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A review of European ash (*Fraxinus excelsior* L.): implications for silviculture

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Summary

European ash (*Fraxinus excelsior* L.) is common throughout much of Europe and is a valuable broadleaved tree due to its ecological characteristics, outstanding wood properties and high economic value. It is a fast growing species, associated with several forest types and with a scattered distribution in many different forest communities. In this review, we sum up essential characteristics of European ash, relevant to the further development of silvicultural practices. The paper covers site requirements, regeneration and stand establishment, growth dynamics and wood quality, and health and robustness. The review also highlights implications for silviculture and summarizes new information on ash dieback, a phenomenon which is observed in many European countries. Ash grows best on fertile, pH-neutral, deep, freely drained soils and such sites should be favoured if the aim is for high quality timber. Ash grows well at wide spacing which can result in enlarged ring width and increased latewood percentage, making the wood denser and stronger. Relatively short rotations may be recommended, depending on site, to avoid black heart: for example, a harvesting diameter of 60 cm can be reached within 60–75 years at 60–80 ash crop trees per ha. Universal recommendations are therefore for wide spacing with heavy, regular thinning in order to get a large diameter within a relatively short rotation. The necessity for pruning depends on the stand density at establishment and the subsequent thinning regime.

Introduction

European ash (*Fraxinus excelsior* L.) is a fast-growing hardwood well known as a source of high-quality timber for which there is high demand (Fraxigen, 2005). It is a common species, associated with several forest types. However, due to its scattered occurrence in the forest, the silviculture of ash has received little attention in the past. The aim of this paper is to present essential characteristics of European ash relevant to the further development of silvicultural practices. The topics included are natural distribution, site requirements, regeneration and stand establishment, growth dynamics and wood quality, and health and robustness.

Throughout, we aim to identify factors which influence one or more of these issues. We do not focus on a particular silvicultural system, but emphasize the identification of factors allowing for rapid growth while producing high quality timber as well as the challenges when growing European ash in mixture with other species.

Natural distribution

European ash (hereafter referred to simply as ash) is common throughout Europe except for central and southern parts of the Iberian Peninsula, south-east Turkey, northern Scandinavia, Iceland and the northernmost parts of the

British Isles (Meusel *et al.*, 1965; Hultén and Fries, 1986; Jahn, 1991). The natural range of ash essentially coincides with that of pedunculate oak (*Quercus robur* L.), the characteristic species of the nemoral forest zone in Europe. In the southern part of its distribution, European ash occurs together with narrow-leaved ash (*F. angustifolia* Vahl) and manna ash (*F. ornus* L.) (Fraxigen, 2005). European ash and narrow-leaved ash are the most common ash species in western Europe. Due to small population sizes in glacial refugia and a low rate of mixing between post-glacial re-colonization lineages, there is a strong genetic differentiation among, but not within, populations of European ash (Heuertz *et al.*, 2004a, 2004b). Hybridization may occur with narrow-leaved ash, but not with manna ash (Fernandez-Manjarres *et al.*, 2006; Heuertz *et al.*, 2006). Due to the valuable timber of *F. excelsior*, genetic contamination by *F. angustifolia* is undesirable (Fernandez-Manjarres *et al.*, 2006). The distribution of the two species and their hybrids is tightly linked with environmental variables, suggesting that climate is an important factor that restricts hybridization (Gerard *et al.*, 2006a, 2006b).

The northern and southern limits of ash coincide with January isotherms of 0–5°C, respectively. However, at the eastern edge of its natural range, ash can withstand temperatures as low as −15°C. In general, it is thought that the northern limit is determined by a minimum energy available for completion of the annual life cycle, the eastern limit by minimum temperatures and the southern and south-eastern limits by moisture deficit. Good sites for ash are where the climate is 'warm', i.e. with an accumulated temperature of >1375 day-degrees >5.6 C (Kerr and Cahalan, 2004). In the northern and western parts of its natural range, ash grows in lowland forests, while in central and southern Europe, it occurs in mountainous areas at altitudes of up to 1600–1800 m and in northern Iran up to 2200 m (Fraxigen, 2005). The European network of forest genetics, Euforgen, has published a map online that illustrates the distribution of ash (http://www.euforgen.org/distribution_maps.html).

Ash plays an important role in both primary and secondary succession, and it occupies large areas of all age classes of primary and secondary woodland. It often occurs in mixed broadleaved forest or as a component of forests dominated by European beech (*Fagus sylvatica* L.), sessile oak (*Quercus petraea* (Matt.) Liebl.), pedunculate oak, sycamore (*Acer pseudoplatanus* L.), black alder (*Alnus glutinosa* (L.) Gaertn.) or grey alder (*Alnus incana* (L.) Moench). The expansion of ash in Europe is a recent phenomenon, which may be related to a decrease in the rural human population (Marigo *et al.*, 2000), rather than increasing nitrogen deposition (Hofmeister *et al.*, 2004).

The ecology of ash has been reviewed by Wardle (1961) and Grime *et al.* (1988). Some aspects are well documented including its light requirements (Gardner, 1975), seedling and sapling ecology (van Miegroet, 1956; van Miegroet and Lust, 1972) and silviculture (Thill, 1970).

Site requirements

Several reviews have been carried out on the site requirements of ash (Fodgaard, 1978; Kerr and Cahalan, 2004) focusing on soil physical properties, soil nutrients, water supply, temperature and light conditions.

Site types

Ash thrives on a wide range of site types, except on acid soils, but dominates mainly on sites that are unfavourable for beech, oak and, to some extent, alder (Jahn, 1991; Ellenberg, 1996). Although ash has been suggested as a very versatile hardwood, being able to grow well on several site types (Kerr and Cahalan, 2004), edaphic and hydrological factors determine on which sites ash may become the dominant species (Wardle, 1961). In eastern parts of its natural range, ash may become a dominant species in floodplain forests and on moist clay-loam lowland sites (Dufour and Piegay, 2008). In contrast, however, ash may also be a dominant component in forests on relatively dry sites, typically on stony mountain slopes and in ravine forests (Weber-Blaschke *et al.*, 2008).

