Ecology, growth and management of black locust (Robinia pseudoacacia L.), a non-native species integrated into European forests

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REVIEW PAPER

Ecology, growth and management of black locust (*Robinia pseudoacacia* L.), a non-native species integrated into European forests

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Abstract Black locust (*Robinia pseudoacacia* L.), a species native to the eastern North America, was introduced to Europe probably in 1601 and currently extends over 2.3×10^6 ha. It has become naturalized in all sub-Mediterranean and temperate regions rivaling *Populus* spp. as the second most planted broadleaved tree species worldwide after *Eucalyptus* spp. This wide-spreading planting is because black locust is an important multipurpose species, producing wood, fodder, and a source of honey as well as bio-oil and biomass. It is also important for carbon sequestration, soil stabilization and re-vegetation of landfills, mining areas and wastelands, in biotherapy and landscaping. In Europe, black locust is drought tolerant so grows in areas with annual precipitation as low as 500–550 mm. It tolerates dry, nutrient poor soils but grows best on deep, nutrient-rich, well-drained soils. It is a fast-growing tree and the height, diameter and volume growth peak before the age of 20. It mostly regenerates vegetatively by root suckers under a simple coppice system, which is considered the most cost-effective management system. It also regenerates, but less frequently, by stool sprouts. Its early silviculture in production forests includes release cutting to promote root suckers rather than stool shoots, and cleaning-respacing to remove low-quality stems, reduce the number of shoots per stool, and adjust spacing between root suckers. In addition, early, moderate and frequent thinning as well as limited pruning are carried out focusing on crop trees. The species is regarded as

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invasive in several European countries and its range here is expected to expand under predicted climate changes.

Keywords Black locust · Ecology · Invasiveness · Climate change · Management

Introduction

Black locust (*Robinia pseudoacacia* L.) originates from the eastern half of the United States with two disjunctive areas: the larger source centered in the Appalachian Mountains, including Pennsylvania, Ohio, Alabama, Georgia and South Carolina States and the smaller source on the Ozark Plateau of Missouri, Arkansas, and Oklahoma. Outlying populations are also found in Indiana, Illinois, Kentucky, Alabama and Georgia (Huntley 1990). In native range, black locust is found in both pure and mixed stands as an associate of shortleaf pine (*Pinus echinata* Mill.), Table Mountain pine (*Pinus pungens* Lamb.), yellow poplar (*Liriodendron tulipifera* L.), white oak (*Quercus alba* L.), and northern red oak (*Quercus rubra* L.) (Huntley 1990).

The species has become naturalized (i.e., forming free-living, self-sustaining populations in the wild unsupported by and independent of humans; Pyšek et al. 2009) in all sub-Mediterranean and temperate regions: Asia (thirteen countries, of which South Korea has over 1.2 million ha and China over 1 million ha), Africa (six countries), Australia and New Zealand, South America (Argentina, Chile) (Keresztesi 1988a, b; Demené and Merzeau 2007; Tu et al. 2007; Contu 2012; Boer 2013; Cierjacks et al. 2013). Worldwide, its area increased from 337,000 ha in 1958 to 3,264,000 ha in 1986 (Keresztesi 1988a, b); in 2010, the estimated area of black locust plantations outside the native range was about 3 million ha (Schneck 2010). The species now rivals hybrid poplars (*Populus* spp.) as the second most planted broadleaved tree species in the world after *Eucalyptus* spp. (Rédei 2013b; Savill 2013; Wojda et al. 2015).

Black locust was the first North American tree species to be introduced into Europe in 1601 (Muller 2004; Hemery and Simblet 2014), although this date has been questioned by some authors (Cierjacks et al. 2013; Vítková et al. 2017). Seeds were sent by John Tradescant the Elder (English naturalist, gardener, collector and traveler, 1570–1638) to his friend Jean Robin (1550–1629), the gardener (or "arborist") of the French kings Henry III, Henry IV and Louis XIII, who sowed them in his garden (now the Place Dauphine in Paris) (Brosse 1977; Jardin des Plantes 2018). In 1636, his son Vespasien Robin (1579–1662) planted the first black locust in the King's Garden, now the Jardin des Plantes. This tree still exists and is the oldest tree in Paris and in Europe (Borde 2011). The year of introduction of black locust to other European countries (parks and gardens, as well as forests) is shown in Table 1.

Currently black locust occurs in forty-two European countries and is naturalised in thirty-two (Pyšek et al. 2009). It covers a total area of more than 2,306,000 ha (Brus pers. comm.) and is the most common broadleaved tree species on the continent. Countries where black locust accounts for at least 100,000 ha are Hungary, Ukraine, Poland, Romania, Italy, France, Serbia, Slovenia and Bulgaria (Table 2).

Initially, black locust was used as a park and garden tree and the first important forest use, in the nineteenth century, was to stabilize mobile sand dunes (Hungary, Romania, Austria—Hofmann 1861; Drăcea 1919) and to create shelterbelts (Austria—Hofmann 1861). Black locust has become an economically important multipurpose species in many parts of Europe, as a nitrogen-fixing species for waste land and surface-mine reclamation, for erosion prevention and control, for carbon sequestration, as windbreaks and shelterbelts, as an ornamental tree in parks, gardens, alleys, and as a street tree as it is tolerant of air pollution and salinity and thrives in the urban environment. If managed as short rotation coppice as in, for example, Austria, Croatia, Hungary, France, Germany, Greece, Italy, Poland, Slovakia (Paris et al. 2006; Facciotto et al. 2008; Rédei and Veperdi 2009; Borde 2011; Rédei et al. 2011; Maltoni et al. 2012; Steinegger and Reh 2013; Crosti et al. 2016; Giulietti 2016; Vítková et al. 2016), it is used for biomass production/bioenergy generation, and produces biomass up to 14 dry matter t ha^{-1} a^{-1} (Straker et al. 2015). In former mining

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Table 1 Year of introduction of black locust into different European countries

Country	Year of introduction of black locust in…	
	Parks, gardens	Forests
Austria	First individual planted by Emperor Leopold I (1656–1705) in Vienna (Jacquin 1825)	
Bulgaria	Mid nineteenth century (Kirov 1886)	1890 (Naydenov 2015)
Croatia	1856 (Vuković et al. 2013)	1880 (Đodan et al. 2018)
Germany	Ca. 1650 (Seeling 1997; Krausch 2001)	Ca. 1700 (Seeling 1997; Krausch 2001)
Hungary	1710–1720 (Rédei pers.comm.)	Beginning of nineteenth century (Rédei pers.comm.)
Italy	1662 (Botanical garden of Padua) (Pignatti 1982)	Beginning of nineteenth century (Zucchini 1800)
Romania	Ca. 1750 (Drăcea 1919)	1852 (Crăciunescu 1904; Drăcea 1919)
Slovakia	1720 (Benčať pers.comm.)	1780 (Benčať pers.comm.)
Slovenia	1790–1800 (Strgar 1992)	1810 (Anko 1989)
Ukraine	End of eighteenth century (Kohno 2007)	Beginning of nineteenth century (Vakulyuk and Samoplavskyy 1998)
United Kingdom	1640 s (Savill 2013)	Early nineteenth century (Savill 2013)

Table 2 Area of black locust in different European countries

Country	Area (ha)	Sources	Notes
Hungary	465,000	Rédei et al. (2017)	23% of national forest area; from 37,000 ha in 1885, 109,000 ha in 1911, 186,000 ha in 1938 (Rédei et al. 2017)
Ukraine	422,525	Lavnyy and Savchyn (2016)	
Poland	309,205	Anonymous (2017a)	Total area of stands with black locust in species composition (Anonymous 2017a)
Romania	250,000	Enescu and Dănescu (2015)	From 28,000 ha in 1922–100,000 ha in mid-1950 s (Enescu and Dănescu 2015)
Italy	233,533	Rizzo and Gasparini (2011)	
France	195,000 ± 22,000	IGN (2018)	
Serbia	169,153	Banković et al. (2009)	
Slovenia	157,000	Brus et al. (2016)	
Bulgaria	153,851	Executive Forest Agency (2015)	
Croatia	35,070	Čavlović (2010)	
Slovakia	34,000	Anonymous (2017b)	
Germany	34,000	BMEL (2014)	
Austria	24,000–40,000	National Forest Inventory	
Czech Republic	14,087	Vítková et al. (2016)	
FYR Macedonia	2622	Mandžukovski pers.comm.	
Belgium (Wallonne Region)	Ca. 2000	Claessens et al. (2006)	
Bosnia and Herzegovina	1000–2000	Cvjetkovic pers.comm.	

areas of Germany, this species has produced 3–10 oven-dry t ha^{-1} a^{-1}, substantially higher than poplar and willow clones established on the same sites (Grünewald et al. 2009). In Italy, on poplar sites, its production can reach 10, even 12.5 dry matter t ha^{-1} year^{-1} using selected clones of Hungarian provenance (Giulietti 2016). In Hungary, where black locust is considered the most suitable species for energy plantations (Rédei and Veperdi 2009), its productivity reached 9.7 dry matter t ha^{-1} yr^{-1} (Rédei et al. 2011). Black locust is also important as a raw material in the food industry, as fodder in silvopastoral systems, in biotherapy, and landscaping (Cierjacks et al. 2013; Enescu and Dănescu 2015; Ciuvăț et al. 2015; FOREST EUROPE 2015; Sitzia et al. 2016; Vítková et al. 2016). It is important in honey production (bees can collect up to 1500 kg of honey from one ha of black locust stands in favourable years; Vakulyuk 1991), and it provides habitat for numerous fungi, arthropods, birds and mammals (Saunier 2007; Ślusarczyk 2012; Ciuvăț et al. 2015).

