kupka, pers. comm.) or 116 cm (Romania – Dumitriu-Tătăranu (coord.), 1960), have been reported (Supplementary material S4).

Table 4 Maximum mean or dominant height of northern red oak stands at 20–40 years in different European countries.

Country	Maximum mean/ dominant height at age… (years)			Source
	20	30	40	
Ukraine	15.9	21.0	24.1	Anonymous (1987)
Belgium	16.8	21.0	24.2	Rondeux *et al.* (1999)
The Netherlands	16.9	20.2	22.7	Oosterbaan *et al.* (2016)
Hungary	16.0	20.0	24.0	Rédei *et al.* (2010)
Germany	11.0	16.7	21.0	Bauer (1953)
Slovakia	12.3	17.8	21.5	Stefančik, pers. comm.
Bulgaria	15.5	20.0	22.8	Poryazov *et al.* (2004)

Volume growth and yield

The volume growth of northern red oak stands in various countries is relatively quick compared with other oak species and can be as high as 8–10 m^3 ha^{-1} yr^{-1} at 80 years (Table 6). At age 60, under favourable site conditions, northern red oak produces in Romania as much as sessile oak at age 140 (Haralamb, 1967). In France, the yield of northern red oak 30–60-year-old stands is twice as high as the one of native oaks stands (*Q. robur* and *Q. petraea*) (Pilar-Landeau, 1984).

Table 5 Mean height in northern red oak *vs* pedunculate/sessile oak stands, in some European countries.

Country	Age (years)	Mean height (m) in productivity class…						Source
		I		II		III		
		NRO	SO/PO	NRO	SO/PO	NRO	SO/PO	
Bulgaria	80	27.3	28.3	25.1	24.5	22.8	20.4	Poryazov *et al.* (2004)
Germany	80	29.7	23.8	26.3	20.6	22.9	17.2	Vor, pers. comm. (data from Bauer, 1955 (NRO) and Jüttner, 1955 (SO and PO))
Hungary	70	29.9	32.0	27.2	28.4	24.5	24.7	Rédei, pers. comm. (data from Rédei *et al.*, 2007 (NRO) and Béky, 1989 (SO and PO))

NRO = northern red oak; PO = pedunculate oak; SO = sessile oak.

Table 6 Mean volume growth of northern red oak in some European countries.

Country	Mean annual volume increment, m^3 ha^{-1} yr^{-1}	Age, years	Reference	Obs.
Belgium	7–10	50–100	Rondeux *et al.* (1999)	Elevation below 450 m
Bulgaria	4.1–7.5	80	Poryazov *et al.* (2004)	
Czech Republic	7	120	Kupka *et al.* (2018)	
France	10 (range 7.6–12.3)	30–60	Pilar-Landeau (1984)	
Germany	12 (range (4) 8–17)	80–120	Bauer (1953); Seidel and Kenk (2003)	
Hungary	2.7–9.0	75–80	Rédei *et al.* (2010)	
Latvia	7–9	59–67	Dreimanis and Šulcs (2006)	Loamy soils
Netherlands	3.3–8.6	80	Oosterbaan *et al.* (2016)	
Poland	8.5		Jaworski (2011)	
Romania	8.5 (range 7.7–10.2)	80	Dumitriu-Tătăranu and Costea (coord.) (1988)	
Slovakia	6.1–12.6	72	Réh and Réh (1997)	Thinning from above
	9.5–11.2	72		Thinning from below
Slovenia	14.6	33	Eleršek *et al.* (1994)	
	10.4	30		
Ukraine	7.8–9.3	80	Anonymous (1987)	

Management of northern red oak

Goals

The production of large-sized northern red oak logs, used for lumber, solid furniture, veneer in Europe, requires rotations ranging in general between 70 and 100 years, which are shorter than those of sessile or pedunculate oak stands (Table 7). In France, the proposed rotation age (50–70 years) is shorter, in order to avoid the heart rot, produced by the root rot fungus *Collybia fusipes* (acts especially from the age of 50 years on), as well as occurrence of tree dieback, which becomes quite common towards 80 years of age (CRPF, 2005, 2007; Duyck, 2008).

