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REVIEW

A review of black walnut (*Juglans nigra* L.) ecology and management in Europe

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Abstract
Black walnut (*Juglans nigra* L.) is a light-demanding, competition-intolerant, and tall forest tree species, introduced in Europe from North America at the beginning of the seventeenth century. It has an important economic role in Europe for producing wood and fruits, in agroforestry systems, as an ornamental tree for parks and avenues, for rehabilitation/restoration of degraded lands. The best sites for black walnut growth have warm and mild climates, with frequent and well-spread precipitation, and rich, deep, near neutral, well-drained and moist soils. Black walnut is a fast grower in youth and its height and diameter growth reach their peaks before age 30–35 years. It is globally the best known allelopathic species due to the juglone substance present in all parts of black walnut trees. The species is storm-resistant and not affected by any major pest or disease in Europe. It is regenerated by planting or direct seeding on bare land, in monocultures and mixed stands. The management of stands with black walnut, with a rotation period generally up to 80 years, include weeding (mandatory), cleaning-respacing (in dense stands), thinning (mostly from above), high and formative pruning (mandatory), with the aim of producing valuable wood for sliced veneer, solid furniture, flooring/parquet, cabinetry, panelling, sculpture, musical instruments, gunstocks.

Keywords Black walnut *juglans nigra* L. · Ecology · Growth and yield · Management

Introduction

Black walnut, considered as"the most respected of North America's fine hardwoods" and recognized worldwide as the "aristocrat of the fine hardwoods" (American Walnut Manufacturers Association 1998), is found throughout the central and eastern parts of the United States and in southern Ontario, Canada (Rink 1985). However, the area of greatest commercial importance for the species is limited to the central part of its range, particularly the States of Missouri, Iowa, Illinois, Indiana, Michigan, Ohio, West Virginia, Kentucky, and Tennessee (Landt and Phares 1973).

In the native range, black walnut typically grows in many of the mixed mesophytic forests but is seldom abundant. Usually it is found as scattered individual trees or in small groups among other tree species; pure black walnut stands are rare, small, and usually occur as groves at the edge of hardwood forests. The chief associated species include yellow-poplar (*Liriodendron tulipifera* L.), white ash (*Fraxinus americana* L.), black cherry (*Prunus serotina* Ehrh.), basswood (*Tilia americana* L.), beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), oaks (*Quercus* spp.), and hickories (*Carya* spp.). Near the western edge of its range, black walnut may be confined to floodplains, where it grows either with American elm (*Ulmus americana* L.), hackberry (*Celtis occidentalis* L.), green ash (*Fraxinus pennsylvanica* Marsh.), box elder (*Acer negundo* L.), or with basswood and red oak (*Quercus rubra* L.) on lower slopes and other favourable sites (Landt and Phares 1973; Rink 1985; Williams 1990).

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In the United States, the growing stock of black walnut is 126.7 million m^3, 1.0% of total U.S. hardwood growing stock. The species is growing at a rate of 4.6 million m^3 per year while the harvest is 1.6 million m^3 per year so the net volume (after harvest) is increasing by 3.0 million m^3 per year (https://www.americanhardwood.org/en/american-hardwood/american-walnut, accessed 5 May 2019). An important share of annual harvest is exported, with China as the largest market for walnut logs and Canada the largest market for walnut lumber and veneer (Luppold and Bowe 2013).

It is generally considered that black walnut was first introduced to Europe in England, in 1629 (Benčať 1982; Hermann 1987; Bartsch 1989; Rameau et al. 1989). However, this was contested by Hadfield (1977), who considered black walnut as being introduced to Europe earlier, in 1588, by Thomas Hariot (cartographer, mathematician, astronomer, linguist and philosopher, who lived between 1560 and1621, and was a participant in Sir Walter Raleigh's first attempt to establish a colony in Virginia (1585–1586).

The year of introduction of black walnut in other European countries for use in parks, gardens, arboreta, and avenues, as well as in forests, for its valuable timber, fast growth rate, amenity value, and relatively high resistance to pests and diseases, is shown in Table 1.

It was also introduced to the former Soviet Union (Caucasus Region and Tadjikistan—Colpacci 1971) as well as New Zealand (Nicholas 1988; Nicholas et al. 1997) in the second half of nineteenth century. At the beginning of the1980s, black walnut was introduced to China and the early results show the good adaptation of this species to the lower and middle regions of the Yellow River watershed (Van Sambeek et al. 2004).

Currently, black walnut occurs in Europe as a forest tree in at least 14 countries and is reported to cover a total area of 7802 ha (Brus et al. 2019). This value is underestimated (the total area is probably ca. 20 thousand ha) as countries such as Hungary, Italy, Slovakia, Moldova, Bulgaria, France, Germany, where black walnut grows on thousands or hundreds of ha (Table 2), have not been included into the report.

However, black walnut covers important areas in Hungary (in the following counties: Tolna—over 1700 ha, Baranya—over 1000 ha, Somogyi—over 900 ha, Bács-Kiskun—over 700 ha) (Rédei et al. 2019); Romania, in the Iuliu Moldovan Forest District, in the South West of the country, where it has increased from 276 ha in 1980 (Marinchescu and Maior 1981), to ca. 500 ha in 2012, and in Săcueni Forest District, in the North West where it has increased from over 141 ha in 1997 (Nicolescu 1998) to over 210 ha in 2018; in France, in Alsace, around Strasbourg and Colmar, hundreds of hectares have been recorded (Toussaint and Toussaint 1969; Toussaint et al. 1973) and Germany, especially along the river Rhine (Bartsch 1989).

Initially, black walnut was used in Europe as an ornamental tree in parks, gardens and avenues. Nowadays it is cultivated on a large scale primarily for timber production. The wood has a density, at 12% moisture content, between 520 and 810 kg/m^3, on average 610–640 kg/m^3 (Vakulyuk 1991; Feldmann et al. 1995; Molnár and Bariska 2002; Schaarschmidt 2012; Réh 2014; Chiciuc 2017). Its heartwood

Table 1 Year of introduction of black walnut in different European countries

Country	Year of introduction of black walnut in…	
	Parks (including dendrological), gardens (including botanical), arboreta, alleys (streets, roads)	Forests
Hungary	eighteenth century (Rédei and Antal 2017)	1900–1920 (Rédei and Antal 2017)
Ukraine	1809 (Kohno and Kurdyuk 1994)	1850 (Bondar 1997)
Croatia		Ca. 1890 (Sevnik 1926, in Čavlović et al. 2010)
Romania		End of 19th-beginning of twentieth century (Paşcovschi and Purcelean 1954; Haralamb 1967)
Serbia		Ca. 1890 (Sevnik 1926)
Slovenia	1781–1831 (Dobrilovič 2002)	1889 (Papež 2001)
Czech Republic	1799 (Nožička 1956)	1823 (Mráček 1925, in Hrib et al. 2017))
Slovakia	1750–1770 (Benčať 1982)	End of nineteenth century (Holubčik 1968)
Moldova	1842 (Junghietu and Bucăţel 1987)	Mid-twentieth century (Danilov 2010)
Bulgaria		1910 (Dilyanov 1910)
France	End of seventeenth century (Garavel 1960)	1834 (Garavel 1960; Toussaint and Toussaint 1969)
Germany	1634–1686 (Bartsch 1989; Schaarschmidt 2012)	1881 (Bartsch 1989; Schaarschmidt 2012)
United Kingdom	Early 1600 s (Savill 2013); 1656 (Mitchell 1979, in Kerr 1993)	
Poland	1750–1790 (Seneta 1976)	
Italy	1760 (De Toni 1887)	1923 (Ciancio et al. 1982)

Table 2 Area of black walnut in different European countries

Country	Area (ha)	Sources	Notes
Hungary	Ca. 8000	Rédei and Antal (2017)	0.4% of country's forest land; 3400 ha in 1995 [Sarvary (coord.) 1996]
Ukraine	3952.7	Lavnyy and Savchyn (2017)	0.041% of national forests
Croatia	2376.66	Đodan et al. (2017)	0.1% of national forest cover
Romania	Ca. 2100	Stănescu et al. (1997)	
Serbia	1173.2	Banković et al. (2009)	0.1% of national forests
Italy	Ca. 1000	La Porta pers.comm	0.001 of national forest area
Czech Republic	836	Beran (2018)	0.02% of national forests
Slovakia	535	Anonymous (2016)	0.03% of national forests
Moldova	515	Sfeclă pers.comm	
Bulgaria	345.6	Executive Forest Agency (2016)	0.008% of national forest area
France	200–300 (estimate)	Girard pers.comm	
Germany	Less than 200 (estimate)	Vor pers.comm	
Poland	39.18	Gazda et al. (2017)	Over 410 stands including black walnut cover ca. 805 ha
Bosnia and Herzegovina	Less than 10	Cvjetkovic, pers.comm	

Fig. 1 Black walnut wood. Photo A. Zeidler

ranges from light to dark brown in colour but is darker and more uniform than that of Persian walnut (*Juglans regia* L.) and is the only walnut species with traces of purple coloration (Savill 2013). The sapwood is pale yellow to gray to nearly white (Fig. 1).

It is straight-grained, strong, highly shock resistant, durable and easily worked with hand tools or machine. It is rated as highly resistant to heartwood decay, more than the Persian walnut (Smole 2010). Figured grain patterns such as curl, crotch, and burl also occur and are sought after by designers. It glues, stains and finishes and polishes well, and responds well to steam bending (Zdravkov 1970; Vakulyuk 1991; Comănici and Pălăncean 2000; Molnár and Bariska 2002).

As black walnut wood is extremely valuable it is mostly used in Europe, as in the United States, for sliced veneer, decorative purposes (e.g., television cabinets), and for solid furniture (Evans 1984; Williams 1990; Alden 1995; Benvie 1999; Cassens 2004; CRPF Rhône-Alpes 2014). It is one of the most expensive furniture woods in the world, as a result of its appealing surface colour and figure (Molnár and Bariska 2002). Other important uses include flooring/parquet, cabinetry, panelling, staircases, sculpture, musical instruments, turned and carved ornaments, and marquetry. It is particularly valued as the butts for sporting rifles and expensive shotguns (Vakulyuk 1991; Feldmann et al. 1995; Schaarschmidt 2012; CRPF Rhône-Alpes 2014). It is a good firewood and also produces a very high quality charcoal that is highly sought after (Molnár and Bariska 2002; https://www.cdaf.be/docs/web/pdf/A0_interreg/dossier_noyer.pdf, accessed 5 Oct 2019).