In central parts of Europe (Jahn, 1991; Ellenberg, 1996) and at the northern limit of its natural range (Halden, 1928; Huldén, 1941; Wardle, 1959), ash may dominate on relatively dry calcareous sites. Historically, this gave rise to the theory of two different ecotypes of ash: the so-called 'water ash' adapted to moist site conditions and 'chalk ash' adapted to dry calcareous sites (Münch and Dietrich, 1925). However, subsequent research (Herre, 1928; Leibundgut, 1956; Knorr, 1987; Weiser, 1995) has not been able to corroborate this theory. Consequently, the natural occurrence of ash on such a wide range of site types is due to a high tolerance in respect to water and nutrient supply. Its occurrence on sites which are marginal or less optimal (e.g. gley, chalk or peat soils) is probably due to lack of competition from other species, more or less mediated by the influence of foresters.

Soils that favour ash are often derived from calcareous, marl or sedimentary parent material, rich in clay or silt (pH 5–7.5), moist and well drained (Wardle, 1961; Zollner and Kölling, 1994). Often, such sites have a fast turnover of organic material, a rich invertebrate fauna, especially lumbricid worms, and a rich nitrophilous ground flora (Loidi, 2004). Plant indicators for good ash soils are dog's mercury (*Mercurialis perennis* L.), wild garlic (*Alium ursinum* L.), stinging nettle (*Urtica dioica* L.) and enchanter's nightshade (*Circaea lutetiana* L.) (Bornebusch, 1923; Popert, 1950).

Soil nutrients

Ash is considered to be a demanding species in terms of nutrient requirements with a high demand for nitrogen, calcium, magnesium and phosphorous. The nutrient supply depends on the nutrient content of the soil with respect to exchangeable cations and citric-acid-soluble phosphorous. The level of base saturation determines whether ash can exist at a specific site (Gordon, 1964; Loidi, 2004). Upper mineral soils with a base saturation >50 per cent are optimal for young ash, while a base saturation of <50 per cent is adequate only if other site conditions are favourable, and <30 per cent precludes the growth of ash (Weber and Bahr, 2000b). The height growth of ash is strongly correlated with the nitrogen status of the leaves, which is greatest where the biologically active top soils are rich in base cations; where there is stagnant water and the soil is deficient in magnesium and phosphorous, the shoot and root growth is reduced (Weber and Bahr, 2000b). In summary, ash is demanding with respect to nitrogen (Diekmann, 1996).

In loamy soil derived from basalt with high calcium and magnesium, but low aluminium saturation, the growth and the calcium and magnesium nutrition of ash are excellent (Weber and Bahr, 2000a). In contrast, on a sandy substrate, ash may show magnesium deficiency with typical intercostal chloroses on the leaves. On very acid loamy and clay soils poor in base cations but with a sufficient supply of nitrogen, ash can suffer from aluminium toxicity, leading or contributing to sub-optimal calcium, magnesium and phosphorous concentrations (Weber and Bahr, 2000a). Ash presumably is not able to thrive with high concentrations of aluminium in the soil solution, and, therefore avoids growing on very acid soils (Weber-Blaschke *et al.*, 2002). Toxicity of aluminium ions is thought to reduce growth and even prevent establishment of planted ash on soils with a pH <4 (Zollner and Kölling, 1994). Although ash does grow on several site types with various nutrient regimes, for the production of quality ash timber, it is best to avoid sites that are waterlogged, or with a pH <4 to ensure adequate nutrition for optimal growth (Weber-Blaschke *et al.*, 2008).

Water supply

Ash is adapted to moister sites and consequently can thrive on a wider range of sites than beech (Marigo *et al.*, 2000). Ash grows well when soil moisture is 'fresh' to 'very moist' with a winter water table depth between 40 and 100 cm (Kerr and Cahalan, 2004). High growth rates can be achieved on sites with >110 days of easily available water during the growing season. However, growth is poor on sites with >30 days of waterlogging in the upper half of the main rooting horizon at the beginning of the growing season (Peltier and Marigo, 1998).

Sycamore and cherry (*Prunus avium* L.) are more tolerant of low water availability than ash which prefers slightly more moist sites, e.g. alluvial and colluvial, freely draining sites (Claessens *et al.*, 1999). Ash tolerates short-term flooding, but is intolerant of stagnant water where there is a lack of oxygen (Glenz *et al.*, 2006). It is also intolerant of compacted soils. The negative impacts of flooding are more pronounced for ash than for oak (Vreugdenhil *et al.*, 2006). Fluctuations in ground water can result in desiccation of tree tops. Ash seedlings can tolerate flooding to ground level for two growing seasons but when water is severely limited ash remains a shrub (Wardle, 1961).

Ash is a pioneer species in some parts of its natural range e.g. in England (Wardle, 1959) and Sweden (Halden, 1928). A reduction of stream flow and lowering of the ground water level may adversely affect seedling establishment; larger seedlings can be favoured by a reduction in density of the shrub and herbaceous layer that results from flood damage (Dufour and Piegay, 2008).

Plants that are tolerant to water stress, such as ash, have tissues that can tolerate dehydration (Ludlow, 1989). Osmotic changes and elastic adjustment of the cell walls both contribute to the drought adaptation mechanism of the species where calcium may play an important role (Marigo and Peltier, 1996). Ash also exhibits an altered growth pattern in response to moisture stress (Kerr and Cahalan, 2004). It is for these reasons that it is not recommended to plant pure ash on exposed ground where water loss from transpiration could lead to restricted growth, particularly if weed control around the trees is also poor (Kerr and Cahalan, 2004).

In summary, while ash is broadly tolerant of moderate variations in water supply, prolonged waterlogging is detrimental to growth. Sites that regularly flood, and remain flooded for more than 30 days, should be avoided for planting ash for quality timber production.

Temperature

Ash is sensitive to severe winter and late spring frosts. During very severe winters, ash stems can crack. While the cracks are often triggered by freezing temperatures, their origin is due mainly to interior tension in the xylem and large vessels in the early wood (Savill, 1991). Spring frosts that occur after bud burst can lead to loss of the terminal shoot (Wardle, 1961). The two flanking lateral buds then develop, usually resulting in a fork (Kerr and Cahalan, 2004). On some sites, planting with other species or planting among stump re-growth may alleviate the problem of spring frost (Savill, 1991; Fraxigen, 2005). Due to its sensitivity to late spring frosts, ash should not be planted on exposed sites or in frost pockets unless a suitable nurse is also planted where good quality timber is the objective.