Regeneration and stand establishment

Natural regeneration

As in the home range (Dey, 1996), northern red oak is mostly regenerated naturally using the group shelterwood system, the small gaps reducing the risk of late frost damage to young seedlings (Czech Republic – Miltner and Kupka, 2016; Germany – Nagel, 2015; Vor *et al*., 2015; Slovenia – Mikulič and Kralj, 1990). The regeneration period should be short, i.e. after the establishment of a new seedling cohort in the gaps, the final cut is applied immediately in order to provide enough light for the young seedlings (Kupka, pers. comm.; Nagel, 2015; Vor *et al*., 2015). The use of group selection systems has occasionally been advocated to regenerate northern red oak in Europe (Boudru, 1989) and its native range (Dey *et al*., 2008). The natural regeneration is very prolific (Supplementary material S5), and the stocking of a new cohort can reach 800 000 seedlings ha $^{-1}$ (Germany – Vor, 2005), 790 000 seedlings ha^{-1} (Bulgaria – Delkov, 2004) or 270 00–335 000 seedlings ha^{-1} (Hungary – Rédei, pers. comm). In northern red oak regenerations <2 m in height, the stocking reached 240 000 stems ha^{-1} (Germany – Major *et al*., 2013). This high stocking drops down to 50 000 seedlings ha^{-1} at age 5 (Romania – Ionescu and Lăzărescu, 1966) or 24 000 trees ha^{-1} at age 10 (Bulgaria – Delkov, 2004).

This dense natural regeneration is due to the abundant seed production, good-quality seeds, as well as low levels of predation from acorn weevil (*Balaninus* spp.) (Delkov, 2004). As northern red oak seedlings are 'a delicacy for the deer' (Bellon *et al*., 1977; Jaworski, 2011), deer browsing as well as livestock browsing are a major problem in naturally regenerated red oak stands. This requires the use of protection measures (especially fencing but sometimes spraying with repellents), as recommended in many European countries (Bulgaria, Czech Republic, France, Germany, Hungary, Slovakia). These measures are supplemented by the management of deer and livestock populations, to be kept off the young stands.

Although northern red oak is a prolific stool sprouter, coppicing is not commonly used in Europe as a regeneration method, with the exception of stands damaged by climatic events such as ice breakage or storms. This is the case in northeastern Bulgaria, where red oak plantations were damaged by ice in 1998 and, after the removal of affected trees, the remaining stools were left to sprout (Petkova, pers. comm.).

Artificial regeneration

Northern red oak can be established artificially especially by planting (on an insignificant scale by direct seeding), using acorns collected in certified seed stands (forest genetic resources) including the species and covering important areas: 504 ha (Bulgaria), 71 ha (Germany), 36.6 ha (Romania), etc. In all European countries, the forest reproductive material is of unknown origin; interestingly, the seeds collected from stands established on our continent are of better quality than those from the native range, probably because their major damaging insects (e.g. acorn weevils, acorn moths, acorn gall wasps in the natural range – Sander, 1990; Johnson *et al*., 2002), that can destroy the entire crop in years of poor acorn production, are absent in Europe (Daubree and Kremer, 1993; Delkov, 2004).

For the production of plants, acorns are collected at the beginning of autumn, before the leaf fall, and are sown immediately to avoid the risk of being damaged by low winter temperatures (Rubțov, 1958; Damian, 1978).

If seeding is carried out in the following spring, the acorns are kept in winter at temperatures of −1 to −3°C, followed by a stratification in humid sand under low temperatures over 20–45 days. After keeping the acorns in water for 24 h, they are sown in a nursery (110–120 g m^{-1}, ca. 30 acorns m^{-1}) at 3–5 cm depth, usually in rows 30–40 cm apart. The seedlings are ready

Table 7 Rotation age of northern red oak, compared with sessile oak and pedunculate oak, in some European countries.