In Europe, black locust is cultivated on a large scale for timber production; curiously, it is *not* an important commercial timber species in native range (Huntley 1990), where the best uses are mine timbers, fence posts, poles, railroad crossties, stakes and fuel (DeGomez and Wagner 2001). The wood is dense (specific gravity about 0.73–0.74 g cm^{-3} at 15% moisture content, Erdélyi 1988; Savill 2013), even though the species is fast-growing; this combination of high wood density with high growth rate is rare among woody plant species (Hanover 1990). Black locust wood is naturally durable so can be used outdoors without any treatment. For example, it is the only broadleaved species grown in France with a natural durability specific to class 4 of the European/French Norm NF EN 335-1 and can be used in contact with soil or freshwater and exposed permanently to humidity (Borde 2018). The uses of black locust wood in Europe include general construction, boat building, flooring/parquet, terrace floors, outdoor work, veneer, furniture, mine timbers, barrel staves, railway sleepers, vineyard poles and props, fence posts, boxes, crates, handcrafts, wood chips, pellets, particle board, fibreboard (Erdélyi 1988; Torelli 2002; Cierjacks et al. 2013; Savill 2013; Ciuvăț et al. 2015; Sitzia et al. 2016). The species produces highly-valued firewood, very important in many rural areas of Europe such as in Hungary, Serbia, Romania, Bulgaria, and Croatia. Its calorific power (97%) is comparable to that of native oaks (pedunculate oak, *Quercus robur* L. and sessile oak, *Q. petraea* (Matt.) Liebl.), considered as 100% but lower than hornbeam (*Carpinus betulus* L.) (110%) (CIRAD 2012; Bousse and Richard 2017).

The importance of this species in parts of Europe is underlined by black locust breeding and improvement programs, started in the 1950s in Germany (Schneck 2010), 1960s in Hungary (Keresztesi 1983) and Romania (Bîrlănescu et al. 1966, 1977), 1970's in Bulgaria (Kalmukov 2014), and in the 1980' in Austria (Müller 1990). These programs included initially the selection of individual trees of good stem form and vigor ('plus-trees') and of seed stands, followed by the vegetative propagation of selected 'plus-trees' and establishment of seed orchards. Using selected clones and cultivars, especially in Hungary, wood production has increased significantly, i.e., by 25–30% in Hungary (Rédei et al. 2017) and 48% in Italy (Gras 1991). Breeding and improvement programs are undertaken in Hungary, Bulgaria, France, Greece and Poland, mainly using European provenance stock (van Loo et al. 2017). The array of breeding objectives is very wide, e.g., improvement of wood quality, increase of biomass production for energy purposes, increase of flower nectar production and extension of blossom period, and improvement of drought and frost tolerance (Gras and Mughini 2009; Kalmukov 2014; van Loo et al. 2017).

However, despite its economic and social value, the role of black locust in European forestry is controversial because of its invasiveness. It is ranked amongst the 100 *most invasive alien species* ("… a species that is established outside of its natural past or present distribution, whose introduction and/or spread threaten biological diversity"—Convention on Biological Diversity 1992, in https://www.iucn.org/theme/species/our-work/invasive-species) on the continent (Vilà et al. 2009). However, it is *formally* considered to be invasive only in a relatively low number (13 out of 35 reporting) of European countries (Brus et al. 2016). For example, German forest scientists consider black locust as "partly invasive" since its invasiveness is mostly restricted to open fields and does not occur in dense forests, with closed canopies (Vor et al. 2015). For Slovenian forest experts, black locust is an invasive species (Rudolf and Brus 2006). This emphasizes the ongoing controversy about the species: black locust has many *positive* socio-economic effects as shown above but can also have *negative* environmental effects on native vegetation as a light-demanding pioneer species that can substantially, and rather quickly, change the specific habitats which it invades (Vítková et al. 2016, 2017). Furthermore, as noted by Vítková et al. (2017), black locust has been widely accepted by the general public in central Europe, where it features in cultural and traditional artefacts.

Recent reviews [e.g., Cierjacks et al. 2013; Vitkova et al. (2017)] have described many aspects of the ecology of black locust, including ones that influence the invasiveness of the species in different parts of Europe. However, there is no comprehensive summary of the silviculture, productivity and management of black locust in Europe that can be used to inform about its future role in different countries. In this paper, along with the essential characteristics of black locust in Europe (e.g., site requirements, root system, regeneration ecology, invasive potential, shade tolerance, potential for natural pruning, vulnerability to pests and diseases), we summarize such information to outline principles for the management of this species, including stand establishment, early interventions such as release cutting and cleaning-respacing, commercial thinning and pruning (both formative and high), all with the aim of producing different wood assortments.

Species characteristics

Climate

In its native range, black locust grows in a humid climate (annual total precipitation 1020–1830 mm), with 150–210 frost-free days (Huntley 1990). In Europe, black locust behaves like a thermophilous species, i.e., it grows well where mean annual temperatures are over 8 °C (Roșu 1996; Rédei et al. 2017) and is very drought tolerant (Claessens et al. 2006; Grünewald et al. 2009; Mantovani et al. 2014; CRPF Nord Pas-de-Calais Picardie 2015). In this respect, black locust can adapt to prolonged drought by reducing water loss through both reduced transpiration and leaf size

(Mantovani et al. 2014), as well as due to an extended root system which access water in deeper soil layers (Grünewald et al. 2009). Consequently, the species can grow in regions with 500–550 mm annual precipitation (Roşu 1996; Mantovani et al. 2014), with reports of it tolerating less than 400 mm year^{-1} (Engel et al. 2014), high summer air temperatures of 30–35 °C, and relative air humidity in July of 20–50%, as found in Hungary (Rédei et al. 2002).

Late and early frosts, as well as low winter temperatures, are damaging for black locust both in Europe (Haralamb 1967), and in the USA (Huntley 1990). Early frosts damage un-hardened twigs and are the source of frequent forking of black locust (Haralamb 1967; Claessens et al. 2006). Storms, wet, sticky and heavy snowfall, and ice can break branches, trunks, forks or shoots at their junction with the stem (Kitin 1960; Vajda 1974; Stănescu 1979; Brus 2011; Meyer-Münzer et al. 2015). Strong winds can cause damage (breakage, uprooting) which, although very rare, can occur on forked black locust individuals (Jovanović 1967; Herman 1971; Vajda 1974; Rițiu et al. 1988).

Soil and topography

In the United States, black locust is found naturally over a wide range of soils but grows best on moist, rich, loamy soils or those of limestone origin (Huntley 1990). It thrives on moist slopes of the eastern mountains, the Appalachians, below 1040 m a.s.l. (Harlow et al. 1986), while in the Great Smoky Mountains National Park, its upper elevational limit is 1620 m a.s.l. (Whittaker 1956 in Huntley 1990).

In Europe, the species has been introduced over a wide range of soils and tolerates diverse pH from extremely acid (3.2) to alkaline (8.8) (Vítková et al. 2015). However, it grows best when the soil pH is slightly acid to near neutral, 5.5–7.0 (Roşu 1996; Borde 2011; Zajączkowski and Wojda 2012). Black locust tolerates dry and nutrient poor soils, but grows best on deep, nutrient-rich, moist, uncompacted, well-drained silt loams, sandy loams, or sandy soils (Haralamb 1967; Rédei et al. 2011; Meyer-Münzer et al. 2015). Under these conditions, the root-associated nitrogen fixing *Rhizobium* bacteria, which fixes up to 75 kg of N ha^{-1} year^{-1} (Boring and Swank 1984) or 150 kg of N ha^{-1} year^{-1} (Berthold et al. 2005), are able to thrive. The groundwater table should be deeper than 150 cm (Keresztesi 1988a, b; Zajączkowski and Wojda 2012), as nitrogen fixation aerobic *Rhizobium* bacteria is inhibited by high water table or periods of flooding (Vítková et al. 2015). Rendzinas, calcium-carbonated soils in the upper horizons, poorly-drained and highly compacted (clayey) soils, very dry as well as hydromorphic soils with gley or pseudogley, are not suitable for black locust (Stoyanov 1926; Donchev 1968; Rameau et al. 1989; Claessens et al. 2006; Borde 2011; Boer 2013).