High quality black walnut wood commands very high prices, the highest being reached by individual veneer logs which can fetch up to 400 euro/cu.m in Serbia (https://www.vojvodinasume.rs/sume/cenovnici/, 10 May 2019), over 600 euro/cu.m in Austria (Van Loo et al. 2017), 700–1440 euro/cu.m in France (CRPF Rhône-Alpes 2014), over 800 euro/cu.m in Croatia (Đodan et al. 2017), 800–1600 euro/cu.m in Slovakia (private forests—Pástor pers.comm.), over 1000 euro/cu.m in Czech Republic (Hrib 2005) and Slovenia (Gozd in gozdarstvo 2018), ca. 2000 euro/cu.m in Romania (Hernea et al. 2017), and up to 5000 euro/cu.m in Germany (Nickel et al. 2008; Ehring and Keller 2010). However, these prices are lower than the equivalent price of veneer logs

in the United States, which achieved 5000 US dollars/cu.m at the beginning of the 1980s (Young (ed.) 1982; Walker 1990). Even black walnut sawlogs have commanded high prices, for example 200–500 euro/cu.m in France (CRPF Rhône-Alpes 2014).

With the exception of a short period between the late 1990s and early 2000s, when the walnut price was surpassed by that of black cherry and hard maple (*Acer saccharum* Marshall) (Luppold and Bowe 2013), it has always been the most expensive timber in the United States. After a decade of record demand in the 1990s, production and price of hardwood lumber in the United States suffered a moderate decline between 1999 and 2005 plummeting between 2005 and 2009. Black walnut was the last hardwood to decline in price, starting in 2007, and has had the largest price increase since hitting the lowest point in early 2010 (see evolution of price of sawtimber and face veneer of black walnut in Illinois State, between 1977 and 2018—Figs. 2 and 3).

In Europe (France, Dupraz and Liagre 2008; Romania, Nicolescu pers.comm.), black walnut is used in agroforestry systems such as alley cropping but on much smaller scale than in the United States. The primary function of the tree component is biomass production (timber). This is due to the fact that the species is considered as ideal for alley cropping—with soybeans, wheat, corn, red clover, melons, pumpkins, ginseng (Jose 2013)—because of its short growing season, sparse canopy, large taproot, and deep rooting system (Wolz and DeLucia 2019). In portions of the native range, black walnut-based alley cropping is considered as a viable economic alternative to landowners interested in nut production without a loss of income as the trees mature (Jose 2013).

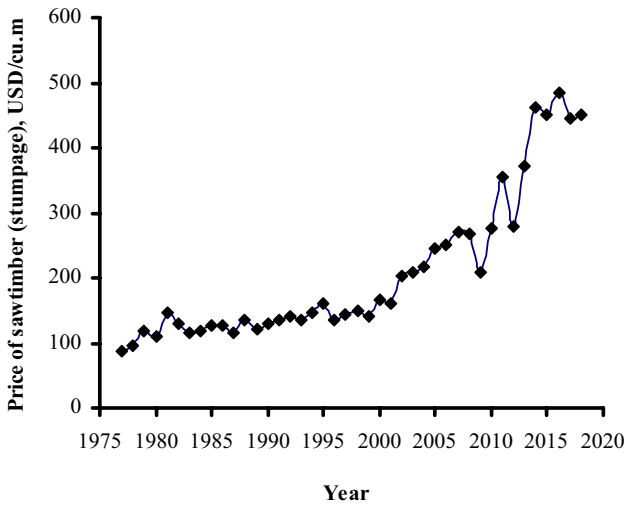

Fig. 2 Evolution of price of sawtimber of black walnut, in US$/cu.m, in the state of Illinois (USA), between 1977 and 2018. Based on the data from https://web.extension.illinois.edu/forestry/illinois_timber_prices.cfm. Accessed 07 Jul 2019

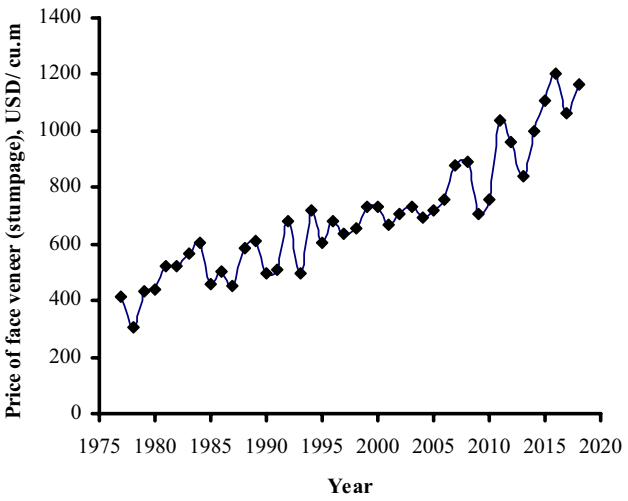

Fig. 3 Evolution of price of face veneer logs of black walnut, in US$/cu.m, in the state of Illinois (USA), between 1977 and 2018. Based on the data from https://web.extension.illinois.edu/forestry/illinois_timber_prices.cfm

Black walnut is also used in Europe, but not as much as in the native range, for nut production, an important food source for wildlife (rodents and birds—Ehring and Keller 2010) and for human consumption. The edible nutmeat (or kernel) is high in mono-saturated fatty acids and antioxidants, such as polyphenols and ɣ-tocopherols. It is used for the prevention and/or attenuation of several of diseases, such as cancer and diabetes and considered a potentially potent dietary supplement for promoting human health (Rodrigues Silva Câmara and Schlegel 2016). The nut is eaten raw, roasted, or pressed to produce oil, and also used as an ingredient for candies, cereals, baked goods and other snacks (Rodrigues Silva Câmara and Schlegel 2016; Wanzel et al. 2017). The green fruit shell (the husk) is well known as natural colorant (Bulatović 1985) and German hunters in particular dye trophies with the dark sap of black walnut husk (Schaarschmidt 2012). In countries like Slovakia, the wooden shell is used to make artefacts, for example pendant necklaces (Kotora pers.comm.).

Black walnut has a high ornamental value, being frequently used in urban areas, parks and gardens of Europe (Kohán 2006; Lozančić 2011; Brus pers.comm.; Petkova pers.comm.). It has also been used in some parts of Europe for the rehabilitation/restoration of degraded land, such as low-productive black locust stands in Moldova (Chiciuc 2017) or former quarries in Croatia (Mayer et al. 1981).

On our continent, black walnut is part of several breeding programs, initiated in the 1980s and 1990s, for example in the UK, France and Italy. The British started with a series of black walnut provenance experiments in 1986–1987, demonstrating the extreme sensitivity of black walnut to site conditions (Kerr 1993). This has continued

with another long-term provenance/progeny programme started in 2001, targeting the identification of superior black walnut trees that can act as seed trees or be cloned for timber production (Russell and Hemery 2004). The French have developed the hybrid *Juglans x intermedia* (*J. nigra* × *J. regia*), with the resulting hybrid cultivar 'Ng23xRa' being well known for its vigour, growth habit and suitability to northern Europe growing conditions (Fady et al. 2003, cited by Van Loo 2018). The hybrid was also planted by farmers in Spain, since the climate there is suitable for timber production in intensively managed plantations. The Italian research program has examined the variability among walnut species for wood production, e.g., growth, shape, and resistance to abiotic and biotic stresses (Gras and Mughini 2010, 2011, in Monteverdi et al. 2017) and prioritise the establishment of orchards with improved selections such as 'Ng23xRa' (Van Loo 2018).

The directions of these programs differ completely than of the United States main breeding effort, which has concentrated on nut production and quality of the black walnut, with the first cultivar ('Thomas') being produced in 1881 (Corsa 1896, cited by Woeste and McKenna 2004). Since then over 700 cultivars have been produced doubling the percentage of edible kernel; seedling walnuts average 17% kernel while some cultivars consistently produced over 34%, even 38% kernel ('Sparks 147′) (Reid et al. 2004; Michler et al. 2007; Ormsby Mori et al. 2018). In addition, efforts have been made to breed a fast-growing, straight-boled, black walnut timber variety (Woeste and McKenna 2004). Other traits of interest in the United States include protandry, resistance to anthracnose (caused by *Gnomonia leptostyla* (Fr.) Ces. & De Not.), high yield, and uniform fruit ripening (Williams 1990; Reid et al. 2004; Victory et al. 2004; Michler et al. 2007). Seed orchards are a fundamental part of most tree improvement plans in the US, and they may be the most tangible product of black walnut improvement (Woeste and McKenna 2004).

There is currently no comprehensive summary of the silviculture, productivity and management of black walnut in Europe that can be used to inform its future role in different countries. In such circumstances, our paper, along with the essential characteristics of the species in Europe (e.g., site requirements, root system, light demands, regeneration ecology and invasive potential, allelopathy, longevity, potential for natural pruning, and vulnerability to pests and diseases), summarizes such information to outline principles for the management of black walnut, including stand establishment, early interventions such as weeding and cleaning-respacing, commercial thinning and pruning (both high and formative), all with the aim of producing top quality wood for superior uses (e.g., veneer, solid furniture, lumber, flooring, piano construction, gun stocks).

Site requirements

Climate

In Europe, black walnut requires a growing season/vegetation period of at least 140 or 150 days, the optimum being 170 days (France—Lestrade et al. 2012; Belgium—https://www.fichierecologique.be/resources/fee/FEE-JN.pdf, Accessed 10 Aug 2019; Bosnia and Herzegovina—Cvjetkovic pers.comm.). This optimum is the same as in the native range, where the growing season ranges from 140 days in the north to 280 days in western Florida (Williams 1990).

The climate in areas suitable for the cultivation of this species should be warm and mild as black walnut requiries mean annual temperatures of 7–10.6°℃ (Belgium, Wallonne Region—https://www.fichierecologique.be/resources/fee/FEE-JN.pdf), 7.5–8.5°℃ (Slovakia—Hančinský 1972), over 8°℃ (Germany—Ehring and Keller 2006), 9.6–11.4°℃ (Bosnia and Herzegovina—Cvjetkovic pers. comm.). In Slovakia, optimal growth of the species is achieved at temperatures ranging from 9.5 to 10.0°℃ (Tokár 2009). In the native range of black walnut, mean annual temperatures range from about 7°℃ in the north to 19°℃ in the south, with about 13°℃ the optimum value for its growth (Williams 1990).