Country	Rotation age of… (years)		Source
	Northern red oak	Sessile oak (SO), pedunculate oak (PO)	
Ukraine	71–75	111–120	Lavnyy, pers. comm.
Hungary	75–80	100–120	Rédei, pers. comm.
Slovenia	80	90–100 (SO), 140–160 (PO)	Brus, pers. comm.
Poland	80	Minimum 120	Wąsik, pers. comm.
Belgium	80–90	120–140 (PO), 140–160 (SO)	Henin, pers. comm.
Slovakia	80–100	120–160	Štefančík, pers. comm.
Germany	80–120	140–240	Vor, pers. comm.
Bulgaria	100	120–160	Petkova, pers. comm.
Czech Republic	110–120	120–150	Kupka, pers. comm.
Croatia	120	120 (SO), 140 (PO)	Perić, pers. comm.

for planting usually in 2 years (sometimes even 1 year) (Supplementary material S6).

In the first year, the plants develop a tap root up to 40 cm long that should be undercut in the same year if targeting the production of a fibrous root system (Haralamb, 1967).

The plants are normally 1 + 0 or 1 + 1 (seldom 1 + 2), with a minimum height of 35–55 cm and a collar diameter of at least 6 mm. The initial stocking in plantations is very variable: from 1000 to 2000 plants ha^{-1} in France (Bastien, pers. comm.), 2000–3000 plants ha^{-1} in Belgium (Boudru, 1978, 1989), 3300–5000 plants ha^{-1} in Bulgaria (Petkova, pers. comm.), 5000 plants ha^{-1} in Germany (Vor and Lüpke, 2004; Nagel, 2015), to 5000–6667 plants ha^{-1} in Romania (Anonymous, 2000). High initial stocking is recommended in order to reduce the risk of establishment failures, to avoid further artificial pruning as well as the development of badly shaped trees (Jenner, 1993; CRPF, 2007; EFA, 2011).

Q. rubra is introduced in pure rows or in small groups (e.g. 15–20 m diameter in Germany or 5–10 individuals in Romania). It forms pure stands (e.g. Belgium, France, the Netherlands) or is used in mixtures, where the proportion of the species reaching usually (10) 20–30 per cent (Slovakia – Tokár, 1998; Romania – Anonymous, 2000). This proportion increases to 50–70 per cent in areas with difficult soil conditions for native oaks (e.g. heavy-textured soils, in the plain areas of Romania – Anonymous, 2000). The admixed species include European beech (*Fagus sylvatica* L.) or other shade-tolerant species such as hornbeam (*Carpinus betulus* L.), to promote self-pruning (Germany), native oaks (i.e. sessile, pedunculate, Turkey, Hungarian – Romania and Slovakia), linden (*Tilia* sp.), field maple (*Acer campestre* L.), black walnut (*Juglans nigra* L.) (Slovakia) or softwood species such as Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and larch (*Larix* spp.) (Slovakia). In Bulgaria, good results (high survival rates and quick early growth) are obtained when mixing northern red oak with black pine (*Pinus nigra* J.F. Arnold), wild service tree (*Sorbus torminalis* (L.) Cr.), service tree (*Sorbus domestica* L.), common ash (*Fraxinus excelsior* L.), narrow-leaved ash (*F. angustifolia* Vahl.), elms (*Ulmus* sp.) (Broshtilova and Broshtilov, 2008; Broshtilov and Broshtilova, 2013).

Young stand management

In Europe, before the first commercial thinning, the management of young and initially dense (crown cover over 80 per cent) naturally or artificially regenerated mixed stands with *Q. rubra* include both release cutting and cleaning–respacing. *Release cuttings* (1–2 interventions) are performed during the first 3–4 years after establishment and with a 2 to 3-year cycle. These interventions are strongly recommended in dense stands, with closed canopy, or when the competition of weeds as well as species of *Rubus*, *Lonicera* or stool shoots is important (IDF, 1979; Bastien, pers. comm.). As northern red oak is a fast-growing species, cleaning–respacing (normally two interventions) in dense stands should start early, and be frequent (cycle 3–5 years) and heavy, in order to preserve large canopies but also help the natural pruning of red oak trees. Stocking at the completion of cleaning–respacing (mean diameter ca. 8–10 cm) should not exceed 1200–1600 trees ha^{-1} (Rédei *et al.*, 2007). In general, a ‘negative selection’ (removing undesired northern red oak individuals – suppressed trees, forked, wolves, from very dense areas – as well as competing or low value species such as pioneers) is performed during cleaning–respacing (Supplementary material S7).