Within the natural range of ash, the number of annual growing degree-days (accumulated mean daily temperatures >5°C), which is an index of energy available for completion of the annual life cycle, ranges between 1300 and 3000 day °C (Prentice and Helmisaari, 1991). When subtracting for degree-days that occur during the spring frost risk period, the number of annual growing degree-days decreases to 1100 day °C (Sykes *et al.*, 1996).

Light

The effect of light on the growth of trees is complex and depends on a range of factors, especially water supply and tree age (Wardle, 1961). The light demands of ash change according to its developmental stage. Seedlings and young juveniles are shade tolerant, but gradually become increasingly light demanding, so regular interventions are considered necessary to ensure light conditions remain optimal within a stand (Wardle, 1959; Okali, 1966; von Lüpke, 1989; Diekmann, 1996; Franc and Ruchaud, 1996; Wagner, 1996). In deep shade, the mortality of ash is high and young trees often have an etiolated appearance (Rust and Savill, 2000). Moderate shading may however increase seedling growth by reduced competition from herbaceous vegetation (Helliwell and Harrison, 1979).

Ash regeneration develops successfully above ~2 per cent of sunlight (Marigo *et al.*, 2000). In low light conditions, height growth may stop quickly. On appropriate sites (e.g. limestone), ash has the ability to establish a seedling bank by which the species is permanently present in the regeneration stratum of a stand (Jaworski, 1995). Therefore, successful establishment and development of ash regeneration often occurs in gaps (Emborg, 1998).

Knowledge of the dynamics of even-aged stands of ash is poor; e.g. there is not yet any explanation for the belief that ash responds less to delayed thinning than many other broadleaved species. Investigating relationships between crown development and stem volume increment could ultimately lead to a better understanding of the stand dynamics of ash.

Regeneration and stand establishment

Regeneration and establishment of ash can be either through natural seed fall or by planting. Both methods are used extensively, depending on site and stand conditions.

Natural regeneration

Ash exhibits a continuum of gender from purely male, through several stages of hermaphrodite to purely female flowers (Fraxigen, 2005). Various categories of flowering in ash have been described, e.g. five categories with various degrees of development of the gynoecium or androecium as functionally male or functionally female trees (Binggeli and Power, 1991). The effect of the different flower categories on seed production of a single tree is not fully understood yet. The number of seeds may be related to diameter at breast height (dbh) by a logistic model, i.e. the larger the dbh, the greater the number of seed up to a specific dbh value, after which the number stays essentially constant (Schmiedel, 2010). However, regardless of dbh, a pure female tree produces more seed than a hermaphrodite (Binggeli and Power, 1991). As ash is a trioecious species, dbh alone is not a good indicator for the amount of seed a single tree can produce in a given year.

Seed production in stands usually begins when the trees are 20- to 30-year old and seed will be produced annually, but with intervals of 2–5 years between heavy crops (Savill, 1991; Harmer, 1995). The seed (a samara) is winged. Depending on stand and wind conditions, the seed may travel to distances of >100 m (Wagner, 1997). The ash seeds may be scattered anisotropically around individual mother trees (Wagner *et al.*, 2004). As an example, the density distribution of seeds, depending on distance to the mother tree, may be represented by a log-normal distribution with mean distances of 43.5 m and 95 per cent of the fruits found within 113 m of a single ash tree of 130 years and a dbh of 45.0 cm (Wagner, 1997).

Generally, the majority of the seeds remain on the tree throughout winter. Ash is deeply dormant and seed germination is delayed by one year compared with sycamore. Assuming that ash and sycamore show similar cycles of seed production, there could be a tendency for these two species to regenerate in alternate years (Kerr, 1995). This could be important in habitats where ground vegetation recovers rapidly following disturbance or simply give a competitive advantage to sycamore. This process could, to some extent, explain the maintenance of both species in the same habitat (Kerr, 1995).

The species composition of a stand influences the establishment and development of ash seedlings. In southern Sweden, the density of ash seedlings appears to be higher in hardwood forests than in mixed forests (Götmark *et al.*, 2005). In Bohemian Karst of the Czech Republic, the highest average height of ash natural regeneration has been recorded in the *Fageto–Quercetum illimerosum* vegetation community, and the lowest height in the *Carpineto–Aceretum saxatile* community (Střeštil and Šammonil, 2006).

The expansion of ash natural regeneration depends on soil conditions and exposure, and relates to the water balance gradient (Ellenberg, 1996). In Belgium, natural regeneration of ash has been found to reach densities of up to 150,000 individuals per ha on medium-deep, heavy-textured soils with a water retention capacity >20 mm, and densities of down to 12,700 individuals per ha on slopes fully exposed to the south with water retention capacity <20 mm (Tabari and Lust, 1999).

Ash will regenerate freely on sites where it will not thrive such as compacted clays or dry soils over chalk; on such soils, regeneration will usually fail after 3–4 years (Tabari *et al.*, 1999). However, on calcareous and other dry soil types in central Europe and at the northern limits of its natural range, ash does survive and compete well to maturity, often forming more-or-less pure stands (Halden, 1928; Huldén, 1941; Wardle, 1959; Jahn, 1991; Ellenberg, 1996). Natural regeneration is very poor where the humus layer is more acidic and the litter layer thick. In contrast, there is a high regeneration rate alongside many European rivers (Dufour and Piegay, 2008). In a British case study, the number of ash seedlings was positively related to the number and proximity of parent trees, but there appeared to be no consistent relationships between decreases in the size of the seedling populations and the type, number or height of vegetation, as seedling cohorts generally declined in number with time, decreasing by 40–50 per cent each year (Harmer *et al.*, 2005).

Throughout Britain, ash shows a remarkable capacity to regenerate naturally both in woodland and in non-woodland situations (Kerr, 1995). Similarly, in continental Europe, it is often so prolific that the species can become invasive (e.g. Wagner, 1990; Fraxigen, 2005). In particular, high vitality and density of ash seedlings and saplings is of concern when mixed stands are aimed for in regeneration phases. In some cases, a lack of beech or low vitality of beech seedlings and saplings has been described in connection with abundant and vigorously growing ash regeneration leading to the term 'fraxinization' which has been discussed in German and northern European literature (Leibundgut, 1954; Fodgaard, 1978; Börth, 1990a, 1990b; Wagner, 1990, see also Fraxigen, 2005).