In Europe, black locust has been used across a wide range of altitudes, from sea level to 1640 m a.s.l. in the Southern Alps of Italy (Sitzia et al. 2016), but grows best in plains and hilly areas at altitudes below 600–700 m a.s.l. (Vuković et al. 2013; Šnjegota et al. 2017).

Root system

The root system of black locust is dimorphic, heart-shaped: when young, it develops a tap root which is supplemented by further vertical roots extending down to 40–60 cm (Spîrchez et al. 1962; Benčať pers.comm.), and horizontal ones spreading radially as far as 20–30 m (1.0–1.5 tree heights) (Wraber 1951; Negulescu and Săvulescu 1957; Cutler 1978, in Huntley 1990; Stănescu 1979).

However, the root architecture (depth and width) depends on soil conditions: on deep, loose and moist soils as well as dry sandy soils, the roots are well developed, densely branched, with a taproot/vertical roots 1.5–3 m depth (a maximum 7.9 m in Europe, Schütt 1994; a maximum 6–7.5 m in native range, Harlow et al. 1986). On shallow soils or eroded slopes, there is no taproot but fine flat, widespread horizontal roots close to the soil surface with an umbrella-like shape. As acknowledged by Huntley (1990), the species deep rooting ability may explain why can grow in regions much drier than its native range such as in Hungary, Romania, Bulgaria, and China.

Regeneration ecology

Both in native range (McAlister 1971; Huntley 1990) and in Europe (Stoyanov 1926; Negulescu and Săvulescu 1957; Haralamb 1967; CRPF 2007; Branquart et al. 2007; Rédei et al. 2008; Vuković et al. 2013) as well as in Asia (Luna 1996), natural regeneration is primarily by root suckers. These are produced abundantly even by trees over 70 years old (Vítková et al. 2017) from superficial roots, particularly following mechanical damage to the root system (Boer 2013; Vítková et al. 2016) or soil disturbance (Savill 2013). The number of suckers per tree can range from 1–2 up to 45–46 (Dimitrov 2001), so initial stocking after one growing season reach 40,000–60,000 suckers ha^{-1} (Pagès 1985, cited by Carbonnière et al. 2007; Nicolescu et al. 2019). More suckers are produced in open, sunny areas, and on sandy loam than in shade, dense vegetation or on heavy soils (Converse 1984; Wieseler 2005, cited by Boer 2013; Stone 2009).

Black locust also regenerates on a much smaller scale by stool shoots arising from dormant buds on the stump crown (the callus zone), or on the lower portion of the trunk; sprouting is intensive and persistent (Brus 2011; Boer 2013).

However, root suckers live longer and are healthier, showing less rot at the same age than stool shoots (Negulescu and Săvulescu 1957; Stănescu 1979).

Black locust produces abundant seed crops with 120–150 kg of seeds ha^{-1} in an average seed year, beginning from around 6 years of age (Rédei et al. 2001; Rédei 2013a, b, c, d). Good seed crops occur every 1–2 years in both Europe (Haralamb 1967; Rédei et al. 2012; Boer 2013; Los et al. 2014; Meyer-Münzer et al. 2015) and the USA (Huntley 1990). The seeds are light (20–23 g for 1000 seeds) and long-lived, mostly gravity- and wind-dispersed in the vicinity of the parent tree. Long-distance spread of seeds by natural means is not very common (Boer 2013; Vítková et al. 2017); however, they have been found up to 67 m away from the parent tree (Morimoto et al. 2010, cited by van Loo et al. 2017). They may persist in a dormant state in the soil for a long time, with a viability longer than 10 years (Haralamb 1967; Boer 2013) or, in some circumstances, up to 40 years (Toole and Brown 1946, cited by Cseresnyés and Csontos 2012), accumulating in a permanent seed bank (Stone 2009; Filipas 2013). This should be taken into consideration when devising strategies to eradicate unwanted black locust (Boer 2013). However, because the heavy, thick seed coat is impermeable to water (both absorption and loss), germination is restricted (McAlister 1971; Vlase 1982; Branquart et al. 2007) so regeneration from seed is rare (Tănăsescu 1961, 1967; Boer 2013). Germination rate is low under natural conditions (Branquart et al. 2007), ranging from 3.5% to 16.3% (Roberts and Carpenter 1983) to 22% (Singh et al. 1999, both cited by Cierjacks et al. 2013). However, natural regeneration from seed can be facilitated by seed wounding with heavy machinery (Tănăsescu 1961) or by natural thermal shock. The latter occurs particularly on sand dunes where temperatures of the surface layer reach 60–65 °C in summer (Spîrchez et al. 1962).

Invasive potential

As a N-fixing species, black locust creates irreversible changes in physico-chemical and biological soil properties. It influences the species composition of ground flora under its canopy by favouring ruderal and species-poor neutrophilous weed associations, eliminating oligotrophic and acidophilous ones typical of forests, thereby reducing plant diversity (Kleinbauer et al. 2010; Benesperi et al. 2012; Cseresnyés and Csontos 2012; Dimitrova 2012; Vuković et al. 2013). In invaded stands, as soil pH is significantly lower and soil NO_3^- significantly higher, soil microarthropode communities suffer significant loss of abundance and richness while nematode taxon richness is significantly lower (Lazzaro et al. 2018).

Black locust also produces different allelopathic compounds (e.g., robinetin, myricetin and quercetin) which may affect the ecological functioning of natural areas by inhibiting the growth of various weeds and crop species (Nasir et al. 2005; Boer 2013). However, as the allelopathic effects of black locust have not yet been tested under natural conditions, it seems that vegetation change towards ruderal and nitrophilous species is caused by the change in the availability of soil nutrients rather than by allelopathy (Vítková and Kolbek 2010).

Once introduced in an area, black locusts expands readily into open sites where they form dense colonies and their shade reduces competition from other sun-loving species hindering their natural regeneration and thus a local, small-scale reduction of biodiversity can occur (Kutnar and Kobler 2013).

However, black locust has also some *positive effects* on biodiversity (Vítková et al. 2016, 2017): (a) Provides habitat for some rare and endangered plant species (e.g., rare ruderal plants). (b) In species-poor agricultural landscapes, black locust stands can increase diversity and play a significant role as migration corridors for woodland animals. (c) The dense undergrowth of shrubs and complex canopy structure provide nesting opportunities and a food source for many bird species. Among the birds are habitat generalists rather than specialist species, and their total number can be higher in the stands invaded by black locust than in, for example, oak stands. (d) Old black locust individuals can provide a refuge for saprophagous beetles, including rare species.

In Central Europe, habitats most often invaded by black locust are confined to low and medium altitudes (Kleinbauer et al. 2010; Boer 2013; Crosti et al. 2016; Vítková et al. 2016, 2017; Lazzaro et al. 2018; https://invasoras.pt/en/gallery/robinia-pseudoacacia-en) and include: (1) Dry and semi-arid grasslands, including those on open sandy steppes and rocky outcrops. (2) Dry (including nutrient-poor oak-dominated) forests and shrubland. (3) Alluvial habitats (banks of watercourses) but only on well-drained sites, sandy, gravel-sandy and gravel banks on flood barriers experiencing only occasional short-term flooding. (4) Agrarian landscapes with abandoned fields, orchards, vineyards, hedgerows, gullies, windbreaks, and roadsides. (5) Urban and industrial environments including toxic man-made substrates (e.g., polluted or salty soils). (6) Disturbed sites in most habitats, e.g., post-fire sites, windthrows, previously flooded areas, forest clearings, degraded forestry plantations.

In native range, black locust is considered an *invasive* in the prairie and savanna regions of the American Midwest where it can dominate and shade these open habitats (Swearingen and Bargeron 2016).

The invasion by root suckers occurs only around areas where it is already established, i.e., invasiveness is limited and the threats that the species could pose to biodiversity are localized. As mentioned, black locust does not occur in dense forests or shrublands, with closed canopies: as seedlings are intolerant of shade, mortality is high in closed forests (Boring and Swank 1984; Kowarik 2011; Boer 2013; Crosti et al. 2016; Vítková et al. 2016, 2017). In such stands, it can only occur as individual trees or groups of trees after disturbance results in a gap in the canopy (e.g., after trees die, fire, windthrow or forest management) where there is less competition (Cierjacks et al. 2013; Vítková et al. 2017).