Black walnut is very resistant to low winter temperatures, down to—30°℃ (Šafar 1946; Jovanović 1967; Bulatović 1985; Brus 2011),—35°℃ (Lestrade et al. 2012) or even—40°℃ (Schaarschmidt 2012). It resists cold much better than Persian walnut so there is less risk of frost cracks (Dumitriu-Tătăranu 1960; Garavel 1960; Martin 1979). Warm periods during winter can lead to tension cracks in the stem (Schaarschmidt 2012).

In both the native range and in Europe, black walnut is extremely susceptible to sudden, late, spring frosts, often losing new foliage and flowers in response (Barkley and Brusven 2007). It is more sensitive than Persian walnut to late frosts as it flushes about 15 days earlier (Paşcovschi and Purcelean 1954; Negulescu and Săvulescu 1965; Haralamb 1967; Martin 1979; Kerr 1993; Lestrade et al. 2012). It is also quite sensitive to early, autumn frosts, which can affect insufficiently hardened young shoots causing forking/multiple stems (Führer et al. 2008; Lestrade et al. 2012; Schaarschmidt 2012; https://www.fichierecologique.be/resources/fee/FEE-JN.pdf).

In Europe, the precipitation in areas suitable for black walnut culture should be frequent and well spread over the year, with minimum yearly rainfall very variable: 600 mm (Bosnia and Herzegovina—Cvjetkovic pers. comm.), 600–700 mm (Slovakia—Hančinský 1972), 700 mm (France—Garavel 1960; Italy—Fenaroli 1973),

800 mm (Belgium—(https://www.cdaf.be/docs/web/pdf/A0_interreg/dossier_noyer.pdf), 850–900 mm (Belgium, Wallonne Region -https://www.fichierecologique.be/resources/fee/FEE-JN.pdf), 900 mm (France—Lestrade et al. 2012). In the native range, where annual precipitation ranges between less than 640 mm, in northern Nebraska, to 1780 mm or more in the Appalachians of Tennessee and North Carolina, the optimum growth conditions require average annual precipitation of at least 890 mm (Williams 1990). However, annual precipitation is less important and black walnut was found to grow well with as little as 530 mm/yr (Bartsch 1989), if the soil is deep enough and the roots are in contact with the ground water table to compensate for the atmospheric water deficit (Vor pers.comm.).

Black walnut is variously considered resistant to drought (Chiciuc 2017), to be moderately drought resistant (Brus 2011) or very sensitive to drought (Lestrade et al. 2012). Obviously, it does not like summer droughts, but can tolerate high summer temperatures well if the soil water reserve is high enough (Lestrade et al. 2012; https://www.fichierecologique.be/resources/fee/FEE-JN.pdf).

Although the species is considered as storm resistant due to its deep taproot (Steinaker and Bachmann 2004), black walnut is rather sensitive to strong winds/wind damage so breakage of branches, crown parts or even of trunk can occur (Becquey 1990; Lestrade et al. 2012; Schaarschmidt 2012; CRPF Rhône-Alpes 2014; Brus pers.comm.).

Generally, the ideal sites for black walnut cultivation should be warm (”wine climate”), sheltered (without strong winds), with low risk of either early or late frost, on mid-slope, with a south or south-west aspect (Chard 1949, in Evans 1984; Brus 2011; Lozančić 2011). Such sites are found in the plain and hill areas of Europe, at variable altitudes between 100–300 m, with those between 300 and 400 m considered high risk (Belgium—https://www.fichierecologique.be/resources/fee/FEE-JN.pdf), 150–300 m (Slovakia—Hančinský 1972), maximum 500 m (Romania—Paşcovschi and Purcelean 1954; Negulescu and Săvulescu 1965; Stănescu 1979), maximum 500–600 (700) m (France—Garavel 1971; Anonymous 1981; Becquey 1990; CRPF 1991), maximum 600 m (Belgium—(https://www.cdaf.be/docs/web/pdf/A0_interreg/dossier_noyer.pdf), maximum 800 m (France—Lestrade et al. 2012; CRPF Rhône-Alpes 2014).

Under predicted climate change scenarios, black walnut is likely to become more suited to the British climate (Savill 2013) and is a promising species to enrich the future timber production of lowland forests of Slovenia (Brus pers.comm.).

Soil and topography

Black walnut demands similar soil conditions to European ash (*Fraxinus excelsior* L.) (Toussaint and Toussaint 1969; Schwab 1990). It requires soils rich in humus and nutrients, with a high requirement for Ca, Mg, K, and moderate need of N (Lestrade et al. 2012), deep (minimum 80–100 cm), well-drained, and moist. Soils should be constantly supplied with either ground water [(80–100 cm) 150–200 cm deep] or rainfall (Haralamb 1967; Garavel 1971; Bartsch 1989; Becquey 1990; Hrib et al. 2002, 2003; Ehring and Keller 2010; Oršanic et al. 2010) throughout the whole growing season.

Soil pH between 5 and 7 (7.5) is acceptable but the ideal is between 6 and 7 (Evans 1984; Tokár 1984, 1985; Schaarschmidt 2012; Rédei and Antal 2017). As black walnut does not tolerate limestone well and suffers from foliar chlorosis on basic soils (Nedev et al. 1983; Lestrade et al. 2012), at least 60 cm depth of soil over strongly calcareous horizons or chalk bedrock is required for good growth (Evans 1984). The species is sensitive to pseudogley (deeper than 60 cm), caused by temporary waterlogging, and compaction (clay, heavy soils), so the soil substrate should have a light or moderate texture: sand-loam, loam-sand or, preferably, loam (Haralamb 1967; Dufour and Jay-Allemand 1986; Führer et al. 2008; Brus 2011; Lestrade et al. 2012; Chiciuc 2017).

Black walnut grows best on alluvial plains and alluvial terraces as well as the lower portions of sun-facing slopes, exhibiting good growth on alluvial sites usually used for ash, elm or poplars, where it tolerates temporary flooding without harm (Zdravkov 1970; Ivkov 1971; Lestrade et al. 2012).

Soil requirements of black walnut in Europe are exactly the same as in the native range (Williams 1990; Benvie 1999; Ponder Jr 2004; Barkley and Brusven 2007; Tigner 2010) or in New Zealand (Haslett 1986; Nicholas et al. 1997).

Rooting pattern

In Europe (Zdravkov 1970; Bartsch 1989), as well as in the native range (Williams 1990; Barkley and Brusven 2007; Loseke and Adams 2014), black walnut is well known for the very strong rooting system, developing a deep taproot and many wide spreading lateral roots. The tap can be 80–90 cm or even 120 cm long in the first year (Croatia—Kovacevic 2006; Belgium—(https://www.fichierecologique.be/resources/fee/FEE-JN.pdf) and reach ca. 3 m long in age 3 (Tarhon 2013, 2017). Taproots of mature black walnut trees, on deep and aerated soils, can reach depths of 8–10 m (Moldova—Tarhon 2013, 2017; Ukraine—Lavnyy pers.comm.). As previously mentioned, the deep taproot makes the species storm resistant (Steinaker and Bachmann 2004).

Light demands

In the juvenile stage black walnut is intolerant of shade but withstands a light covering from above during the first years (Herman 1971; Lestrade et al. 2012). Light shade, from above and the side is favoured to protect against the wind and frost. In the adult stage it requires full light—it is a `genuine` light demanding species—but tolerates light lateral competition (Bartsch 1989; Tarhon 2013, 2017; CRPF Rhône-Alpes 2014; https://www.fichierecologique.be/resources/fee/FEE-JN.pdf). In mixed forest stands, it must be dominant or co-dominant to survive. In such closed canopy stands, black walnut natural reproduction from seed is almost never found.

Regeneration ecology and invasive potential

In Europe, natural regeneration *by* seed of black walnut occurs very seldom in closed forests, presumably due to the low shade tolerance and browsing damage to seedlings from voles (*Arborimus* spp.) and hares (*Lepus* spp.) (Schaarschmidt 2012). Nuts are heavy, with 90 cleaned nuts per kg on average (range 25–220; Brinkmann 1974). Thus the main dispersal vectors are rodents, such as squirrels (*Sciurus* spp.), and birds, such as jays (*Garrulus* spp.), magpies (*Pica* spp.) and crows (*Corvus* spp.) (Mayer and Rajković 2008; Schaarschmidt 2012; Pástor pers.comm.).

The sprouting potential of black walnut is classed from poor (Pástor pers.comm.) to high (Herman 1971), and stump shoots are able to grow up to 2 m annually when young (Herman 1971). Sprouts originating near the root collar are generally free from defects, but those occurring higher on older stumps often develop heart rot or other decay from the parent stump (Williams 1990). As black walnut coppices well for only 20–30 years, both in Europe (Haralamb 1967) and the United States (Schlesinger and Funk 1977), it is not treated as simple (low) coppice but only as standard tree in coppice-with-standards, for example in France (Perrin 1958; Garavel 1960; Toussaint and Toussaint 1969).

Across Europe the species is not regarded as invasive. However, the exception is in the Czech Republic, where nature conservationists consider it as undesirable, even invasive (Podrázský pers.comm.).

Allelopathy

Black walnut, in common with other walnut, hickory and pecan (*Carya* spp.) trees, but in higher amounts than these species, produces an allelopathic substance known as juglone (5-hydroxy-1, 4-naphtoquinone). It is present in all parts of black walnut trees but particularly concentrated in the buds, leaves, bark, outer covering of the nut (the husk), and roots (Williams 1990; Michler et al. 2007; Savill 2013). Juglone protects the tree (it is repellent to mosquitos—Tarhon 2013, 2017), and affects formation of micorrhiza (Fisher 1987), as well as seed germination, root and shoot elongations (Rietveld 1982). Seed germination and plant growth are prevented up to 15–18 m away from the black walnut tree (Milošić 2012). Many species are sensitive to juglone: most vegetable crops (Crist and Sherf 1973), corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] (Jose and Gillespie 1998), wheat (*Triticum aestivum* L.) and alfalfa (*Medicago sativa* L.) (all in Scott and Sullivan 2007), tomatoes (*Lycopersicum esculentum* L.), chicory (*Cichorium intybus* L.), fruit trees (e.g., apple *Malus* spp.) (Appleton et al. 2015). However, some of these species such as corn, soybeans, and wheat, which are not very sensitive to juglone, are used with black walnut in alley cropping systems as shown before. Some forest trees are also sensitive to juglone for example paper birch (*Betula papyrifera* Marshall), red pine (*Pinus resinosa* Sol. ex Aiton), eastern white pine (*Pinus strobus* L.), Scots pine (*Pinus sylvestris* L.) (Williams 1990). Pines are particularly sensitive to juglone, and conifers are more sensitive than broadleaves (Rietveld 1982). Juglone even inhibits the growth of young plants of black walnut (Tigner 2010).