Ash is usually an intermediate species in ecological succession and takes advantage of disturbances in stands and is highly competitive in mixed species regeneration. The advantages of this strategy compared with beech, which is a late successional species, are (Wagner, 1990)

1 fruiting in short intervals but with high density and moderate dispersal distances;
2 accumulating seed banks;
3 increased growth in response to gap creation, and
4 effective leaf positioning which avoids self-shading within a single sapling but casts deep shade underneath when combined with high seedling densities.

The differences in the regeneration niche (seed production and dispersal) of ash and beech result in a high probability of ash establishing before beech in gaps (Emborg, 1998), but there is a negative correlation between canopy openness and mean density of ash seedlings (Modrý *et al.*, 2004).

In Germany, it is considered advisable to initiate the natural regeneration of a mixed beech–ash stand using a dense shelterwood (Petritan and Lüpke, 2009). Then, after successful establishment of the desired tree species, it is recommended to continue with a group selection, strip or irregular shelterwood cutting, in order to provide for the higher light demand of ash (Petritan *et al.*, 2007). However, these conditions are not always easy to manage in mixed hardwood stands.

The development of natural regeneration can be limited by the presence of herbivores and this should be taken into account when planning the regeneration strategy (e.g. Čermak and Mrkva, 2006). Ash can regenerate vegetatively but this is not common practice outside of coppice forests. However, it has been recommended cutting down young ash of poor form (stumping) to promote high quality regrowth as ash is capable of vigorous sprouting when young (e.g. van Miegroet, 1956). Ash may also regenerate by layering which can occur in shady forests (e.g. Polatayčuk and Šparik, 1993).

Planting

Recommendations on planting density for ash vary across Europe. Some states in Germany recommend planting 4000 to 5000 plants per ha (HE-MIN, 1999), whereas British or French sources recommend considerably lower densities ranging from 300 to 2500 plants per ha (Kerr and Evans, 1993; Armand, 1995; Duflot, 1995). In many countries, 2-year-old seedlings are usually planted, with 1- and 3-year-old seedlings rarely so. In Poland, e.g., ash is often planted after patch scarification and at spacings from 1.3 × 1.3 to 1.6 × 1.6 m (6000–4000 trees per ha) (Jaworski, 1995). In Britain, ash is nearly always planted at 2 × 2 m (2500 trees per ha). Better growth at closer spacing may be a characteristic of young ash (Kerr, 2003; Kerr and Cahalan, 2004), whereas survival may be better at wide spacing (Espahbodi *et al.*, 2003). Observations from many new woodlands in the UK indicate that growth of ash is generally poor at wide spacing, even when weed control is being used.

The recommended minimum size of planting stock for bare rooted ash is 5-mm root collar diameter and 20-cm height; cell grown stock should be 6 mm and 60 cm, respectively (Kerr, 1995). An area of at least 1 m^2 around the tree should be kept weed free for at least 3 years after planting to maximize water and nutrient availability to the tree. Early side shelter is essential for ash establishment and it has been recommended that it should not be planted pure on exposed grounds (Burckhardt, 1870; Hauch, 1922; Kerr, 1995). The diameter growth of ash responds strongly to planting distance. In a planting distance trial with 1 × 1, 1.5 × 1.5, 3 × 1.5 and 5 × 5 m spacings (with an admixture of black alder), it was found that all establishment methods can be used for the production of good quality saw logs, but taking costs of planting and tending into account, there was a preference for a spacing of 1.5 × 1.5 m and without the admixture of alder (Oosterbaan, 1994).

Growth dynamics and wood quality

The earliest publications with an emphasis on quantitative growth and yield are from the early 20th century (Tables 1 and 2). However, the degree of accuracy with which they describe data sampling, methods for data treatment and, more importantly, what their objectives in the investigations were, vary widely (Table 1).

Early growth

Cleaning at the sapling stage of regeneration is generally considered important for growing ash stands of good quality (Leclercq, 1988), and it is also believed that ash needs intensive tending. Controlling undesirable species and initiating pruning at the sapling stage has been demonstrated to have a positive effect on the development and increment of ash (Vuckovic *et al.*, 2002).

Height growth

Ash grows rapidly during its first years (Wardle, 1961; Jaworski, 1995). It is considered to respond quickly to thinning only at young ages. Maximum height may be achieved by age 50, but this depends on site characteristics (Marigo *et al.*, 2000). In Belgium, height at age 50 was 27.5 m in valleys and hollows and 28.1 m on alluvium

Table 1: Publications on yield tables and other quantified decision tools on European ash in Europe (in chronological order)

Authors	Growth description	Objectives	Material
Wimmenauer (1919b)	Two site index classes; classical yield table	*	German; 25 long-term experimental plots
Oppermann and Bornebusch (1929)	One site class; mathematically formulated growth model and classical yield table	*	Danish; 8 long-term experimental plots
Zimmerle (1942)	Two site index classes; classical yield table	*	German; 12 long-term experimental plots
Carbonier (1947)	Two site index classes; classical yield table	*	Swedish; 15 long-term experimental plots
Møller and Nielsen (1959)	Four site index classes; classical yield table	*	Danish; 23 long-term experimental plots and 142 temporary plots. Swedish; four plots
Volquardts (1958)	Two site index classes; classical yield table	*	German; 49 long-term experimental plots, 35 + 169 temporary plots
Hamilton and Christie (1971)	Five site index classes; classical yield table	*	British; ash, sycamore and birch
Sopp (1974)	Six site index classes, classical yield table	*	Hungarian
Thill (1970)	General guidelines to control growth, first to mention target diameter for individual trees	Target circumference corresponding to $d_{1.3}$ = 220 cm	Belgian
Kovàcs (1986)	Six site index classes, classical yield table	*	Hungarian; 84 long-term experimental plots
Scohy (1990b)	First to describe both an objective diameter for individual trees and a clear bole length	Target diameter: $d_{1.3}$ = 200 cm. Clear bole length: 7–8 m, including formative pruning and pruning	Belgian
Pilard-Landeau and Le Goff (1996)	Two site index classes	Target diameter: $d_{1.3}$ = 40–60 cm or $d_{1.3}$ = 60–70 cm Clear bole length: 6–8 m	French
Hein (2004); Hein and Spiecker (2009)	No yield table, but a detailed description of target diameter, clear bole length and their interdependence; several decision tools	Growth models designed for flexible objectives on target diameter and clear bole length, including artificial pruning and knottiness	1501 ash trees measured on temporary plots from 13 European countries and open grown trees

Volquardts (1958) was used for ash in the Dutch collection of yield tables (Jansen *et al*., 1996). Sopp (1974) was used for ash in the collection of yield tables of the Austrian Forest Service (Sterba, 1976).
* No objective given; description of growth and yield, typically for yield tables with thinning regimes from below or above.