In general, habitats that are *resistant to black locust invasion* (Crosti et al. 2016; Vítková et al. 2016) include: (1) areas with compacted and poorly aerated soils such as gleysols in alluvial forests subject to frequent and long-term waterlogging; (2) intensively managed sites where the vegetation is permanently disturbed (e.g., trampled sites, mown lawns and meadows or arable fields); (3) dense forests of competitive shade-tolerant species such as European beech (*Fagus sylvatica* L.); and (4) mountain and subalpine areas with frosts, short growing seasons and cold climate. These are the reasons why black locust is sometimes considered only a "partly invasive" species as proposed by German forest experts (Vor et al. 2015).

Interestingly, agricultural landowners consider black locust as invasive only when it spreads onto agricultural lands; they appreciate and manage black locust stands on poor and dry sites (e.g., sand dunes, south-facing slopes, with shallow soils), where it performs better than other native tree species (Kutnar and Kobler 2013; Stančič 2015).

The current range of black locust in Europe is under strong temperature constraints, and it is projected to expand in response to climate change (Boer 2013; Kutnar and Kobler 2013; Giuliani et al. 2015; Dyderski et al. 2017), so the species is expected to invade new sites and also increase its population in already occupied areas (Kleinbauer et al. 2010). It is the case of managed temperate forests of Europe, currently dominated by European beech and Norway spruce (*Picea abies* (L.) Karst), where species like black locust, northern red oak (*Quercus rubra* L.), Turkey oak (*Quercus cerris* L.) and fluttering elm (*Ulmus laevis* Pall.) are considered as *interesting alternatives* if the predicted northward shift of 461 km and 697 km for thermophilic species under warming scenarios of 2.9 °C and 4.5 °C, respectively, over the 2060–2080 period is realized (Thurm et al. 2018).

Under climate changes, *preventive* and *control measures* are needed and should include: (1) Establishment of a managed buffer zone around black locust plantations to act as a biological barrier for the species (Crosti et al. 2016); (2) Planning its introduction close to and within areas of ecological and environmental value (e.g., Natura 2000 sites) as well as in rare or threatened forest habitats (Borde 2011; Crosti et al. 2016); (3) Conversion from coppice to high forests by cessation of coppice cuts combined with lengthening rotation age and use of an alternative cutting system (Radtke et al. 2013; Nadal-Sala et al. 2019; La Porta pers.comm.); (4) Application of mechanical, chemical or biological control measures to eradicate or reduce the presence of black locust.

The detailed application of these preventive and control measures will be presented in the 'Management of black locust' section of this article.

However, we fully agree with Vítková et al. (2016, 2017) and Sádlo et al. (2017) that a *stratified and site-specific management approach*, *tolerating* (or even *favouring*) black locust in selected areas and *strictly eradicating* it from naturally valuable habitats, is the only solution for a strict and rational management of the species in Europe. This approach should take into account both the ecological and economic aspects associated with the occurrence of black locust in different types of *Robinia* habitats.

Shade tolerance

In both the native range (Trimble 1975, cited by Huntley 1990; DeGomez and Wagner 2001) and in Europe (Poskin 1926; Negulescu and Săvulescu 1957; Haralamb 1967; Herman 1971; CRPF 2007; Brus 2011; Vuković et al. 2013), black locust is considered a strong light-demanding tree species, intolerant of shade (growing best in full sun) and competition; therefore it is found in closed stands only as a dominant tree (McAlister 1971; Huntley 1990), requiring spacing at crown level for optimal growth (Poskin 1926). Black locust grown on poor sites cannot withstand shade so self-thinning is very high under such conditions (Herman 1971). Lyr et al. (1963) found a lower shade tolerance of black locust compared to *Q. rubra*, *Pseudotsuga menziesii* (Mirbel.) Franco, *Pinus sylvestris* L., *Betula pendula* Roth, *Alnus glutinosa* (L.) Gaertn. in terms of lower relative growth rates under shade and higher shoot/root ratios under increasing shade. As with other light-demanding tree species (e.g., *Populus nigra* L., *Fraxinus pennsylvanica* Marsh.), mature black locust trees show a pronounced phototropism and develop a leaning stem (a deformity reducing the milling potential) in search for light (Evans 1984; MAPPM 2000b).

Potential for natural pruning

Black locust, as a strong light-demanding tree species, shows a good potential for natural pruning but when trees are grown in abundant light, they do not self prune and tend to develop large and deep crowns (Rédei 2013b). Kalmukov (1995) showed the influence of six different planting spacings (1.5 × 0.5 m, 1.5 × 1.0 m, 1.5 × 1.5 m, 2 × 0.5 m, 2 × 1 m, and 2 × 1.5 m) on natural pruning of black locust: at age seven, the branch-free part of the bole ranged from 1.5 m in the widest planting scheme to 2.8 m in the closest one.

However, even when grown in dense stands, it is not a perfect self-pruner so the removal of low branches is necessary to produce 1st grade sawlogs designated for top-quality wood products such as veneer (Haralamb 1967; Rédei 2013b; Meyer-Münzer et al. 2015).

Vulnerability to pests, diseases and wildlife

In Europe, black locust appears to have high pest and disease resistance; however, in recent decades, several insects, fungi and semi-parasites have been reported to affect mature trees, seeds and seedlings. For instance, the leaves have been affected by black locust leaf miner (*Phyllonorycter robiniae* Clemens), locust digitate leaf miner (*Parectopa robiniella* Clemens), black locust gall midge (*Obolodiplosis robiniae* Hald.), gall midge (*Platygaster robiniae* n.sp.), soft scale (*Parthenolecanium corni* Bouché), and black bean aphid (*Aphis fabae* Scopoli). In countries like Bosnia and Herzegovina, Bulgaria, Croatia, Germany, Hungary, Italy, Romania, Poland, these have caused reduced leaf assimilation, loss of the aesthetic attributes of leaves, reduced value for honey production and, in extreme cases, premature leaf drop/defoliation (Trenchev et al. 1993; Maceljski and Mešić 2001; Tomov 2003; Duso et al. 2005; Mihajlović and Stanivuković 2009; Pernek and Matoševic 2009; Branco et al. 2016; Olenici and Duduman 2016; Šiljeg 2017).

Black locust seeds have been affected in Bulgaria, Romania and Slovakia by insects such as locust sawfly, *Eurytoma caraganae* Nikolskaya being the most common, as well as lima bean pod borer *Etiella zinckenella* Tr. and locust seed beetle *Kitorrhinus quadriplagiatus* Mots., the proportion of damaged seeds reaching ca. 80% (Iliev et al. 2005).

Black locust is considered a species very resistant to wood decay caused by fungi (Glavaš 1999). However, some fungi genera such as *Fusarium, Polyporus, Perenniporia, Ganoderma, Laetiporus,* and *Fomes* have caused white, brown or red rot, especially after stems or roots have been damaged (Schütt 1994; Tomiczek et al. 2008; Meyer-Münzer et al. 2015). Black locust roots are also affected by *Armillaria* spp., causing root decay especially if the trees are stressed by drought (Aslam 2015).

The semi-parasitic mistletoes, *Viscum album* L. and *Loranthus europaeus* Jacq. are sporadically found on black locust (Idžojtic 2003; Idžojtic et al. 2006).

Fortunately, the most important pest in native range, the locust borer *Megacyllene robiniae* (Forst.), is not yet present in Europe. Tunnels produced by its larvae in the heartwood weaken tree limbs, making them susceptible to breakage by wind and also serve as primary infection sites for wind-borne spores of the fungus *Phellinus rimosus* (Berk.) Pilát which causes damaging heart rot disease. This combined attack makes growing black locust for timber production impractical where this pest is present (Huntley 1990).

In countries like Bulgaria, Germany, Hungary, Slovakia, Austria and Romania, the European hare (*Lepus europaeus* Pallas) and European rabbit (*Oryctolagus cuniculus* L.) peel-off the bark of young trees (in nurseries and in forest stands), while red deer (*Cervus elaphus* L.) and roe deer (*Capreolus capreolus* L.) browse the young shoots, leaves and buds, causing significant damage (Juhásová and Hrubík 1984; Trenchev et al. 1993; Iby 1997; Claessens et al. 2006; Rédei et al. 2012). Similarly, in the USA, white-tailed deer (*Odocoileus virginianus* Zimmerman) is a major problem for young black locust, with reports of up to 92% of shoots browsed in the southern Appalachians (Della-Bianca and Johnson 1965, cited by Huntley 1990).