The allelopathic activity of juglone is low (or even absent) in dry soils but high in those with high water content such as poorly drained, compacted soils (Fisher 1978; Rietveld 1982). The effects of toxic juglone do not occur immediately after planting black walnut but can appear after 12–15 years (Beineke 1985) or 12–25 years (Rietveld 1982; Rink 1985).

Longevity

The longevity/life-span of black walnut in Europe is long, exceeding 200 years (Garavel 1960; Lanier 1986), 250 years (Mayer and Rajković 2008), 270 years (Pavolini 1999; Cassarino 2011) or even 300 years (Gathy and Evrard 1976; Rameau et al. 1989). A good example is the largest black walnut tree in Central Europe, also one of the largest in Europe, located in the Castle Park in the town of Sereď (western Slovakia). It was planted in 1712 so is 308 years old and had a dbh of 201 cm and a height of 25 m in 2012 (Majko 2012) (Fig. 4).

Potential for natural pruning

Self-pruning is considered from good, in dense stands (Paşcovschi and Purcelean 1954; Negulescu and Săvulescu 1965; Haralamb 1967; Stănescu 1979) to satisfactory (Toussaint et al. 1973) or even bad, with black walnut trees unable to prune themselves cleanly and readily, even under conditions of heavy side shade, so artificial pruning is required to produce high-value, knot-free trees (Schlesinger 1988a, b; Schlesinger 1989; Mayer and Rajković 2008). The data

Fig. 4 The largest black walnut tree in Slovakia. Photo B. Biro

obtained in a pure black walnut plantation 2.0 × 1.0 m, with five R&D plots (150 sq.m each; mean diameters of trees in the five plots: 6.2–9.2 cm) showing a stocking between 2,533 and 3,800 trees per ha is in line with the latter conclusion. At age 12 years, only 21 trees (10%) out of 213 individuals were perfectly pruned with no branches or stubs up to 2.0 m height. The remaining 192 trees had 807 branches (range 1–12 branches per tree) of which 87% were dead and 13% alive; of the total branches, 9% were at least 3 cm in diameter. The majority of living branches were at least 3 cm in diameter and oblique-ascendant (acute angle to vertical), with the majority of the length in full light so natural shedding was impossible (Nicolescu et al. 2003a, b). The angle of insertion of branches from the horizontal in the same black walnut plantation was relatively constant, with a mean value of 62.47° (range 55.53–74.08°), making the natural shedding of branches impossible and imposing the requirement for artificial pruning to produce knot-free logs (Kruch and Nicolescu 2012).

An initial spacing of 2.0 × 1.0 m in black walnut plantations seems to be an acceptable compromise for a good natural pruning (Bulgaria: Nenkov et al. 1991), but this is at the expense of diameter increment, therefore wider spacings combined with artificial pruning are preferred in European countries like Germany (Bartsch 1989; Ehring and Keller 2010). In the United States, the sacrifice of diameter growth at the higher density may be acceptable since black walnut log buyers are increasingly seeking higher quality logs with smaller diameters over lower quality logs with larger diameters, given advances in veneer production technology (Phelps 1989, Kesner 1986, cited by Bohanek and Groninger 2003).

Vulnerability to pests and diseases

In Europe, black walnut is considered to suffer very little from insect outbreaks (Jovanović 1967; Nenkov et al. 1991), compared to the USA, where it suffers damage by more than 300 species in Illinois State, although only a few are considered serious pests (Williams 1990; Katovich 2004). These are:

1. Defoliating insects, such as walnut caterpillar *Datana integerrima* Grote and Robinson, yellow necked caterpillar *Datana ministra* Drury, and fall webworm *Hyphantria cunea* Drury;
2. Boring insects, such as ambrosia beetle (*Xylosandrus germanus* Blanford), the flatheaded apple tree borer (*Chrysobothris femorata* Olivier), and the walnut shoot moth (*Acrobasis demotella* Grote), which damages the terminal buds, causing multiple forks and crooks in the main stem;
3. Sucking insects, such as aphids or plant lice (*Monellia* spp. and *Monelliopsis* spp.), and the walnut lace bug (*Corythucha juglandis* Fitch).
4. Insects damaging developing nuts, such as black walnut curculio *Conotrachelus retentus* Say.

Black walnut has a relatively high resistance to various diseases (Nenkov et al. 1991; Kohán 2006), so rarely suffers damage (Kovačević 2006; Mayer and Rajković 2008). In Europe, there have been several reports of disease damages for example from fungi *Gnomonia leptostyla* (Fr.), the most serious leaf disease of black walnut in the native range (Mielke and Ostry 2004), causing leaf blotch and leaf spots (Tomiczek et al. 2008), *Inonotus hyspidus* (Fr.) Karst. causing white rot of wood (Tomiczek et al. 2008), and white berried mistletoe (*Viscum album* L.) and yellow mistletoe (*Loranthus europaeus* Jacq.) infesting the crown (Idžotić 2003; Idžotić et al. 2006, 2007). Black walnut is also sensitive to root collar decay caused by the fungus *Phytophthora cactorum* (Lebert & Cohn) S. Schröt. (Nedev et al. 1983).

In Europe, the species is also affected by wild boars (*Sus scrofa* L.), squirrels (*Sciurrus vulgaris* L.), crows (*Corvus* spp.) and mice (*Apodemus* spp.), who dug up the freshly sown seeds. Young seedlings can be damaged by slugs (*Limax* spp.), voles or hares, and saplings are often frayed by

roe deer (*Capreolus capreolus* L.) (Herman 1971; Bartsch 1989; Ehring and Keller 2010).

In the United States, white-tailed deer (*Odocoileus virginianus* Zimmermann) browses the new growth of young trees; between years 3 and 5, male deer rub their antlers on the young stems in the autumn. Rabbits (*Sylvilagus* spp.) and voles can be destructive in young plantations (McKenna and Farlee 2013).

As browsing damage is rare, fencing of black walnut plantations in Europe is not necessary (Germany—Ehring and Keller 2010); however, like in Hungary, where both red (*Cervus elaphus* L.) and roe deer browse the new growth of black walnut, success of planting depends on fencing, which is considered sometimes essential, although expensive (Führer et al. 2008).

In the native range, deer damage can be reduced through fencing, tree tubes or wire cages, increased hunting pressure to reduce populations, extremely high density plantings, or techniques to scare away the deer using dogs or noise (Pierce and Wiggers 1997).

Growth and yield dynamics

Height growth

Young black walnut seedlings grow quickly in height (up to 1 m year^{-1}) in the first years, reaching 7–8 m tall at 8 years of age (France, ONF 1988; Germany, Bartsch 1989; Bulgaria, Marinov and Kanev 1983; Ukraine, Lavnyy pers. comm.). Such high early increment is similar to that of black walnut in the United States, where values of 60–90 (even 120) cm year^{-1} on good sites have been recorded (Brinkman 1965; Williams 1990; Barkley and Brusven 2007). The height increment reaches the peak at maximum 15–20 (25) years of age (Sarvary 1996; Čavlović et al. 2007). Height performances of pure walnut plantations in different European countries are shown in Table 3.

These values are similar to the mean heights of black walnut plantations in the United States, recorded by Kellog 1937 (in Brinkman 1965: heights at 12–16 m in 20 years) and Williams (1990—mature trees, on good sites, may reach 30 to 37 m in height).

Individual black walnut trees have reached impressive heights in Europe, for example 28 m in Bosnia and Herzegovina (Cvjetkovic pers.comm.), 35 m in France (Martin 1979), Belgium (Baudouin 1990) and Slovenia (Oršanić

Table 3 Mean height of black walnut cultures in several European countries

Mean age (years)	Mean height (m)	Country	References
15	12.2	Romania	Nicolescu et al. (2003a, b)
15	13.0	Bulgaria	Kalmukov (2009)
20	14.0	Bosnia and Herzegovina	Mataruga pers.comm
20	15.9	Romania	Nicolescu et al. (2003a, b)
20	17.4	Czech Republic	Šálek and Hejcmanova (2011)
20	19.0	Italy	Postal (2019)
28	20.7	Serbia	Banković et al. (2000)
30	18.0	Bulgaria	Kalmukov (2009)
31	20.3	Serbia	Banković et al. (2000)
39	24.8	Slovakia	Tokár (1998)
39	24.8	Romania	Nicolescu et al. (2003a, b)
40	25.1	Czech Republic	Šálek and Hejcmanova (2011)
42	23.2	Germany	Riebeling (1991)
44	26.8	Serbia	Banković et al. (2000)
49	23.5	Bulgaria	Marinov and Kanev (1983)
50	28.5	Romania	Nicolescu et al. (2003a, b)
50	30.0	Croatia	Čavlović et al. (2007)
50	30.0	Italy	Postal (2019)
59	30.4	Germany	Riebeling (1991)
60	29.6	Czech Republic	Šálek and Hejcmanova (2011)
80	32.8	Czech Republic	Šálek and Hejcmanova (2011)
100	35.3	Czech Republic	Šálek and Hejcmanova (2011)
107	35.9	Czech Republic	Hrib et al. (2003), in Šálek and Hejcmanova (2011)

2011), 36 m in the UK (Mitchell et al. 1990), 37 m in Germany (Schepp pers. comm.). The tallest black walnut tree in Europe is presumed to be one found in Italy at 40.5 m (https://www.monumentaltrees.com/en/ita-easternblackwalnut/, accessed 11 Sep 2019). These performances are less than the tallest black walnut tree in the United States which is 46 m height (Harlow et al. 1979; Williams 1990).

Diameter growth

Black walnut grows quickly in diameter in favourable conditions: 0.7–0.8 cm year^{-1} (UK, McDonald et al. 1964), 0.8–0.9 cm year^{-1} (Belgium, Gathy and Evrard 1976), or 1.0 cm year^{-1} [France, Garavel 1960; Toussaint and Toussaint 1969; Toussaint et al. 1973; Becquey (coord.) 1997]. The mean diameter increment of free-grown trees in France (Alsace Region) reached 1.2–1.5 cm year^{-1} (Toussaint and Toussaint 1969; Toussaint et al. 1973). This is similar to the highest diameter increments in the native range (maximum 1.2 cm year^{-1}—Landt and Phares 1973; Rink 1985, or even 1.4 cm year^{-1}—Van Sambeek and Rink 1985) and in New Zealand under exceptional growth conditions and with most of the trees open-grown (1.5–1.7 cm year^{-1}, Nicholas 1979, 1988; Levack (ed.) 1986). Maximum diameter increment of black walnut trees is achieved between 20 and 35 years of age (Sarvary 1996).