Table 2: Publications on height growth on European ash in Europe (in chronological order)

Authors	Definition of stand height	Methods	Material
Wimmenauer (1918, 1919a, 1919b)	Mean height	Measurement of tree height, graphical smoothing	German
Oppermann and Bornebusch (1929)	Mean height after thinning	Measurement of tree height, mathematical smoothing	Danish
Zimmerle (1942)	Mean height	Graphical smoothing	German
Carbonier (1947)	Dominant height	Combination of mathematical and graphical smoothing	Swedish
Volquardts (1958)			German
Møller and Nielsen (1959)	Mean height corresponding to the quadratic mean diameter between two thinnings (H_g)	Graphical smoothing	Danish and Swedish
Brüel (1969)	Mean height	Graphical smoothing	Danish
Hamilton and Christie (1971)	H_{100}, i.e. stand top height		British
Sopp (1974)	Dominant height		Hungarian
Sterba (1976)	H_{100}, i.e. top (dominant) height	Based on Sopp (1974)	Hungarian
Devauchelle and Levy (1977)	Mean height	Stem analysis, mathematical smoothing	French
Le Goff (1982)	Mean height of dominant trees	Stem analysis, mathematical smoothing according to Bailey and Clutter (1974)	French
Anonymous (1984)	Mean height		Romanian
Kovàcs (1986)	Dominant height	Mathematical smoothing	Hungarian
Knorr (1987)	Mean height	Mathematical smoothing	German
Uhúl (1990)	Mean height of stand		Czech
Thibaut *et al*. (1992)	Dominant height	Measurement of tree height, stem analysis, mathematical smoothing according to Johnson (1935)/Schumacher (1939)	Belgian
Jansen *et al*. (1996)	Dominant height	Based on Volquardts (1958), Richards (1959) and Chapman (1961)	German
Hein (2004)	Dominant height	Stem analysis, mathematical smoothing according to Sloboda (1971)	13 European countries

geological strata (Claessens *et al.*, 1999). In Slovenia, the fastest height growth was observed for ash trees growing on sites where hornbeam typically grows; however, above age 60, the height growth was fastest on sites typical for ash (Kadunc, 2004). The slowest growth rates were recorded on mountainous calcareous beech sites; however, the diameter growth was moderate but very consistent and did not decline with age (Kadunc, 2004). In moist forests in Poland (Bialowieza National Park), ash achieves 130–200 cm in diameter, 45 m in height and a stand volume of ~700 m^3 ha^{-1} at age 150 (Faliński and Pawlaczyk, 1995). Ash reaches its maximum height 30–40 years earlier than beech does. The tallest individuals of ash (>40 m) in unmanaged forests in Europe were found in Slovakia in Hrončokovský grúň, where the total live and dead wood volume was >1000 m^3 ha^{-1} (Holeksa *et al.*, 2009).

Soils which are fertile, pH-neutral, deep, moist and freely draining create optimal conditions for the growth of ash and it is only these optimal site types that provide the fast growth rates (Fraxigen, 2005). Consequently, pure stands of ash should only be grown on the best sites. On infertile and dry sites, ash becomes dependant on water supply from rainfall and rapid growth rates are not realized (Fraxigen, 2005).

The concentration of some micro- and macro-elements influences ash growth (Bugała, 1995). The relationship of foliar nitrogen concentrations with height growth has been demonstrated for ash growing in the Lake District in northern England (Gordon, 1964). In contrast, there was no relationship between the foliar nutrient level of any element and mean annual height growth for ash in Bavaria (Knorr, 1987).

When comparing height growth from different yield tables across Europe, significant variation is evident (Table 2; all height growth curves cited here are graphically displayed in the annexes of Hein, 2004). Some height growth models predict a very great height increment (e.g. Le Goff, 1982) even at older ages (between 80 and 100 years: 0.25 m per year) whereas other models expect height growth to slow as ash matures (e.g. Hamilton and

Christie, 1971, between 60 and 80 years: 0.06 m per year). This may indicate site-specific differences in height growth. However, most probably, it is a result of biased data selection, with (too) few trees at older ages and thus unbalanced datasets, or different definitions of what is meant by 'mean height' (Hein, 2004). Poor graphical or mathematical smoothing technique may be another contributing factor.

Volume growth

The volume growth of ash stands can be illustrated by two selected yield tables by Volquardts (1958) and by Hamilton and Christie (1971). In the yield tables prepared by Volquardts, the current annual volume increment (CAI) culminates at 35 years and reaches 12.2 m^3 $year^{-1}$ (mean annual volume increment (MAI): 8.6 m^3 $year^{-1}$, 50 years) for the first yield class, and with 8.6 m^3 $year^{-1}$ at 45 years (MAI: 6.2 m^3 $year^{-1}$, 60 years) for the second yield class. His tables allow for estimation of the productivity of ash in northern Germany: the cumulative volume production (CVP) at 80 years is 504 m^3 $year^{-1}$ for the best and 352 m^3 $year^{-1}$ for the poorest yield class (all values given are for volume over bark with a diameter limit of 7 cm and at moderate thinning from below). The yield table of Hamilton and Christie (1971) was set up as a joint table for ash, sycamore and birch (and consequently confounded by the mix of species). The growth pattern differs slightly from the yield table previously mentioned. The CAI peaks at 25 years for the best site class with 14.6 m^3 $year^{-1}$ (site class 10) or at 20 years with 6 m^3 $year^{-1}$ for the poorest (site class 4). The values for the MAI are 10.0 m^3 $year^{-1}$ at 45 years (best) and 4.0 m^3 $year^{-1}$ at 50 years (poorest), respectively. There is a great difference in the CVP values: the productivity amounts to 647 m^3 ha^{-1} for the best and 274 m^3 ha^{-1} for the poorest yield class (both at 80 years).