Growth and yield dynamics

Height growth

In both the native range (Harlow et al. 1986) and in Europe (France, Merzeau et al. 2008; Hungary, Rédei 2013b; Poland, Zajączkowski and Wojda 2012; Romania, Haralamb 1967; Germany, Meyer-Münzer et al. 2015; Carl 2018), black locust grows rapidly in height for the first 10–15 years. Consequently, the trees can reach heights of 10 m at 5 years and 14 m at 10 years on the best sites (Rédei 1984; Ruhm 2013). The peak growth rate in height occurs on the best sites with warm climate, rich and deep soils within the first decade: in the first 5 years (France, Merzeau et al. 2008; Germany, Lockow and Lockow 2015; Hungary, Rédei 1984; Poland, Zajączkowski and Wojda 2012) or in the first 10 years (Austria, Ruhm 2013; Ukraine, Lavnyy pers. comm.; Romania, Negulescu and Săvulescu 1957). The better the site potential, the earlier the peak of height growth. This slows after 15 years (Haralamb 1967), although growth remains relatively rapid in older trees; black locust stands in Europe can reach mean or dominant heights of over 20 m at 20 years and up to 25–30 m at 30 years (Tables 3, 4).

Stool shoots grow more rapidly in height (maximum 4.9 m year^{-1} in Germany, Lockow and Lockow 2015) than either root suckers (up to 2–3 m a^{-1}, Lockow and Lockow 2015) or planted seedlings up to 15–20 years of age (Haralamb 1967; Stănescu 1979; Stănescu et al. 1997). This trend in height growth rate reverses later, with the height of seed-originating stands outstripping that of coppice stands of the same age (Haralamb 1967; Negulescu and Săvulescu 1957; Stănescu 1979) (Tables 3, 4).

Currently, the tallest trees in Europe are found in France (38 m, IGN 2018) and Germany (39 m, Lockow and Lockow 2015).

Table 3 Maximum and minimum mean height at different ages in pure black locust stands in different European countries

Country	Mean height at… years (m)								Source	Notes
	10		20		25		30			
	Min	Max	Min	Max	Min	Max	Min	Max		
Hungary	6.5	13.6	10.2	21.5	11.3	23.8	12.1	25.4	Rédei et al. (2014)	
Romania	5.0	14.7	8.7	23.4	10.3	26.6	11.7	*29.5*	Giurgiu and Drăghiciu (2004)	Plantation
Romania	5.5	*15.8*	8.8	22.8	10.1	25.1	11.2	27.2	Giurgiu and Drăghiciu (2004)	Coppice
Bulgaria	5.8	13.0	10.2	19.8	11.5	21.5			Poryazov et al. (2004)	Plantation
Bulgaria	5.0	14.2	7.4	19.6					Poryazov et al. (2004)	Coppice
Croatia	9.0	13.0	14.0	19.0	15.5	20.5	17.0	22.0	Đodan pers.comm.	
Germany	6.3	12.3	10.8	18.8	12.4	21.1	13.7	23.0	Lockow and Lockow (2015)	

Min, minimum; Max, maximum

Table 4 Maximum and minimum dominant heights at different ages in pure black locust stands in different European countries

Country	Dominant height (m) at. years								Source	Obs.
	10		20		25		30			
	Min	Max	Min	Max	Min	Max	Min	Max		
Romania	6.7	17.6	11.1	26.5	12.8	29.6	14.4	32.4	Giurgiu and Drăghiciu (2004)	Plantation
Romania	7.2	18.8	11.2	25.8	12.7	28.2	13.9	30.1	Giurgiu and Drăghiciu (2004)	Coppice
Belgium (Wallonne Region)	6.4	12.2	10.6	20.1	12.2	22.9	13.8	25.7	Claessens et al. (2006)	
France (Aquitaine Region)	9.0	17.5	14.0	25.2	16.0	27.8	17.5	29.8	Merzeau et al. (2008)	

Min, minimum; Max, maximum

Diameter growth

Black locust trees have rapid early diameter growth that can reach 3–4 cm in the first year (stool shoots and root suckers, Jovanović 1967) on the best sites. The diameter increment peaks early on such sites: before age 10 (at 5 years in Germany, Lockow and Lockow 2015; 6–8 years in Poland, Węgorek and Kraszkiewicz 2005; Klisz et al. 2014; 7 years in Slovenia, Kadunc 2016), at the end of the first decade (Austria, Ruhm 2013; Bulgaria, Dimitrov 2001; Hungary, Rédei 1984; Rédei et al. 2008; France, Merzeau et al. 2008) or between 12 and 20 years (Romania, Negulescu and Săvulescu 1957; Belgium, Claessens et al. 2006; Slovenia, Kadunc 2016). The better the site potential, the earlier the peak of diameter growth (e.g., from 7 years on the best sites to 18 years on the poorest in Slovenia, Kadunc 2016).

In France, black locust trees grow 1 cm a^{-1} on average (range 0.5–1.9 cm a^{-1}, Merzeau et al. 2008; CRPF Nord Pas-de-Calais Picardie 2015). Savill (2013) mentions diameter increments of 0.2–2.0 cm, the maximum being similar to the one from German production tables (1.8 cm a^{-1}, Lockow and Lockow 2015).

As in the case of height, stool shoots have larger diameters than root suckers and planted seedlings up to 15–20 years of age. The trend in diameter growth rate reverses later with the diameter of seed-originating stands exceeding that of coppice stands of the same age (Haralamb 1967).

In the best growing conditions in native range and in Europe, 20 cm diameter trees take 25–30 years to be produced (Roach 1965, in Huntley 1990; Giurgiu and Drăghiciu 2004; Kalmukov 2014; Rédei et al. 2014). Trees 50 cm in diameter can be produced before 60 years of age (Claessens et al. 2006; Dancart 2019).

Large diameter black locust trees are found in Europe in Germany (244 cm in diameter—https://www.ddg-web.de/index.php/rekordbaeume.html), Belgium (208 cm), Great Britain (198 cm), Austria (172 cm), Hungary (170 cm), Romania (169 cm), Slovakia (161 cm), Poland (156 cm), Netherlands (156 cm) (all from https://www.monumentaltrees.com/en/trees/blacklocust/records), and Italy (140 cm, MIPAAF 2017). These large diameters are produced by old trees, 415 years of age in France, 340 years (Netherlands), 290 years (Germany), 240 years (Poland), 260 years (Great Britain), 210 years (Italy) (all from https://www.monumentaltrees.com/en/trees/blacklocust/records).

Volume growth and yield

Black locust quickly increases in volume while young, reaching maximum mean annual volume increment of

10–12 m^3 ha^{-1} a^{-1} in Germany and Bulgaria or 14–16 m^3 ha^{-1} a^{-1} in Romania as early as 5–10 years (coppice stands) and 15–22 years (plantations), depending on the productivity class (Table 5).

These values are similar to those achieved in native range (up to 14 m^3 ha^{-1} a^{-1} on the best sites; Hanover 1990). In other countries black locust grows 2.5–11.5 m^3 ha^{-1} a^{-1} (Ukraine, Lavnyy pers.comm.), 3.1–7.4 t ha^{-1} a^{-1} (Slovakia, Benčať 1989), 4–14 m^3 ha^{-1} a^{-1} (Belgium, Claessens et al. 2006), 4.5–12 m^3 ha^{-1} a^{-1} (Croatia, Đodan pers. comm.), 6–10 m^3 ha^{-1} a^{-1} (Netherlands, Mohren pers.comm.), 7.5 m^3 ha^{-1} a^{-1} (over 60 years; Germany, Lockow 2005), 7.7 m^3 ha^{-1} a^{-1} (France, Borde 2011), 8–14 m^3 ha^{-1} a^{-1} (Belgium, Dancart 2019), and 9.5 m^3 ha^{-1} a^{-1} (over 78 years; Poland, Feliksik et al. 2007).

As black locust grows rapidly in the first decades, wood production can reach important levels quite early: over 200 m^3 ha^{-1} at 20 years, 290 m^3 ha^{-1} at 30 years and 350 m^3 ha^{-1} at 40 years in the best site conditions (Table 6).

However, these data do not reveal the relationship between productivity and method of reproduction; for both stool shoots and root suckers, wood production decreases significantly over time (particularly in the case of stool shoots), from the first to the third generation (Table 7).