Diameter performances of pure black walnut plantations in different European countries are shown in Table 4.

These values are similar to the mean diameters of black walnut plantations in the United States as shown by Baker 1921 (diameters of 12.5 cm at 20 years, 22 cm at 30 years, 31.3 cm at 40 years etc.), Kellog 1937 (in Brinkman 1965: diameters of 12.5 cm to 20 cm in 20 years) and Williams (1990—mature trees, on good sites, may reach 76–102 cm in diameter).

Individual black walnut trees, on favourable sites, e.g. in the Alsace Region of France, can reach 60–65 cm in diameter at 60–70 years of age (Toussaint and Toussaint 1969; Toussaint et al. 1973; Becquey (coord.) 1997). This is also the case of black walnut forest stands in the north-west of Romania (Săcueni Forest District), where trees over 70 cm dbh have been produced in less than 70 years (Fig. 5).

The largest individual black walnut trees can reach impressive sizes in different European countries: over 100 cm dbh in Moldova (Sfeclă pers.comm.) (Fig. 6), 116 cm in Romania, 125 cm in France, 132 cm in Czech Republic, 134 cm in Austria, 151 cm in Belgium, 159 cm in Netherlands, 174 cm in Poland, 200 cm in Hungary, 201 cm in Slovakia, 205 cm in Italy, 221 cm in the UK, and 232 cm in Germany (www.monumentaltrees.com/en/trees/easternblackwalnut/records/, accessed 11 Sep 2019).

The largest black walnut trees in Europe are similar in size to the record for the United States: dbh of 205 cm at 157 years of age (2018) (https://www.monumentaltrees.com/en/usa-easternblackwalnut/, accessed 11 Sep 2019). The former record in the native range was 224 cm in diameter (Harlow et al. 1979; Williams 1990).

Table 4 Mean diameter of black walnut cultures in several European countries

Mean age (years)	Mean diameter (cm)	Country	References
13	13.0	Italy	Mantovani and Calvo (2013)
15	13.6	Romania	Nicolescu et al. (2003a, b)
15	12.0	Bulgaria	Kalmukov (2009)
20	15.3	Romania	Nicolescu et al. (2003a, b)
20	15.1	Bosnia and Herzegovina	Mataruga pers.comm
26	23.6	Italy	Bordin et al. (1997)
28	23.1	Serbia	Banković et al. (2000)
30	18.0	Bulgaria	Kalmukov (2009)
31	25.7	Serbia	Banković et al. (2000)
39	23.3	Slovakia	Tokár (1998)
39	25.2	Romania	Nicolescu et al. (2003a, b)
42	28.3	Germany	Riebeling (1991)
44	33.6	Serbia	Banković et al. (2000)
49	23.3	Bulgaria	Marinov and Kanev (1983)
49	20.0–22.7	Slovakia	Tokár (1998)
50	36.4	Romania	Nicolescu et al. (2003a, b)
50	30.0	Croatia	Čavlović et al. (2007)
59	40.3	Germany	Riebeling (1991)
80	42.0	Croatia	Mayer and Rajković (2008), Mayer (2011)
98	50.1	Romania	Nicolescu et al. (2003a, b)

Volume growth and yield

The mean volume increment of black walnut in several European countries and at different ages is shown in Table 5.

In pure plantations of black walnut in the central United States, mean volume increment ranges between 2 and 5 m^3 ha^{-1} yr^{-1} (Ferrell and Lundgren 1975, in Pedlar et al. 2006).

On ideal sites, with a high growing potential for black walnut (e.g., floodplains, with alluvial soils—Croatia, Czech Republic), the species grows faster than native species such as pedunculate oak (*Quercus robur* L.), narrow-leaved

Fig. 5 Large black walnut tree (dbh 72.8 cm, at 68 years of age) in Săcueni Forest District. Photo VN Nicolescu

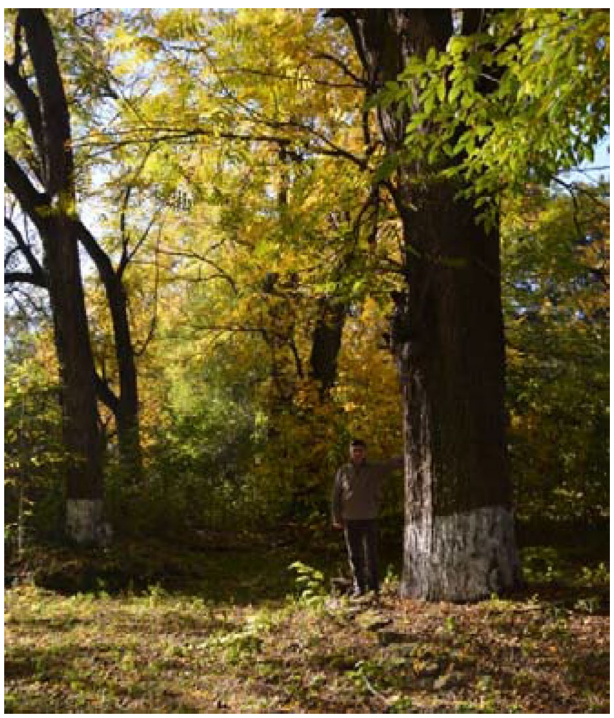

Fig. 6 The thickest black walnut tree in Moldova: over 100 cm in diameter at 130 years. Photo V. Sfeclă

ash (*Fraxinus angustifolia* Vahl), black alder (*Alnus glutinosa* (L.) Gaertn.) as well as non-natives such as green ash (*Fraxinus pennsylvanica* Marshall). At 100 years, differences in standing volume are ca. 100 m^3 ha^{-1} compared with pedunculate oak and more than 200 m^3 ha^{-1} compared with narrow-leaved ash (Šálek 2012; Šálek et al. 2012). Consequently, black walnut can be an alternative to other tree species growing in the same natural conditions (Šálek et al. 2012).

However, these figures must be considered very cautiously, as volume and yield/production tables do not exist for black walnut in Europe, so the volume calculations use those for domestic oaks in Czech Republic (Šálek 2012; Šálek and Hejcmanova 2011), Bosnia and Herzegovina (Cvjetkovic pers.comm.), Slovakia (Pástor pers.comm.), or Bulgaria (Petkova pers.comm.). In other countries, black walnut volumes are calculated using volume tables for domestic ash (Czech Republic, Šálek 2012; Šálek and Hejcmanova 2011), black alder or black locust (*Robinia pseudoacacia* L.) (Bosnia and Herzegovina, Cvjetkovic pers.comm.). The Romanian volume tables show that such calculations induce bias as the black walnut bole (average form factor FF 0.435) has a more conical shape than both pedunculate oak (FF 0.475) and sessile oak *Quercus petraea* (FF 0.480), but a more cylindrical shape than ash (FF 0.420) and black locust (FF 0.380) (Decei et al. 1986).

Other relevant biometric traits

In black walnut, the proportion of branches with respect to total tree volume varies between 7 and 21%; it is the highest in thick, short trees and lowest in thin and tall ones. The double thickness of bark increases with increasing dbh: it is 4 mm when dbh is 2 cm and reaches 51 mm when dbh is 50 cm (Decei et al. 1986) (Fig. 7).

The volume of bark as % of total tree volume decreases from 32% (dbh 12 cm) to 22% (dbh 50 cm) (Fig. 8).

The double bark thickness is 4–16 mm, in trees with d = 2–10 cm, and 43–52 mm, in trees with 30–50 cm in diameter (Hulea 1988).

Management of black walnut

Goals

In European countries (e.g., Belgium, Bosnia and Herzegovina, Croatia, Czech Republic, France, Germany, Romania, Serbia, Slovakia, Ukraine) where black walnut is cultivated on different scales, the exclusive goal of its culture is the production of top quality wood for superior uses (e.g., veneer, solid furniture, lumber, flooring, piano construction, gun stocks). To achieve this goal, in countries like France, the veneer logs should have a minimum diameter

Table 5 Mean volume increment of black walnut in several European countries and at different ages

Mean volume increment $m^3\ ha^{-1}\ year^{-1}$	Country	References	Observation
3.5–4.0	France-Alsace Region	Gathy and Evrard (1976)	Age 60
5–6	Italy	Fenaroli (1973), in Ciancio et al. (1982)	
7.5	Germany	Riebeling (1991)	Age 59
5.5	Germany	Bartsch (1989)	Age 73
4.8	Croatia	Čavlović et al. (2010)	Age 50
2.7	Croatia	Čavlović et al. (2010)	Age 80
5.6–6.3	Serbia	Banković et al. (2000)	Age 31
8.1	Serbia	Banković et al. 2000	Age 28
11.0	Serbia	Banković et al. (2000)	Age 44
(6) 8–9	Slovakia Belgium Hungary	Tokár (1982, 1984, 1987, 1989) Bary-Lenger et al. (1988) Sarvary (1996)	Age 60

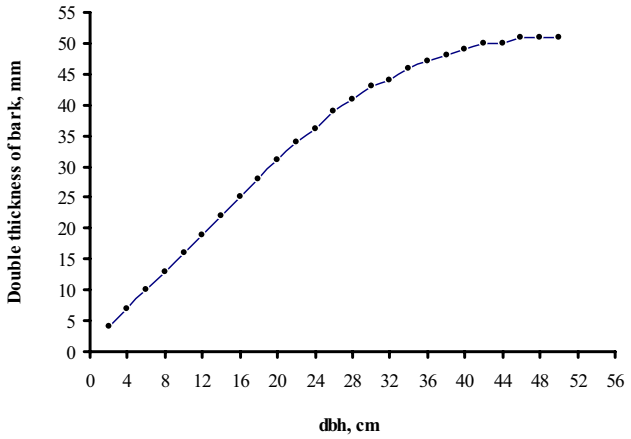

Fig. 7 Correlation between dbh and double bark thickness in black walnut trees. Romania, Decei et al. (1986)

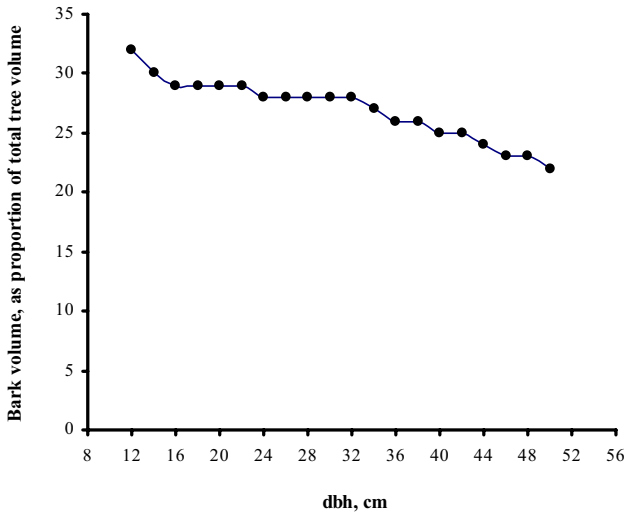

Fig. 8 Correlation between dbh and bark volume in black walnut trees, as % of total tree volume. Romania, Decei et al. (1986)

at mid-length of 60 cm, and a minimum length of 2.5 m, whereas the sawlogs should be minimum 45 cm in diameter at mid-length and have a minimum length of 2–2.5 m (CRPF Rhône-Alpes 2014). Such large-diameter trees are produced in stands managed as high forests, with the exception of France where black walnut has been used historically as a standard tree to improve coppice-with-standards (Perrin 1958; Garavel 1960; Toussaint and Toussaint 1969).