Generally speaking, the yield tables for ash shows one particular characteristic. Volume increment, either CAI or MAI, irrespective of site can reach significant values and reaches its maximum early in the life of a stand, especially when compared with European beech. The observed differences in the two tables selected above illustrate a general finding typical when comparing yield tables across Europe: there are large differences in all classical growth and yield measures, indicating not only potential differences in growth but also differences in data sampling and modelling or construction techniques.

Diameter growth and natural pruning

As for most other tree species, the diameter growth and natural pruning of ash clearly depend on silvicultural practices, but so far only few experiments have been conducted to quantify the effects. These include a study in Lithuania, where thinning clearly promoted the diameter growth of ash, especially in young stands, and the increase of diameter increment was positively correlated with thinning intensity, but declined after 2 years (Juodvalkis *et al.*, 2005).

To alleviate the lack of experimental evidence, recent research has been directed towards modelling efforts that account for specific production objectives. Production objectives for ash vary across Europe (Thies and Hein, 2000, 2009). Besides a different perception of the growth potential of ash, differences in the silvicultural traditions between countries are also apparent. Growing ash at wide spacing increases the bole volume of individual trees. Moreover, the increased mean ring width (and thus the increased latewood percentage) associated with wide spacing results in a reduction of heartwood percentage because the target diameters are reached more quickly and with an increase in wood density, elasticity and strength (Oliver-Villanueva and Becker, 1993). The main disadvantages with wide spacing are the increased shrinkage and swelling of the wood (drying anisotropy) and the slowing down of natural pruning.

Ideally, ash should be grown at faster rates by increasing the growing space per tree from youth onwards and controlling branch development through stand density or high pruning. It is generally recommended to initiate pruning on potential crop trees before the stem reaches 7–10 cm at the point of the lowest live branch. The arguments for this are not only mainly practical and independent of tree species but also relate to wood technological properties:

1 at the first pruning, the stem should have reached a size where its future potential can be reliably assessed,
2 if the end use is veneer, current technologies require a piece of wood with a diameter of ~7–10 cm for the machine to hold the log, and
3 shrinkage is often excessive at the centre of the log, and fibres have an irregular pattern, both of which are less desirable wood properties for high quality end uses.

There are differing goals for diameter growth of ash among forest owners. Therefore, flexible growth models are needed for managing diameter growth. The following aspects of production objectives are derived from simple allometric models describing the relationship between crown width, dbh and tree age or from allometric models describing the relation between clear bole length, dbh, tree height and tree age (for further literature reviews, see Lavny, 2000; Hein, 2004, 2009; Hemery *et al.*, 2005; Hein and Spiecker, 2009). These relationships can be used as a basis for controlling diameter growth and for defining production objectives (e.g. Hein, 2009; Hein and Spiecker, 2009) and can also be translated into thinning guidelines.

Different management objectives concerning dbh and mean radial increment result in differences in total production time (rotation), and in the desired number of crop trees per ha at the end of the rotation. The length of the branch free bole is also affected. Table 3 presents a variety of production aims for ash. For the calculation of production objectives, it is assumed that the crown coverage of ash is similar to sycamore which amounts on average to ~70 per cent (Hein, 2004). For instance, a harvesting diameter of 60 cm can be reached within 75 years, assuming a mean radial increment of 4 mm per year. Because of the specific crown width development of ash, 64 mature crop trees per ha (dominant layer trees) are expected at the end

Table 3: Example of production objectives based on simple allometric models (from Hein, 2004, 2009; Hein and Spiecker, 2009) for ash

Harvesting (target) diameter (cm)	Mean radial increment (mm $year^{-1}$)	Production time (rotation)(year)	Number of crop trees (N ha^{-1})	Length of the clear bole (m)
60	2	150	88	–
	3	100	71	20.3
	4	75	64	16.0
	5	60	61	12.8
50	2	125	124	–
	3	83	100	19.3
	4	63	90	15.2
	5	50	85	12.0

Site index – European ash: 33 m at age 60 years (for site index calculation, see Hein, 2004).

of the rotation. If trees should grow at a mean radial increment of 3 mm $year^{-1}$, the production time is extended by 25 years with a final crop of 71 ash trees per ha. The last column shows the expected length of the clear bole for the site indices indicated above. It should be noted that only the last column is affected by site conditions, whereas the crown width dbh tree age relation has been shown to be almost independent of site index (e.g. Hein, 2004). To obtain shares of crop trees in mixed stands, the figures for pure stands can be taken and multiplied with the desired share of the mixed species at the end of rotation (with a possible adjustment for species- or mixture-specific crown dimensions). As the production objectives in Table 3 are based on models, other objectives can be calculated according to the needs of the forest owner.

A more simple approach to calculate the number of crop trees per ha has been proposed by Hemery *et al.* (2005). Without accounting for the effect of thinning grade on crown width as done by Hein (2004), the crown diameter is related directly to dbh. This way, it is assumed that ash maintains a reasonably constant ratio of crown diameter to bole diameter even through the silviculturally critical parts of its rotation.

Branch development

Ash has a very low branch order and generally produces canopies large enough to eliminate competitors for light (Marigo *et al.*, 2000). Thinning affects branch size, branch occlusion and thus knottiness. A bole with no dead or living branches visible from the outside can have a substantial knotty core (inversely cone-shaped part of the interior trunk where knots are located). Using species-specific taper functions for ash (Dagnelie *et al.*, 1999), the width of the knotty core can be calculated and simple rules for controlling its size and location can be derived from the allometric model mentioned above.

The quality of ash trees can be improved by formative shaping (Bulfin and Radford, 1998a, 1998b). Formative shaping should begin as early as possible, ideally when trees are around 1-1.6 in height, and can have a significant positive effect on the height growth and significant negative effect on diameter growth of ash. However, other observations have demonstrated that a moderate intensity of formative shaping that removed forks and large branches may not improve the form of ash (Kerr and Morgan, 2006). Attempting to improve the quality of timber by minimizing the number of trees planted and applying formative pruning may be risky and likely to fail in forestry practice. A more secure way of obtaining quality improvement is to use traditional pruning after a period of canopy closure (Kerr and Morgan, 2006).

Severe branch pruning leads to a reduction in foliage area which directly affects photosynthesis and indirectly affects internal physiological processes (Li *et al.*, 2001). When photo-assimilates, derived from carbon dioxide fixation, are not sufficient for whole-plant growth, as e.g. in defoliated trees, they are allocated preferentially to the nearest growing point from the source. This may lead to uneven growth rates at different stem heights (Li *et al.*, 2001).