Table 5 Mean volume growth of pure black locust stands in different European countries

Country	Mean volume growth of main crop at… years (m^3 ha^{-1} $year^{-1}$)										Age of maximum volume growth (year)	Source	Notes
	10		20		25		30		40				
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max			
Bulgaria	2.9	11.0	3.7	11.6	3.6	10.6					15–20	Poryazov et al. (2004)	Plantation
Bulgaria	2.1	11.2	2.0	10.3							5–10	Poryazov et al. (2004)	Coppice
Germany	2.7	10.0	3.7	10.5	3.8	10.2	3.8	9.7	3.8	8.9	15–20 (25)	Lockow and Lockow (2015)	
Hungary	2.7	8.4	2.9	9.7	2.8	9.6	2.7	9.3	2.5	8.5	20	Rédei et al. (2014)	
Romania	2.6	14.1	2.9	15.8	3.0	15.4	3.1	14.9	3.3	13.7	18–22 (24)	Giurgiu and Drăghiciu (2004)	Plantation
Romania	2.8	14.5	2.8	13.6	2.7	12.8	2.7	12.2	2.6	10.8	10	Giurgiu and Drăghiciu (2004)	Coppice

Min, minimum; Max, maximum

Table 6 Yield of pure black locust stands at different ages in some European countries

Country	Yield of black locust stands at.years (m^3 ha^{-1})										Source
	10		20		25		30		40		
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	
Bulgaria (plantation)	51	177	73	231	90	264					Poryazov et al. (2004)
Bulgaria (coppice)	31	163	40	206							Poryazov et al. (2004)
Germany	50	159	74	210	96	254	115	292	150	354	Lockow and Lockow (2015)
Hungary	43	141	58	194	71	241	82	280	98	341	Rédei et al. (2014)
Ukraine	108[a]/129[b]		156[a]/177[b]		198[a]/219		233[a]		277[a]		Anonymous (1987)
Romania (plantation)	40	233	57	316	74	385	94	447	133	549	Giurgiu and Drăghiciu (2004)
Romania (coppice)	28	145	56	272	69	322	81	365	105	433	Giurgiu and Drăghiciu (2004)

Min, minimum; Max, maximum

Ukraine: [a]best site type, plantation; [b]good site type, coppice

Table 7 Evolution of total wood production in stands regenerated by planting, stool shoots and root suckers, depending on the generation (Bîrlănescu and Costea 1962)

Total wood production (%)						
Plantations	Stool shoots			Root suckers		
	1st generation	2nd generation	3rd generation	1st generation	2nd generation	3rd generation
100	86	70	40	89	89	89

Management of black locust

Goals

The goals of managing black locust depend on the location of the stand (e.g., areas of high ecological and environmental values versus stands under regular forest management) and the function (e.g., protection/conservation vs. wood or biomass production) (Sádlo et al. 2017).

In *areas with high ecological and environmental values, such as Natura 2000 sites,* or *with rare or threatened forest habitats*, the goal (e.g., Germany, Poland, Slovakia, Ukraine, Vor pers.comm.; Klisz pers.comm.; Benčať pers. comm.; Lavnyy pers.comm.) is to *strictly eradicate* existing black locust from species compositions and return to native species (Vítková et al. 2016). To avoid further invasion of black locust into as yet un-colonized spaces within protected areas, the *prevention* of introducing the species by deliberate planting, based on legal restrictions, is the target (Kleinbauer et al. 2010; Boer 2013).

Management of black locust in areas with high conservation values

In such areas, the main goal is *strict eradication* and replacement with native species. The most important eradication techniques for black locust control are manual, mechanical, chemical, mechanical/chemical and biological.

Manual control consisting of hand pulling is preferred for seedlings and small saplings and should guarantee that no roots are left in the ground (Boer 2013; https://invasoras.pt/en/gallery/robinia-pseudoacacia-en).

The *mechanical control* of black locust includes *low cutting* and *girdling* of trees (Sabo 2000; Boer 2013). The most efficient method is *incomplete girdling* which includes the removal of a strip of bark and sapwood 8 cm wide from 9/10ths of the girth, followed by complete girdling in the following growing season and later low cutting. The tree does not produce further root suckers and stool shoots (Starfinger and Kowarik 2003). However, the efficiency of both low cutting and girdling is debated (Boer 2013) since killing the main stem is often followed by formation of shoots from the tree base (Sabo 2000).

Chemical control includes *foliar spraying* (late in the growing season) and *tree injection* (after making incisions into the sapwood). Active chemical substances to be used are glyphosate, triclopyr, picloram, each diluted with water, as well as an atrazine-simazine mixture (Boer 2013; invasoras.pt/en/gallery/robinia-pseudoacacia-en).

The *combination of mechanical and chemical control* involves (1) cutting or girdling the trees; (2) applying herbicide on the stump or the girdled area of the trunk (Vítková 2011; Vítková et al. 2016; https://invasoras.pt/en/gallery/robinia-pseudoacacia-en). The chemical substances are as above (most cited: glyphosate) (Sabo 2000; https://invasoras.pt/en/gallery/robinia-pseudoacacia-en).

Biological control makes use of domestic goats and cattle which defoliate black locust; in the native range after 4 years of browsing, all trees had been killed (Stone 2009).

As complete eradication of black locust is not possible since such treatment is expensive because of continuous stump sprouting, one way to fulfill the objective of replacing the species is *prolonging the rotation age* until the trees become senescent and are replaced naturally by native species (Motta et al. 2009). Prevention measures, like *avoidance of disturbances* (e.g., soil disruption) that favor black locust colonization/dispersal by root suckers, are also possible (Boer 2013).

Management in areas with wood production objectives

The rotation length is shortest when black locust is grown for *biomass energy production*: 3–5 years in very short rotation coppice (Borde 2011; Rédei 2013a, b, c, d; Steinegger and Reh 2013), and is 5–7 years in Italy (Facciotto et al. 2008) or 10 years in France (Bousse and Richard 2017) in short rotation coppice.

In black locust stands for *wood production*, the rotation age depends on:

1. *Type of wood product*: rotation age is 50–60 (even 70) years when sawlog (dbh > 40 cm) production is targeted as in Germany (Engel et al. 2014) and Austria (Hochbichler et al. 2015). In France, the rotation age for sawlog production is 40 years and decreases to 25 years for the production of vineyard poles (coppice stands) (Pagès 1986; Bousse and Richard 2017).
2. *Production (fertility) class* (and correlated type of wood product): it ranges between 20 and 25 years in the lowest production classes (V in Romania, VI in Hungary, for poles, props, pulp, other small-size industrial wood) and 35–40 years in the Ist class for good quality sawlogs (Rédei 1984; MAPPM 2000d).
3. *Regeneration pathway* this is 20–25 years in coppice stands compared with stands of seed origin (30–35 year-old plantations), as in Bulgaria (Dimitrov 2001). The rotation age in these coppice stands is similar to ones in Germany and Austria (10–30 years, Iby 1997; Ruhm 2013; Engel et al. 2014; Meyer-Münzer et al. 2015) as well as in Slovenia (15–20 years in the western part of the country, Kadunc 2016, and 20–30 years in the south, Čarni et al. 2016).

Finally, there are countries like Croatia and Poland where the rotation age is not dependant on any criterion but legally fixed at 35–40 years (Poland, Zajączkowski

2013; Zajączkowski and Wojda 2014) or 40 years (Croatia, Croatian Forests Ltd. 2016).

Silviculture of black locust stands for wood production

Natural regeneration

As mentioned earlier, natural regeneration of black locust is primarily by root suckers. The species is also regenerated, on a much smaller scale, by stool shoots and by seed.

When the rotation age has been reached, the main silvicultural system used in black locust stands in Hungary, Romania, Bulgaria, Croatia, France, Germany, Poland, and Slovenia is *simple (low) coppice*, considered *the most cost-effective management system* (Sitzia et al. 2016). This creates light-abundant sites suitable for the vegetative (and generative) regeneration of black locust (Radtke et al. 2013). After the cut, the stools are (1) left to produce adventitious or proventitious sprouts, or (2) dug out, followed by ploughing/scarification to wound shallow roots to promote root suckers (Romania, MAPPM 2000c; Bulgaria, Kostov and Alexandrov 2018; Germany, Meyer-Münzer 2015; Ukraine, Lavnyy pers.comm.) (Fig. 1).

This method is cheap and efficient, allowing local people (e.g., from Romania) to collect the stool wood, which is highly valued as firewood. After the third coppice cut at about 90 years of age, after which the sprouting potential—and so the economic viability—decreases (e.g. Table 7), and the proportion of heart rot increases, all black locust stools are removed and the stand is regenerated by planting (Iby 1997; MAPPM 2000c).