In different European countries, production of large-diameter veneer logs requires rotations ranging between 60 and 100 years; the majority are a maximum of 80 years. In case of sawlogs, the rotations are maximum 60 years. Rotation ages of black walnut stands in several European countries are shown in Table 6.

In the United States, the rotation age of black walnut for high-quality wood assortments was 80 or 90 years a century ago (Baker 1921). It has dropped to 70–80 years in natural stands and 40–60 years in well-managed plantations established on good sites (McKenna and Farlee 2013); currently it is 60–80 years (https://files.dnr.state.mn.us/forestry/ecssilviculture/covertype/covertype_blackWalnut.pdf, accessed 12 Aug 2019).

In New Zealand, rotation ages of black walnut plantations is 40–50 years (stands established under very favourable growing conditions; trees ca. 60 cm in diameter—Knowles 1978; Nicholas 1979; Haslett 1986; Levack (ed.) 1986) or 60–70 years (less favourable site conditions, same target diameter—Nicholas 1988).

Regeneration and stand establishment

Natural regeneration

In Europe, as mentioned earlier (sub-section "regeneration ecology"), black walnut is not able to regenerate naturally by seed under the canopy of high forest stands. As the

Table 6 Rotation age of black walnut in different European countries

Rotation age (years)	Country	References	Observations
30–50	Italy	Ferraris et al. (2001)	For lumber production; it can be shorter under optimal conditions
40	United Kingdom	Evans (1984)	For lumber production (minimum 30 cm)
40–60	Bosnia and Herzegovina	Cvjetkovic pers.comm	For lumber production
40–60	Italy	Brocchi-Colonna and Mezzalira (2003)	For lumber production
51–60	Ukraine	Lavnyy pers.comm	For lumber production; no target diameter
60	United Kingdom	Russell and Hemery (2004)	For high quality timber
60–70	Belgium (Wallonne Region)	https://www.fichierecologique.be/resources/fee/FEE-JN.pdf	
60–70	France	Garavel (1971), Anonymous (1981)	Target diameter 60–65 cm
60–70	France	Becquey (coord.) (1997)	
60–80	Germany	Ehring and Keller (2010), Rumpf and Nagel (2014)	Target diameter at least 60–65 cm
70	France (Alsace)	Toussaint and Toussaint (1969), Toussaint et al. (1973)	Trees can reach 65–70 cm in favourable site conditions
70–80	Belgium	Boudru (1989)	
75–85	Hungary	Führer et al. (2008), Rédei and Antal (2017)	
80	Serbia	Andrašev pers.comm	
80	Slovenia	Brus pers.comm	Target diameter 50 cm or more
80	Croatia	Mayer and Rajković (2008), Mayer (2011), Perić et al. (2017)	
80	Hungary	Sarvary (1996)	
80–100	Slovakia	Petráš et al. (2017)	Depending on site conditions
90	Czech Republic	Podrázský pers.comm	
90–100	France	Garavel (1960)	
100	France	ONF (1988)	Target diameter 70 cm
100	Bulgaria	Regulation no. 18 of 07.10. 2015 for inventory and planning of the forest territories	

coppicing potential is low and only at young ages (maximum 20–30 years), black walnut is not treated in simple (low) coppice but only as standard tree in coppice-with-standards, as in France (Perrin 1958; Garavel 1960; Toussaint and Toussaint 1969).

Artificial regeneration

Black walnut can be established artificially by both direct (manual) sowing and planting. The forest reproductive material is collected from individual 'plus' trees, certified/selected seed stands and seed orchards; these exist in Croatia, Czech Republic, Germany, Hungary, Romania, Serbia, Slovakia (Ehring and Keller 2010; MMP-RNP-ICAS 2012; Rumpf and Nagel 2014; Mettendorf 2016; Ministry of Agriculture 2017; Anonymous 2018; Andrašev pers.comm.; Podrázský pers.comm.; Rédei pers.comm.).

Individual black walnut trees start bearing fruits at 8–10 years (Haralamb 1967; Herman 1971) but the first large seed crops do not occur in the stands until the trees are (15) 20–30 years both in Europe (Toussaint et al. 1973; https://www.fichierecologique.be/resources/fee/FEE-JN.pdf) and the United States (Landt and Phares 1973; Williams 1990). Abundant seed years occur annually (Romania, Haralamb 1967; Germany, Jestaedt 1990) or twice in 5 years in Europe (France, Toussaint et al. 1973; Bosnia and Herzegovina, Cvjetkovic pers.comm.) and the native range (Landt ad Phares 1973; Barkley and Brusven 2007). The nuts ripen in autumn (September–October) of the same year and drop shortly after the leaves fall.

Direct seeding of cleaned (without green husk) nuts, after soil preparation, is carried out either in autumn, immediately after fruit dispersal, which eliminates additional seed handling, or in spring (March–April), resulting in higher stocking, possibly due to the decreased time of exposure to seed predators, generally at 6–8 (10) cm depth (Schaeffer 1971; Hubert 1981; Ciancio et al. 1982; Oršanić et al. 2010; Brus pers.comm.; Sfeclă pers.comm.). In case of spring sowing, stratification of cleaned nuts in sand or other media for 90–120 days at 1–5 °C is required for optimum seed

germination in Europe (Rubțov 1958; Damian 1978) and the United States (Williams 1990; Farlee 2013). Seeds are sown in nests (2–3 nuts/nest), at 1.5 × 1.5 m spacing (Paşcovschi and Purcelean 1954; Haralamb 1967) or more frequently in rows. Initial sowing distance: 4.0 × 0.25 m in Croatia (Mayer 2008, 2011), 3.0 × 0.5 m in Serbia (Andrašev pers.comm.), 1.0 or 2.0 m × 1.0 or 2.0 m in Slovakia (Pástor pers.comm.). The success of direct sowing can be high: when using the 4.0 × 0.25 m seeding scheme, the success rate in year three was 55% or around 5,000 seedlings per ha (Croatia, Mayer 2008, 2011).

In practice, direct (manual) sowing is used when targeting the reduction of establishment costs or when there is a risk of damaging the long taproot of black walnut seedlings when transplanting from the nursery (Serbia—Andrašev pers.comm.; Lavnyy pers.comm.). This method is cheaper than planting but challenged frequently as the seedlings are fragile at the end of first growing season and are sensitive to low winter temperatures. Consequently, direct seeding should be used only in frost-free areas and where full protection from predation can be assured (Evans 1984).

For seedling production, the cleaned nuts are sown in bare-root nurseries in spring (March–April), after the winter stratification. They are placed horizontally, at 3–6 cm depth and 30 × 10 (12) cm distance (Rubțov 1958; Haralamb 1967; Toussaint et al. 1973). The nuts need 2–3 to 6–10 weeks to germinate (hypogeal) and emerge, and the seedlings are ready for planting after 1 year, when they are a minimum of 30 cm tall (can reach up to 60–70 (80) cm) and develop a strong taproot at least 50–60 cm long. Interestingly, germination of some black walnut seeds is delayed until the second year, both in Europe (Herman 1971, Jovanovic 1967) and the United States (Beineke 1989; Williams 1990; Farlee 2013). The reason for using cleaned nuts rather than those with husks for seedling production is because of the better nursery germination: 91.67%, compared to only 73.00% (Oršanić et al. 2010).

This solution of producing 1-year-old seedlings is preferred all over Europe (in Belgium, Gathy and Evrard 1976; Boudru 1989; Bosnia and Herzegovina, Cvjetkovic pers.comm.; Croatia, Oršanić et al. 2010; Lozančić 2011; France, Martin 1979; Hubert 1981; Becquey (coord.) 1997; Romania, Paşcovschi and Purcelean 1954; Haralamb 1967; Damian 1978; Ukraine, Lavnyy pers.comm.), as it is cheap, provides the best survival rate and the long taproot is not damaged during the transplanting. The same solution is preferred in the United States (Chapman 1961; Brinkman 1974; Schlesinger and Funk 1977; Burke and Pennington 1989) and New Zealand (Nicholas 1979). The only difference consists in the proposal of cutting the taproot 25–30 cm below the collar level, when lifting the plants for transplanting, as in the US (Brinkman 1974) and New Zealand (Knowles 1978; Nicholas 1979). In Europe, as the taproot is considered extremely important for survival, vitality and early growth of seedlings, and is sensitive to undercutting, it should not be damaged by undercutting or lifting in nursery when transplanting (Podrázský pers.comm.; Vor pers.comm.).

Bare-rooted black walnut seedlings are usually planted in spring (Paşcovschi and Purcelean 1954; Schaeffer 1971; Gathy and Evrard 1976); the months of April and May, after the danger of late freezes, are considered as the most desirable (Führer et al. 2008). Spring planting is also preferred in the US (Beineke 1985). Autumn planting (October–November) is sometimes proposed, on a much lower scale, but can be successful only under certain conditions (e.g., frost-free areas) (Führer et al. 2008).

The initial stocking density of black walnut plantations for timber production in Europe is highly variable and ranges from less than 100 to 5000 plants ha^{-1} (Table 7).