This intervention can also consist of a ‘positive selection’ including the early choice of ‘potential final crop trees’, when they are 7–8 cm d.b.h., based on ‘vigour’ (the thickest and tallest), ‘quality’ (vertical, straight, without forks or wounds, with large and symmetrical crowns, thin branches, etc.) and ‘distribution’ (as regularly spaced as possible) criteria. If these trees (maximum 400 individuals ha^{-1}) are granted a free-growth state at crown level during the last cleaning–respacing by the removal of main competitors (dominant and co-dominant trees), their diameter increment can reach 1–1.2 cm yr^{-1} (Sandi and Nicolescu, 2011).

Commercial thinning

All over Europe, commercial thinnings in northern red oak stands are selective (from above); they should start early (before dominant height reaches 14 m) and have short cycles (4–6 years) (Kremer, 1979; Lanier *et al.*, 1980; Štefančík, 2011; Nagel, 2015).

The intensity of thinning is either (1) ‘moderate’ (intensity (10) 15–20, seldom 25 per cent, of basal area or volume), such in Bulgaria (Hristov, 1992), Slovakia (Štefančík, 2011) or Ukraine (Lavnyy, pers. comm.), or (2) ‘heavy’ (intensity up to 30 per cent of standing volume), as in Germany (Bauer, 1953; Nagel, 2015), France (Gelpe *et al.*, 1986; Lanier *et al.*, 1980) or Belgium (Thill, 1975; Boudru, 1978, 1989). The second option, combined with frequent interventions, targets the production of regular annual rings, with a diameter growth rate of 1 cm yr^{-1} (Boudru, 1982, from Kremer and Destremau, 1984) as well as the quick healing of pruning wounds (Sandi *et al.*, 2012; Nicolescu *et al.*, 2013). In addition, northern red oak trees in very dense (full crown cover) stands following too light thinning have small crowns and are covered with epicormics, the quality of trunks being strongly affected (Crave, 1991). The same defect (presence of epicormics) occurs in widely spaced stands after very heavy thinning, opening too much the canopy and exposing the trunk to strong light, as well as on trees from lower Kraft classes (III, IV and V) (Sander, 1990; Jenner, 1993).

The task of high-diameter growth rate of northern red oak trees can be fulfilled by the application of an intensive, crop tree silviculture, as positive selection, targeting the free-growth state at crown level of final crop trees designated at the beginning of pole stage (Štefančík, 2011; Nicolescu *et al.*, 2013) (Figure 1).

The final crop trees are selected, based on the same ‘vigour–quality–distribution’ criteria, as mentioned for cleaning–respacing. Their number per ha is very variable: 60–70 (France -Crave, 1991), 60–120 (Germany – Bauer, 1953; Nagel, 2015), 70–80 (Belgium – Jenner, 1993), 100–120 (France – Lanier *et al.*, 1980; Lanier, 1986), 110–140 (Slovakia – Štefančík, 2011), 200–400 (Czech Republic – Kupka, pers. comm.), 340–400 (Hungary – Redei, pers. comm.). This number depends on the intensity of thinning: it is lower (maximum 100–120 trees ha $^{-1}$) when heavy thinning from above are applied like in France, Germany and Belgium. In these countries, the number of final crop trees is corelated with the target crown size width necessary to reach a certain target d.b.h. (minimum 50–55 cm) or diameter growth rate (ca. 1 cm yr^{-1}).