Stem and wood defects

Production objectives should also consider production risks. Unfortunately, ash trees face two major defects: forking (Ningre *et al.*, 1992) and black heart (for a review on black heart, see Kerr, 1998). Both defects reduce the potential use of ash for high value products and silvicultural practices often aim at limiting their extent. These include weeding, spacing (to favour height growth and natural pruning), proper choice of site or micro-site for ash (to avoid frost prone areas and the associated likely incidence of loss of the terminal bud) and thinning.

Late spring or early autumn frost injury, water stress, damage by deer or insect attack are all significant causes of terminal bud failure and the consequent development of stem forking (Ningre *et al.*, 1992). Other causes of forking in ash are thought to be genetic characteristics, wind or bird damage (Kerr and Boswell, 2001). Artificial and formative pruning (especially in widely spaced plantations) may increase the length of clear bole produced (Nicolescu and Simon, 2002). At a young age, the incidence of black heart is rare and thus does not drastically affect timber quality. As black heart seems to be related to tree age, a short rotation is recommended (Kerr, 1998).

Another important ash defect is canker, caused by the bacterium *Pseudomonas syringae subsp. savastanoi pv. fraxini*, or the fungus *Nectria galligena* Bres. It is generally recommended to remove cankered trees by thinning at the earliest opportunity (Butin, 1995; Kerr, 1995).

Root system

Compared with riparian trees such as poplars, willows and alders, young ash seedlings have a superficial ('surface rooter') root system (Köstler *et al.*, 1968). As an example, a maximum depth of 0.15 m after 4 months has been observed (Rust and Savill, 2000). The root system of older ash is quite uniformly regular with deeply penetrating vertical roots originating from the strongly developed horizontal roots (Köstler *et al.* 1968). In mixed stands, the deep rooting of ash may be reinforced by competition from shallow-rooted species (Rust and Savill, 2000).

The roots may penetrate >2 m in fresh, loamy soils whereas on gleyed meadow soils of heavy clay, roots do not penetrate beneath the gley horizon (Shparik and Polataycuk, 1988). Root growth continues vigorously throughout the tree's life and, consequently, old ash have a root system that is greater in volume and biomass than that of beech, hornbeam (*Carpinus betulus* L.) or maple of similar stem dimensions (Köstler *et al.* 1968; Collin and Badot, 1997).

The plate root systems are far reaching, with tough horizontal roots that send laterals vertically downwards (Rust and Savill, 2000). The fine roots are very intensive and dominate the upper 0–5 cm of the soil profile where they are concentrated in clumps with root-free zones in between, and usually end suddenly and bluntly (Rust and Savill, 2000).

The distribution of roots in recently established ash compared with more mature trees has been found to be mainly determined by competition for light (Wagner, 1990). Where there is a high proportion of ash and sufficient light, the soil is dominated by tough ash rootlets (the first-order and second-order roots). The character of ash root systems changes dramatically in the shade of tree canopies; rooting is reduced in the surface horizon (0–5 cm) compared with trees growing in the open (Wagner, 1990).

Ability to grow in mixture

In a study of ash mixed with cherry, these two rapidly growing species altered their stem form in response to interspecific competition, and both species maintained a position in the upper canopy (Kerr, 2004). In the ash-oak and ash-beech stands, a two-tier canopy formed with ash in the upper canopy, and interspecific competition resulted in an early nursing effect on the ash. The maximum relative yield totals were 178 per cent for ash–cherry, 177 percent for ash–oak, and 144 per cent for ash–beech when compared with pure ash stands (100 per cent), indicating that these mixtures may be more productive in their early phase of growth than pure stands. Competition between trees is responsible not only for the differences observed in tree dimensions and growth but also for the differences in foliage efficiency expressed as bole volume increment per unit of foliage biomass (Le Goff and Ottorini, 1996). Seedlings of beech and elm are not capable of quickly changing their growth rate and are usually less successful in competition with ash (Hofmeister *et al.*, 2004). Due to this, ash is frequently termed a gap specialist in the climax forest.

It has been suggested that ash litter has phytotoxic effects and that this may limit the regeneration of other plants (Marigo *et al.*, 2000). The dominance of ash over other broadleaves does not appear to be linked to allelopathic effects, but there are contrasting hypotheses as to whether the competitive advantage of ash relative to other species in youth is due to species-specific differences in drought tolerance (Rysavy and Roloff, 1994 *vs* Horn, 2002).

Health and robustness

Some aspects of health and robustness have already been addressed under the headings of wood quality. This section mainly focuses on the recent phenomenon of ash dieback, threats from invasive alien pest species and the issue of grazing.

Ash dieback

Since the 1990s, ash dieback has been observed on a large scale in countries around the Baltic Sea, and more recently spreading to other regions of Europe (Kowalski, 2006; Skovsgaard *et al.*, 2010). Currently, wide spread dieback of ash is observed in countries of eastern, northern and central Europe, and the reasons for it are unclear (Bakys *et al.*, 2009). The symptoms include wilting of leaves, cankers on young shoots and stem bark necroses (Kowalski, 2001; Juodvalkis and Vasiliauskas, 2002; Przybyl, 2002; Barklund, 2005, 2006; Thomsen and Skovsgaard, 2006; Thomsen *et al.*, 2007). The symptoms initially appear mainly at the tree tops and often lead to extensive top-dry or crown dieback. Subsequently, the disease may affect the lower parts of the stem, with reddish discoloration of the bark changing the visual impression of the stand. Eventually, diseased trees may die unless they are harvested to salvage the timber. Macroscopic symptoms of top dry and canker in the crown were found to be statistically associated (Kowalski and Lukomska, 2005). The fungus *Chalara fraxinea* sp. nov. has been hypothesized as the primary cause of ash dieback (Kowalski, 2006).