Artificial regeneration

Black locust may be established by planting using reproductive material collected in certified/selected seed stands and seed orchards. These exist in Hungary, Bulgaria, Romania, Germany, Italy, Belgium, Czech Republic, Slovakia, Croatia, Bosnia and Herzegovina, FYR of Macedonia, Poland, and Ukraine (Cvjetkovic pers.comm.; Đodan pers.comm.; MMP-RNP-ICAS 2012; Executive Forest Agency 2014; http://ec.europa.eu/forematis; Lavnyy pers.comm.; Mandžukovski pers.comm.). When no local seed sources exist (for example in the case of France where establishment of a seed orchard is in progress, or in Austria), seeds are imported, mostly from other European countries (e.g., Hungary, Romania, Bulgaria), rather than from the United States (Bastien pers. comm.; Pötzelsberger pers.comm.).

The seeds are light and the yield from 100 kg of pods is 20 kg (Haralamb 1967; Rédei et al. 2001; Rédei 2013a). Because the heavy, thick and impermeable seed coat restricts germination, the seeds need pre-treatment to remove seed dormancy. In both native range (Olson 1974; Harlow et al. 1986) and in Europe (Bîrlănescu and Belu 1968; Costea et al. 1969; Savill 2013; Jastrzębowski et al. 2017; Pedrol et al. 2017), mechanical scarification using rotary tools or electric grinders, soaking in concentrated or diluted sulphuric acid, soaking in boiling or nearly boiling (70–80 °C) water, using low liquid nitrogen or high temperatures in an incubator are the usual methods. After appropriate pre-sowing treatment, germination rates can be as high as 85.0 ± 5.8% (Kheloufi et al. 2018) or 89.0–100% (Cierjacks et al. 2013; Vuković et al. 2013).

Seeds are sown in bare-root nurseries from late April to early May to avoid late frosts. The minimum distance between rows is 35–40 cm (Costea et al. 1969; Keresztesi 1988) and 2–3 g of seeds are used per m^2 with a sowing depth of 2–4 cm (5–6 cm on sandy soils prone to excessive summer warming) (Rubțov 1958; Vakulyuk and

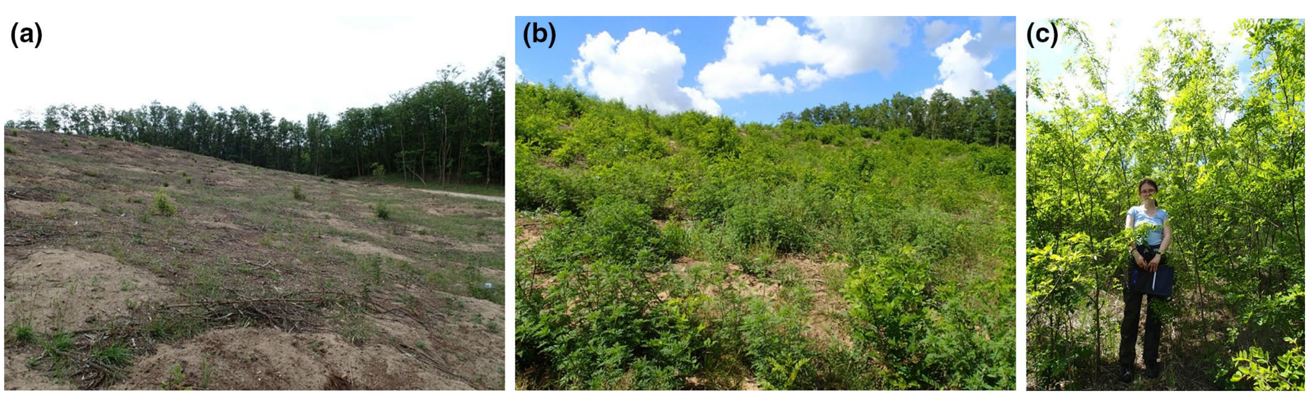

Fig. 1 Black locust stand **a** immediately after removal of stools, **b** two months and **c** 2 years afterwards on continental sand dunes in Romania (photos V.N. Nicolescu)

Samoplavskyy 1998; Iancu 1999). The bare-root seedlings are ready for planting in 1 year after reach a minimum 6-mm root collar diameter and 50–200 cm in height (Iancu 1999; Rédei 2013a). In addition, artificial regeneration of black locust using plants originating from root cuttings as well as in vitro micropropagation (tissue culture) is carried out in Hungary, Bulgaria, and Poland for the reproduction of superior individuals or varieties, such as the 'shipmast' locust *Robinia pseudoacacia var. rectissima* Raber, with a very straight bole, extremely durable wood, and resistance to fungal diseases and insect pests, and *Robinia pseudoacacia f. semperflorens* (Carr) Voss. (up to five blooming periods during a vegetation season) (Keresztesi 1988; Kalmukov 2000, 2012; Szyp-Borowska et al. 2016).

The initial stocking density of black locust plantations for timber production in Europe is highly variable and ranges from 1100 to over 5000 plants ha^{-1} (Table 8).

The distance between rows should be wider than that between the seedlings in the row, approximately 2.5–3.0 m to allow for mechanical cultivation (Austria, Ruhm 2013; Bulgaria, Ministry of Agriculture and Food 2013; France, French Ministry of Agriculture 2018; Croatia, Đodan pers. comm.).

Black locust is usually planted as a monoculture. However, mixed plantations have been recorded: black locust with hybrid/native poplars (*Populus* spp.) in Hungary (Rédei et al. 2002), and Serbia (Andrašev et al. 2015), with silver lime (*Tilia tomentosa* Moench.) and European cornel (*Cornus mas* L.) in Bulgaria (Kalmukov 2005), with poplars and hybrid walnut (*Juglans x intermedia*) in France (Gavaland and Pagès 2007), with pedunculate oak, common ash (*Fraxinus excelsior* L.), and sweet cherry (*Prunus avium* L.) in Ukraine (Lavnyy pers.comm.), with pines (*Pinus* spp.), oaks or maples (*Acer* spp.) in Germany (Carl 2018), as well as with honey locust (*Gleditsia triacanthos* L.), black cherry (*Prunus serotina* Ehrh. Fig. 2), Siberian elm (*Ulmus pumila* L.), and different shrubs in Romania (Spîrchez et al. 1962; MAPPM 2000a).

Protection, either for individual trees or stands using tubes, grids, or fencing (a minimum height of 1.5 m), is recommended in some countries (Austria, Bulgaria, France, Germany), and is necessary when regenerating black locust

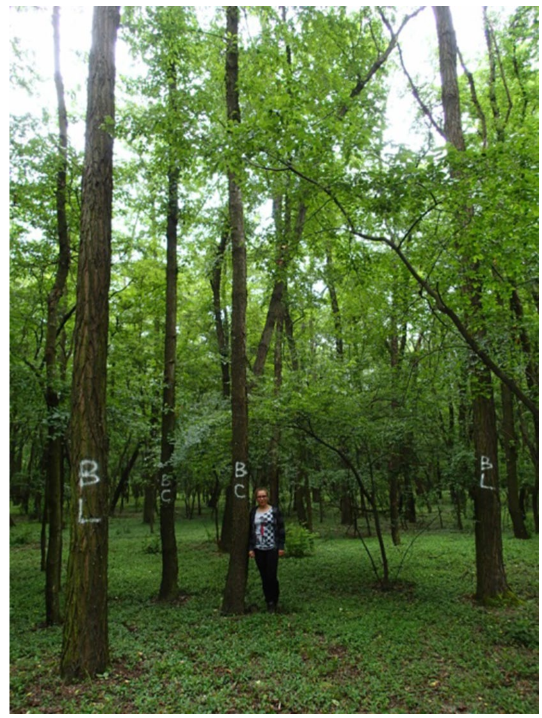

Fig. 2 Mixed black locust (BL)-black cherry (BC) stand in Romania (photo V.N. Nicolescu)

Table 8 The initial stocking of black locust plantations for timber production in different European countries

Initial stocking (plants ha^{-1})	Initial spacing (m)	Country	Source
1100–1900		France (Bourgogne Region)	Borde (2011)
1200–1700	4×2; 3×2	France (Aquitaine and Poitou–Charentes Regions)	Carbonnière et al. (2007), CRPF (2007) and French Ministry of Agriculture (2018)
1700–2500	3×2; 2×2	France (Bourgogne Region)	CRPF Bourgogne (2014)
2000–2500	2.5×2; 2.5×1.6	Poland	Zajączkowski (2013) and Wojda et al. (2015)
2500	3×1.3	Croatia	Đodan pers.comm.
2500		Germany	Meyer-Münzer et al. (2015)
2500–3300	2.0×1.4–2.0	Austria	Hochbichler et al. (2015)
2500–4000		Serbia	Andrašev pers.comm.
3300–5000	(2.0–3.0)×(1–1.5)	Bulgaria	Ministry of Agriculture and Food (2013)
4000–5000	2×1.25; 2×1	Romania	MAPPM (2000a)
4000–5000	2.4×(0.7–0.8); 2.4×1.0	Hungary	Rédei et al. (2008, 2011) and Rédei (2013a)
8900	1.5×0.75	Ukraine	Lavnyy pers.comm.

in areas with high browsing pressure (e.g., hares, roe deer, red deer as well as domestic goats or cattle) (Iby 1997; Ministry of Agriculture and Food 2013; Meyer-Münzer et al. 2015; Lemonnier Nursery 2018).