Pruning

'Formative pruning (shaping)' is necessary in *Q. rubra* trees because of the poor natural pruning in widely spaced plantations, the tendency of forking due to frosts as well as close-to-vertical growth of remaining shoot after deforking (Gelpe *et al.*, 1986; Boudru, 1989; Hubert and Courraud, 1998). The forks as well as thick branches (over 1/3–1/2 of trunk diameter) are removed when tree height is 1.5–3 m. The operation is 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, 1989; Hubert, 1994).

Figure 1 Northern red oak final crop tree in a free-growth state (photo V.N. Nicolescu).

'High pruning', which is carried out similarly to the formative pruning, should start early, eliminating dead branches and a part of small living branches (maximum 3 cm diameter). After the removal of such branches, the majority of pruning wounds heal within 3 years (Soutrenon, 1990a, 1990b, 1991a, 1991b; Nicolescu *et al.*, 2013). This 3 cm value is also the 'threshold level' when considering the effect of branch size on occurrence and amount of discoloured or even rotten wood in northern red oak trees: if branches are thicker than 3 cm, the size of wood discoloration becomes very important and can affect the potential use of northern red oak timber for valuable wood assortments (Sandi *et al.*, 2012; Nicolescu *et al.*, 2013) (Figure 2).

Only final crop trees with large diameters and quick diameter increments should be pruned up to 6 m height, in one or two lifts (first up to 3 m, when trees are 8–10 m tall, then to 6 m) (AFOCEL-ARMEF, 1990; CRPF, 2007). This measure is a part of a dynamic silviculture, combining high pruning with heavy and frequent thinning in favour of final crop trees growing freely (no competition at crown level) (Schulenburg, 1966; Lanier *et al.*, 1980; Gelpe *et al.*, 1986; Lanier, 1986; Crave, 1991; CRPF 2005, 2007).

Conclusion

Northern red oak is a fast-growing, ornamental and tall forest species, able to adapt to poorer ecological/site conditions, which are less favourable for native oaks. So far, the species has not been seriously affected by fungi and insects colonizing its roots, branches, leaves and wood.

It is wind-firm, regenerates readily by seed, coppices easily, is well-adapted to dynamic silvicultural management, including heavy thinning from above and high pruning, in favour of final crop trees. Northern red oak has a shorter rotation than native oaks and produces valuable wood of various end uses; it was therefore considered the 'homologous broadleaved to Douglas-fir' (Lanier, 1986).

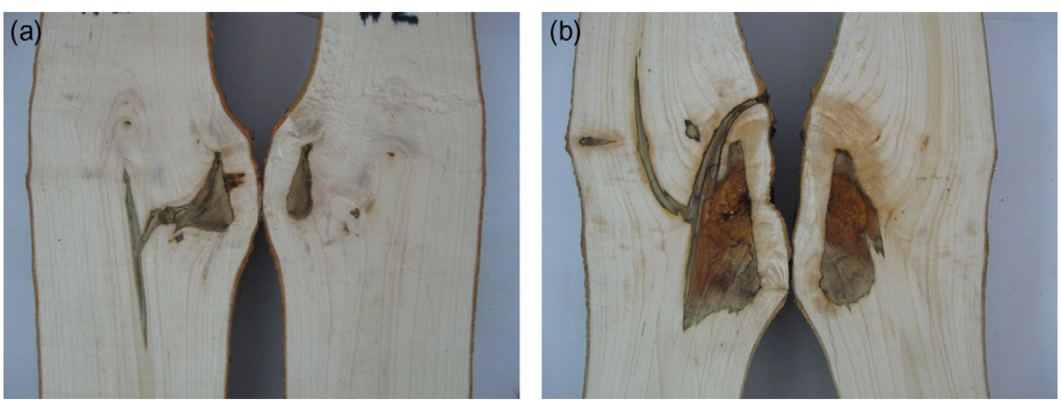

Figure 2 The effect of pruning small branches (a) *vs* large branches (b) on the size of wood discolouration and presence of rot in northern red oak trees (photos V.N. Nicolescu).

As its adaptation potential to predicted climate changes (especially drought) seems to be higher than in case of European native oaks, its importance on our continent is expected to increase in the future.

Supplementary data

Supplementary data are available at *Forestry* online.

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