In close spacing (at least 4000 plants per ha), trees grow slower in diameter, and there are additional trees from which to select the future crop trees in early thinnings, that will produce a higher quality timber and veneer trees. Wider spacing, such as 3.0 × 3.0 m (1100 plants per ha), can produce a reasonably high quality timber in fewer years than narrow spacing; therefore, such spacing is considered in the native range to produce a good trade-off between black walnut growth, wood quality and silvicultural input levels, and optimal for black walnut growth in the absence of thinning up to 30 years of age (Van Sambeek 1988; Pedlar 2006). The closer the spacing, the sooner you will have to thin (Barkley and Brusven 2007).

In addition, wider spacings (3.0 m, 3.6 m, or 4.0 between rows) are recommended in both Europe (see above), the native range (Schlesinger and Funk 1977; Beineke 1985; Burde (ed.) 1988; Van Sambeek 1988; Pedlar 2006) and New Zealand (Knowles 1978; Masterson 1990) because they reduce the costs of tending young plantations by mechanized weed control (Funk et al. 1978).

In Europe, black walnut is planted as both a monoculture (e.g., in Bosnia and Herzegovina, Czech Republic, Hungary, Serbia, Slovenia) and in mixed stands. Mixed plantations of black walnut and pedunculate oak, elm (*Ulmus* spp.) and narrow-leaved ash (Croatia, Lozančić 2011), northern red oak (Slovakia, Tokár, 1982, 1987, 1989), oaks (*Quercus* spp.), maples (*Acer* spp.), ash (*Fraxinus* spp.), and linden/lime (*Tilia* spp.) (Slovakia—Pástor pers.comm.), hickories (*Carya* spp.) (France- Alsace, Toussaint and Toussaint 1969, Schwab 1990), silver linden (*Tilia tomentosa* Muench) and narrow-leaved ash (Bulgaria, Marinov and Kanev 1983), black locust and Italian alder (*Alnus cordata* (Loisel.) Duby) (Italy, Buresti and de Meo 1995; Paris et al. 2005) have been reported. A special situation is encountered in the north-west of Romania (Săcueni Forest District), where the stands including black walnut cover ca. 430 ha, of which the species itself

Table 7 The initial stocking of black walnut plantations for timber production in different European countries

Initial stocking (plants ha^{-1})	Initial spacing, m	Country	Sources	Comment
70–100	10.0×10.0; 12.0×12.0	France	CRPF Rhône-Alpes (2014)	On former agricultural land, or after a clear cut
100–120	9.0×9.0; 10.0×10.0	Italy	Buresti and Mori (1995)	Requires good water availability and fertile, well-drained soils with subacidic pH
200–280	6.0×6.0; 6.0×8.0	Italy	Ferraris et al. (2001)	In pure plantation or sometimes mixed with poplar which is cut at 1/3 of the rotation (30–50 years)
300–1,000		Germany	Ehring and Keller (2010)	To save costs, provide enough space per trees; artificial pruning is necessary regardless initial stocking
400–833	3.0×4.0; 3.0×5.0 4.0×4.0; 5.0×5.0	France	Becquey (coord.) (1997)	
625–1100	3.0×3.0; 3.6×3.6; 4.0×4.0	France Belgium	Schaeffer (1971), Toussaint and Toussaint (1969), Evrard and Gathy (1976)	
625–1100	3.0×3.0; 4.0×4.0	United Kingdom	Evans (1984)	
1500–2500		Germany	Rumpf and Nagel (2014)	Maximum distance between rows 3 m to promote self-pruning and provide enough future crop trees
1600	2.5×2.5	Germany	Schwab (1990)	
1600	2.5×2.5	France	ONF (1988)	Colmar-Niederwald (Alsace Region)
2222	3×1.5	Moldova	Comănici and Pălăncean (2000), Danilov (2010)	
4000–5000	2.5–2.8×0.7–1.0	Hungary	Führer et al. (2008)	
4444	1.5×1.5	Romania	Paşcovschi and Purcelean (1954)	
4762–5000	3.0×0.7; 4.0×0.5	Ukraine	Lavnyy pers.comm	
5000	2.0×1.0	Romania	MAPPM (2000)	On bare lands and for rehabilitation-substitution of low productivity stands

is found on over 210 ha. Black walnut is part of 134 stands, of which only 23 are monocultures; the rest are mixed stands, where black walnut grows along with either native (e.g., pedunculate oak, European ash, small-leaved linden *Tilia cordata* Mill.) or non-native (e.g., northern red oak, black cherry, pin oak *Quercus palustris* Muenchh., bitternut hickory *Carya cordiformis* (Wangenh.) K. Koch) tree species (Fig. 9).

In the United States, within the plantation and among the walnut trees, northern red oak is complementary in growth to black walnut. It is not the case of black alder (*Alnus glutinosa* (L) Gaertn.), a N-fixing species agressive as a competitor, which consistently overtopped the walnut at different ages (Bohanek and Groningen 2003). Other species with timber value that can be included and that can thrive where black walnut may fail are white oak (*Q. alba* L.), bur oak (*Q. macrocarpa* Michx.), chinkapin oak (*Q. muehlenbergii* Engelm.), swamp white oak (*Q. bicolor* Willd.), and black cherry.

As black walnut is usually planted on the best sites (e.g., with rich soils, constantly supplied with water), there is no need for any fertilization or irrigation. Fertilizing is sometimes achieved by intercropping black walnut with N-fixing species such as *Eleagnus angustifolia* L. in Europe and *Eleagnus umbellata* Thunb. in the USA. Using these species, the N level in the soil is enhanced, with beneficial effects on height growth of black walnut, the development of the grass layer is reduced and the climate above and within the upper soil level is moderated (Schlesinger and Funk 1977). Protection with tree shelters or tubes is recommended in Germany to prevent roe bucks fraying young black walnut seedlings (Ehring and Keller 2010). Fencing can sometimes be necessary when regenerating black walnut in areas with high browsing pressure (Hungary, Redei et al. 2019; Czech Republic, Podrázský pers.comm.; Serbia, Andrašev pers.comm.).

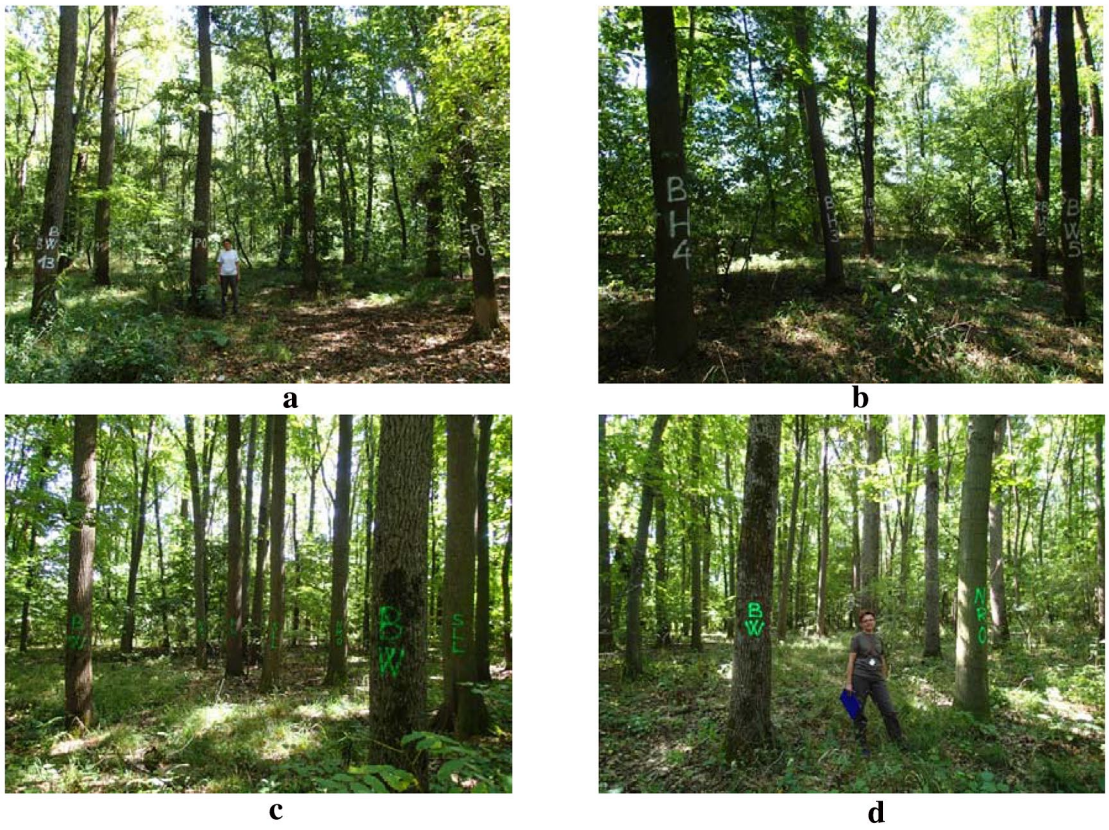

Fig. 9 Mixed black walnut (BW)-northern red oak (NRO)-pin oak (PIO)-pedunculate oak (PO) (**a**), black walnut (BW)-bitternut hickory (BH) (**b**), black walnut (BW)-northern red oak (NRO)-small-leaved linden (SLL) (**c**), and black walnut (BW)-northern red oak (NRO) stands in the NW of Romania. Photos VN Nicolescu

Young stand management

As a young tree, black walnut has low potential if there is competition with herbaceous weeds. These reduce the height, diameter and volume growth of black walnut, so the control of competing vegetation (*weeding*) is essential and mandatory for the success of established plantations (Boudru 1989; Tokár 1998; CRPF Rhône-Alpes 2014). Mechanised weed control, by hoeing, disking, or mulching, or chemical control, should be carried out both within and between the rows of plantation or areas manually seeded. If the whole site cannot be cleaned then an area of at least 1 m in diameter should be cleared around each tree (Evans 1984). Control of all weeds, of which grasses (*Poaceae* spp.) are the most serious competitor, is necessary in the first 2–3 years after planting, usually twice a year (Evans 1984; Führer et al. 2008; Mayer and Rajković 2008). In the native range and in New Zealand young black walnut trees grow best when all competing vegetation (or at a minimum all forbs and grasses) are controlled, until full canopy cover is achieved (Schlesinger and Funk 1977; Haslett 1986; Levack (ed.) 1986; Schlesinger and Weber 1987; Masterson 1990; Williams 1990; Van Sambeek and Garrett 2004; McKenna and Farlee 2013).