After 2–3 coppice cycles, growth depression with a reduction of timber production and an increase of heart rot have been observed (Berthold et al. 2005; Borde 2011; Meyer-Münzer et al. 2015; Vítková et al. 2016). Standard practice in some European countries (e.g. Austria, Romania, Bulgaria, Germany) is for planted trees to be coppiced three times, after which stools are removed and the stand regenerated by planting (Iby 1997; MAPPM 2000c; Dimitrov 2001; Meyer-Münzer et al. 2015). In France, black locust coppice stands are managed with four or even five coppice cycles (Borde 2011). However, when the state of coppice stands is poor, they may be clearcut and replanted after only one or two coppice cycles in order to restore the production potential.

Young stand management

Widely-spaced plantations do not require any *release cuttings* but one-two interventions, on a cycle of 1–3 years are necessary in stands vegetatively regenerated from root suckers or stool shoots, targeting the removal of badly shaped or forked trees (‘wolves’) as well as to favour root suckers over stump shoots (Haralamb 1967; Debenne 1988; MAPPM 2000b; Meyer-Münzer et al. 2015). However, such interventions are costly, particularly as the wood removed is not marketable. Therefore, combined with the high natural mortality in young root sucker-originating stands, which can be up to 70% in the first 5 years (Pagès 1985, in Carbonnière et al. 2007), these interventions are not recommended in countries like France (Carbonnière et al. 2007; Borde 2011).

At ages 4–5, the first *cleaning-respacing* (mostly *negative selection*) is performed to remove defective stems (i.e., forked, badly shaped, wounded, or bent-over as an effect of strong phototropism), to reduce the number of shoots per stool, adjust the spacing between root suckers and reduce stocking to a maximum of 2500 stems ha^{-1} (Zajączkowski 2013; Wojda et al. 2015). After 3–4 years, this is followed by second cleaning-respacing, mostly based on *positive selection*, with the same aims but especially to reduce stocking to ca. 1700 or even 2000 stems ha^{-1}, with spacing as regular as possible to provide additional growing space to the remaining individuals (Constantinescu 1976; Halupa and Rédei 1988; Rédei et al. 2011; Wojda et al. 2015).

A more intensive approach is practiced in France, with much lower initial stocking of plantations (Table 8) which is reduced, after the second cleaning-respacing, to 1000–1200 stems ha^{-1}. In addition, extraction racks of 3–4 m wide, and at 10 m intervals are considered necessary due to the high stocking of young stands. These are opened during the first cleaning-respacing operation (Debenne 1988; Carbonnière et al. 2007; CRPF 2007).

The wood volume removed by cleaning-respacing may be 4–6 m^3 ha^{-1} (first intervention) and 15–20 m^3 ha^{-1} (second intervention), depending on the site potential and productivity class (Rédei 1984). The correct application and timing of cleaning-respacing is the key to good management (Halupa and Rédei 1988). If this intervention is too late or too light, the remaining trees do not develop their crowns normally and they are deformed or too small, as black locust is a strong light-demanding species. The crowns do not recover no matter how much light is subsequently available (Haralamb 1967; MAPPM 2000b).

Commercial thinning

In black locust stands, early, selective, moderate and frequent *thinning* is undertaken. The operations are carried out at 5–7 years intervals and are either *mixed* as in Romania (Costea et al. 1963; MAPPM 2000b) or *from above* as in Austria (Hochbichler et al. 2015), Germany (Vor pers. comm.), France (Borde 2018) and Slovenia (Čarni et al. 2016). Thinning aims to keep the crowns of the final crop trees (e.g., those which are cylindrical, with straight grain, monopodial growth, and healthy dense foliage) free from competition to encourage vigorous growth to reach the target diameter as soon as possible (Borde 2018; Vor pers.comm.). During thinning from above, 2–3 (CRPF Bourgogne 2014), 2–4 (Hochbichler et al. 2015) or a minimum of 4–5 (Borde 2018) of the strongest competitors are removed for each final crop tree. It is advisable to keep the viable trees in the lower (IV and K) Kraft classes as these contribute to the natural pruning of dominant black locust trees and reduce the danger of epicormics by shading the trunks of the most valuable individuals in the upper classes (Bîrlănescu and Clonaru 1960).

The intensity of each thinning intervention is generally between 15 and 25% of the standing volume, although the volume removed per intervention varies between different European countries and ranges from 18 to 30 m^3 ha^{-1} in Croatia (Đodan pers.comm.), 20 m^3 ha^{-1} in Serbia (Andrašev pers.comm.), 30–50 m^3 ha^{-1} in Hungary (Rédei 1984) to 80 m^3 ha^{-1} in Germany (Lockow and Lockow 2015). In countries like Hungary and Bulgaria, 25–35% of the total wood production is removed during thinning operations (Rédei 2013c). In Hungary, the thinning intensity is determined on the basis of the “growing space index”, calculated as the mean distance between trees × 100/mean stand height after thinning. This should be 23–24% in pure black locust stands (Rédei 1984; Rédei 2013c).

Generally, the number of trees per ha after the last thinning equals the stocking at rotation age and ranges between 120 and 150 stems in Austria (Hochbichler et al. 2015) and

Table 9 Stocking of pure black locust stands after the last thinning/at rotation age in some European countries

Number of trees after last thinning/at rotation age (ha^{-1})	Country	Source	Obs.
120–150	Austria	Hochbichler et al. (2015)	Sawlog production
150–200	France	Borde (2018)	Sawlog production
150–300	France	CRPF Bourgogne (2014)	Sawlog production
Ca. 200	France	Borde (2011)	Sawlog production
300	Italy	Maltoni et al. (2012)	Sawlog production
400	Germany	Meyer-Münzer et al. (2015)	Sawlog production
400–500 (600)	Hungary	Rédei et al. (2017)	Sawlog production
400–700	Poland	Wąsik pers.comm.	
500	France	CRPF Aquitaine (2018)	Vine stake production
700–800	Italy	Maltoni et al. (2012)	Pole and prop production

700–800 stems in Italy (Maltoni et al. 2012), depending on the country and intended range of final products (Table 9).

Pruning

The terminal shoot of black locust may be repeatedly affected by frosts, causing forking multiple. Rectifying this by *formative pruning (shaping)* is an intervention-to-waste so is not advisable.

Green high pruning is tolerated well by black locust (Halupa and Rédei 1988) and is carried out only on crop trees, from 120 to 160 individuals ha^{-1} in Austria (Pötzelsberger pers.comm.) to 300/400–600 individuals ha^{-1} in France (Merzeau et al. 2008; CRPF 2011). This is completed in two or three lifts and stems are cleared of branches to a height of 4–6/7 m (Halupa and Rédei 1988; Rédei et al. 2017; CRPF Aquitaine 2018) or even 6–8 m (Dancart 2019). The crown length after pruning should be at least a third of the tree height (Meyer-Münzer et al. 2015).

Conclusions

Black locust is a light-demanding, competition-intolerant, fast-growing and relatively tall tree species, able to adapt to difficult site conditions (e.g., dry climates, with nutrient poor and dry soils). It is an *important multipurpose species* with major economic, ecological and social roles for producing wood, fodder, honey, a source of bio-oil, for biomass production and carbon sequestration, soil stabilization/erosion control, re-vegetation of landfills, mining areas and wastelands, in biotherapy, and in landscaping. It grows rapidly when young, and height, diameter and volume growth peak before the age of 20 years. It is wind-firm, not affected by any major pest or disease, and coppices easily. Consequently black locust has a simple silvicultural management regime, clearcutting with regeneration either naturally from root suckers or stool shoots, or by planting, with the aim of producing valuble wood with various end-uses, from parquet, veneer, furniture, barrel staves, vineyard stakes to firewood, under short rotation periods of up to 40–50 years compared to major European native broadleaved tree species such as oaks and European beech.

As its potential to adapt to predicted climate changes, particularly drought, seems to be high, the importance of black locust, a species both "beloved and despised" (Vítková et al. 2017) in Europe, is expected to increase in the future. However, not only will its importance increase under expected climate conditions, but also its invasiveness potential. This reality necessitates a more complex, integrated approach to the management of such controversial species, i.e., large-scale use or tolerance in forest stands in areas of economic importance, and strict eradication in other, ecologically valuable or sensitive sites.

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