Young black walnut stands, planted at high density (4,000 stems per ha or more), are kept closed until the thicket trees are 8–10 years, when the first cleaning-respacing is carried out. This is a negative selection and removes poorly formed, wolfs, damaged, diseased trees, including overtopped individuals growing slowly, so reducing density to 2000–2500 trees per ha. After the second cleaning-respacing in such stands, at 13–15 years of age, the density is reduced to 1200–1400 trees per ha in Hungary (Rédei and Antal 2017). As a genuine light-demanding species, black walnut needs the crowns to be released early to support high growth rates and the vitality of individual trees; this is done during cleaning-respacing, when potential final crop trees are selected. The operation starts when top height is ca. 8 m and ends at 12–15 m, when the age is 15–25 years (Germany, Bartsch 1989; Ehring and Keller 2006, 2010; Romania, Nicolescu pers.comm.).

In widely-spaced plantations, there is no need for cleaning-respacing following weeding; in such stands, trees can reach a 12.5 cm average dbh without any additional

silvicultural treatment (Van Sambeek 1988; Pedlar 2006). However, initial wide spacing contributes to an increase in the depth of the crown. This in turn increases size and retention of branches (so application of pruning becomes mandatory when targeting the production of knot-free trees) and the taper of the bole (Haygreen and Bowyer 1989, in Phelps 1989).

Commercial thinning

Black walnut, a light-demanding tree species, requires a free-growth state from the surrounding trees. This state, part of crop tree silviculture (CRPF Rhône-Alpes 2014) and favouring the diameter increment of the best trees by releasing their crowns, is commonly achieved using thinning from above, started at the pole stage (Czech Republic, Podrázský pers.comm.; United Kingdom, Evans 1984; Slovakia, Tokár 1984, 1998; Slovenia, Brus pers.comm.). In mixed stands with black walnut, the recommended thinnings are from both above and below, to regulate the species composition by favouring the walnut trees from the upper storey and also to manage the lower storey species (Ukraine, Lavnyy pers. comm.; Croatia, Đodan pers.comm.; Romania, Nicolescu pers.comm.).

Fig. 10 Final crop tree: side view (**a**) and crown view (**b**). Photos VN Nicolescu

Thinning interval is very variable in Europe, ranging from 3 to 4 years (Germany, Rumpf and Nagel 2014), 5–10 years (Czech Republic, Podrázský pers.comm.; Ukraine, Lavnyy pers.comm.), to a maximum of 10 years (Croatia, Đodan pers.comm.; Serbia, Andrašev pers.comm.; Slovakia, Tokár 1984, 1998). The interval of 6–10 years is favoured in the United States to maintain the crowns of black walnut trees in a free-growth state, as in Germany (Williams 1990).

The intensity of thinning is usually a maximum of 15% of standing volume (Tokár 1984, 1998; Steinaker et al. 2008), and depends on the stand density; the most important thing is to permanently release the crowns of the best trees from competition (Rumpf and Nagel 2014).

Black walnut silviculture requires the selection of the best (future, final, elite) trees to favour during the application of thinnings until the rotation age. These are chosen based on the vigour (thickest and taller)—quality (straight, no forks, with large and regular crowns)—distribution (as regularly spaced as possible) criteria (Fig. 10).

Such trees (up to 200 'candidates' per ha—Rumpf and Nagel 2014) are selected during the pole stage, and are freed from competition through high thinning; their number decreases to no more than 150 final crop trees per hectare at rotation age (Table 8).

In the USA, the density of black walnut plantations at rotation age is ca. 80 trees ha^{-1} (Schlesinger and Weber 1987), such value being similar to the one proposed in New Zealand (less than 100 trees ha^{-1}, even 60–70) (Nicholas 1979; Masterson 1990).

Pruning

High pruning is performed in both narrow- and widely-spaced black walnut plantations as it is considered compulsory and essential (especially in widely-spaced stands) in both Europe (Ehring and Keller 2006, 2010; Führer et al. 2008) and the United States (Schlesinger and Weber 1987) to improve the wood and produce superior assortments such as veneer wood.

The removal of both dead and green branches must start early, when trees are 3–4 m tall (Europe, Hubert and Courraud 1987; CRPF Rhône-Alpes 2014; USA, Schlesinger 1982; Schlesinger and Weber 1987; Burde (ed.) 1988; New

Table 8 Number of black walnut final crop trees in different European countries

Number of final crop trees per ha	Country	References	Comment
40–70	United Kingdom	Evans (1984)	Open-grown trees, orchard-like grove or plantation
(60) 80–120	Germany	Rumpf and Nagel (2014)	
100–150	Hungary	Rédei and Antal (2017)	
120–150	Slovakia	Pástor pers.comm	

Zealand—Knowles 1978; Nicholas 1979). Pruning cuts should be neat, clean, perpendicular to the branch, and protect the branch collar as well as bole bark (Shigo et al. 1979; Williams 1990; Mori 2015). Cutting 'flush with the trunk', and removing the branch collar, as proposed in the US about one century ago (Baker 1921), are no longer allowed as it produces large wounds, difficult to heal, and acting as genuine gates for pathogens (Shigo et al. 1979). Black walnut crop trees should be high pruned to at least 5–6 m in height, preferably using instruments handled from the ground, to reduce the costs of intervention (Gathy and Evrard 1976; Anonymous 1981; CRPF Rhône-Alpes 2014; Hemery and Simblet 2014; https://www.cdaf.be/docs/web/pdf/A0_interreg/dossier_noyer.pdf). Seldom, the target pruning height is 8 m (Kruch and Nicolescu 2012; Kotora pers.comm.) or even 10 m (Ehring and Keller 2006).

Usually three lifts/interventions are necessary to prune up to the target height (Ehring and Keller 2006; https://www.cdaf.be/docs/web/pdf/A0_interreg/dossier_noyer.pdf). The maximum size of black walnut branches to prune in Europe ranges between 2.5 cm (Schaeffer 1971; Toussaint et al. 1973), 3 cm (Soutrenon 1990, 1991, 1993—provides quick healing and minimum risk of infections), 3.5–4.0 cm (Martin 1979; Hubert 1981; Becquey (coord.) 1997), and 4 cm (Ehring and Keller 2006) (Fig. 11).

These values are lower than the target pruning diameter in the United States and New Zealand of 5 cm (Nicholas 1986; Schlesinger and Funk 1987; Burde (ed.) 1988; Schlesinger 1989; Masterson 1990; Williams 1990; McKenna and Farlee 2013). No more than 25 percent of the live crown should be released in a single lift; the pruning coefficient (ratio pruned height/total tree height) should be a maximum of 50% (Van Sambeek and Rink 1982; Schlesinger 1989; Williams 1990). This coefficient can be up to 60%, without affecting significantly the height and diameter growth, when starting pruning very early (Funk 1979; Schlesinger 1982; McKenna and Farlee 2013).

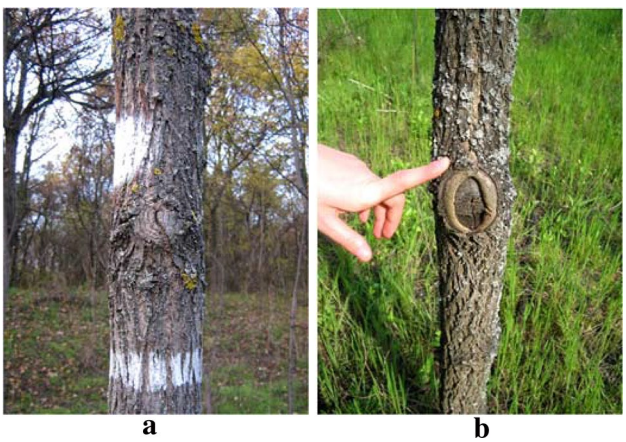

Fig. 11 Effect of pruning small: **a** and large-diameter, **b** branches of black walnut. Photos VN Nicolescu

In Europe, black walnut is pruned at the end of the growing season, in early summer (mid-June–mid-July), to avoid the sap "bleeding" profusely, resulting in greater susceptibility to disease and slowing growth (Evans 1984; Soutrenon 1990; CRPF Rhône-Alpes 2014; Hemery and Simblet 2014). Sometimes, it is pruned in late winter/end of dormant season (March–April—in the case of the United States, Schlesinger and Funk 1977; Phelps and McGinnes 1984; Burde (ed.) 1988; Williams 1990), with a more rapid healing of wounds but higher risk of epicormic branches being produced from dormant buds near the wound (Ehring and Keller 2010; Schaarschmidt 2012).

In addition to high pruning, formative *(*corrective*)* pruning is necessary in black walnut trees to correct their tendency to produce multiple leaders/forks due to frost or insect damage to the terminal bud (Führer et al. 2008; Hemery and Simblet 2014). The intervention, aiming to maintain a single leader and limit the number of developing branches, starts at 2 years, when trees are ca. 1 m tall, and is applied until they reach ca. 4–6 m in height (Schaeffer 1971; Anonymous 1981; Schwab 1990; Collas 1994). The cutting season, as well as the technique of branch removal, are similar to high pruning (Schaeffer 1971; Anonymous 1981; Schwab 1990; Collas 1994; CRPF Rhône-Alpes 2014; https://www.cdaf.be/docs/web/pdf/A0_interreg/dossier_noyer.pdf).

Conclusions

Black walnut, 'the most respected of North America's hardwoods', is a light-demanding, competition-intolerant, tall forest tree species. It has an important economic role for producing wood and fruit in agroforestry systems, as an ornamental tree for parks and avenues, and for rehabilitation/restoration of degraded lands.

In Europe, the best sites for black walnut growth have warm mild climates, with frequent and well-spread precipitation, and rich, deep, well-drained, moist soils.

Black walnut is a fast grower when young and its height and diameter growth reach their peak before the age of 30–35 years. It is globally the best known allelopathic species due to the chemical juglone that is present in all parts of black walnut trees.

The species is wind-firm and not affected by any major pest or disease. Black walnut is regenerated by planting or direct seeding on bare land. The management of monocultures or mixed stands with black walnut include weeding (compulsory), cleaning-respacing (only in dense stands), thinning (mostly from above), high and formative pruning (mandatory), with the aim of producing valuable wood with important end-uses such as sliced veneer, solid furniture,

flooring/parquet, cabinetry, panelling, sculpture, musical instruments and gunstocks, with rotation periods up to a maximum of 80 years.

As black walnut seems to have a quite high adaptation potential to predicted climate change, particularly drought, the importance of the species is expected to increase in some parts of Europe in the future.

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Compliance with Ethical Standards

Conflict of interest No conflict of interest (financial or non-financial). Our research has not involved any human participants and/or animals.

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