A recent analysis suggested that crown dieback of ash is a primary disease (Skovsgaard *et al.*, 2010). Moreover, the disease was clearly associated with symptoms of honey fungus (*Armillaria lutea* Gillet) as a secondary damaging agent, but not with symptoms of ash canker due to *N. galligena* or *Pseudomonas syringae subsp. savastanoi pv.*

fraxini, or attacks of ash bark beetles (*Hylesinus fraxini* Panzer or *H. varius* Fabricius) when considered collectively. Dieback was more frequent on trees of average or below-average size within a stand, indicating that individual tree resistance decreases with decreasing growth or tree vigour (Skovsgaard *et al.*, 2010). A direct association of plot-specific characteristics with canker in the crown indicated that the extent of canker may depend on site conditions and possibly on silvicultural practices. Based on these findings, it has been suggested that the immediate development of phytosanitary prescriptions for silviculture should primarily be targeted towards young stands as these represent the most critical phases of stand development (Skovsgaard *et al.*, 2010).

A range of fungi have been identified in ash cankers as well as on dead shoots and in the dead roots of living trees (Heydeck *et al.*, 2005; Kowalski and Lukomska, 2005; Bakys *et al.*, 2009). Ash dieback is often initially detected in nurseries and young stands, but it appears to occur equally frequently on older trees (Mikułowski, 1998; Kowalski, 2006). Studies in clonal seed orchards in Denmark (Olrik *et al.*, 2007; McKinney *et al.*, 2010) and Sweden (Stener, 2007) indicate substantial genetic variation in the resistance of ash to dieback. So far, the pathogenesis is poorly understood, and consequently only few silvicultural prescriptions (e.g, Skovsgaard *et al.*, 2009) have been developed.

Grey squirrel

Ash is relatively free from attack by grey squirrels (*Sciurus carolinensis* Gmelin.) (Savill, 1991), an alien species introduced to the UK and Italy from North America in the 19th and 20th centuries. However, sycamore is damaged by grey squirrels which strip the bark, and this can reduce the amount of valuable timber. Because ash and sycamore often grow in the same forest communities, the probable threat of grey squirrels should be considered in silviculture.

Emerald ash borer

Emerald ash borer (*Agrilus planipennis* Fairmaire) is an exotic beetle from Asia, discovered in North America in the summer of 2002. The adult beetles nibble on ash foliage but cause little damage. The larvae (the immature stage) feed on the inner bark of ash trees, disrupting the tree's ability to transport water and nutrients and have killed millions of ash trees in North America. Emerald ash borer probably arrived in the US on solid wood packing material carried in cargo ships or aeroplanes originating from its native Asia. Emerald ash borer has recently been found in Europe, with reports in Russia (Baranchikov *et al.*, 2008) and Sweden (J.P. Skovsgaard, personal communication).

Grazing

Shoots, bark, flowers and fruits of ash are utilized by animals for forage. The presence of such food resources is important for the herbivore populations. However, browsing may harm ash and even reduce population sizes and affect the reproduction success of the species (Gill, 1992; Hester *et al.*, 1996; Latham and Blackstock, 1998; Hofmeister *et al.*, 2004).

High grazing intensity directly prevents ash seedling establishment, whereas low grazing intensity allows seedlings to establish through herbaceous vegetation neglected by livestock (Marie-Pierre *et al.*, 2006). Under a high grazing intensity, ash may develop a subterranean vegetative reproduction method (Marie-Pierre *et al.*, 2006). The season of grazing has an important impact on ash. In a trial investigating grazing pressure in the UK (McEvoy and McAdam, 2008), no significant tree damage to either oak or ash was measured during February; however, significant damage to the lateral branches of both oak and ash was observed in October. Leader damage did not occur on trees >1.5 m. Ash was more commonly browsed than oak. Annual height increment of both tree species was unaffected by grazing, but annual stem diameter increment was significantly reduced in both oak and ash in February grazed plots. The analysis of deer browsing of the terminal leaders showed a considerably higher impact on oak and ash whereas beech were browsed so rarely that they indirectly benefited by the browsing of the competing species.

European beaver (*Castor fiber* L.) can cause some damage to ash trees. In the Czech Republic, their diet included 14 tree species with tree diameters ranging up to 2 m. The most preferred species was ash (40.5 per cent) with a diameter of 1–10 cm and willow (*Salix* spp.) (31.7 per cent) with a diameter of 11–20 cm (Urban *et al.*, 2008). Although ash regenerates easily, damage by browsers can locally reduce the amount of valuable timber.

Conclusions

Ash is an important tree species in Europe and a critical component of European forest communities because it commonly occurs in mixtures. It produces high quality timber for which there is a high demand. Ash grows best on fertile, pH-neutral, deep, freely drained soils and such sites should be favoured if the aim is for high quality timber. For the production of timber, it is best to avoid sites that may be waterlogged or have a pH <4.

Ash grows relatively rapidly and its height growth depends on soil characteristics. Volume growth culminates at relatively young ages and shows large variation across Europe. When ash is grown at wide spacing, it leads to enlarged ring width, and consequently increased latewood percentage, which makes the wood denser and stronger. The main disadvantages with wide spacing are the slowing down of natural pruning and increased shrinkage and swelling of the wood.

Planting of ash in Europe is most commonly as 2-year old, nursery, bare-root seedlings. Planting density shows great variation across Europe from 500 to 10,000 trees per ha. High density favours height growth in the first years; however, wider spacing results in faster diameter growth. A wide range of planting densities can be used, and the choice has to be made based upon local conditions and costs in relation to expected silvicultural practices. In mixed stands, the spacing should depend on the species mixture. It is best to avoid areas where late spring frosts can occur as this may lead to a decreased survival rate or increased forking. There is little information available on the cost effectiveness of different establishment methods employed across Europe.

The length of the clear bole depends on the spacing regime and thinning practice. An important management criterion for the production of high quality timber is to carry out pruning before the stem reaches 7–10 cm at the point of the lower live branch. Universal recommendations are for wide spacing with heavy, regular thinning in order to get a large diameter within a relatively short rotation, while simultaneously reducing the risk and frequency of black heart, the occurrence of which significantly reduces timber value. The necessity for pruning depends on the stand density at establishment and the subsequent thinning regime. At this stage, there unfortunately is no ideal, universal decision tool for control of diameter growth or natural pruning of ash.

Although much research has been carried out across Europe, there is still much unknown about the optimal and objective-oriented silviculture of ash. When comparing data from various countries, it becomes apparent that there are many differences in silvicultural practices. We need to know more about wood quality aspects, such as the targeted production of clear bole length. There is also uncertainty concerning production objectives, especially the relationship between target diameter at time of harvest, rotation length and other elements such as timber quality and production risks. A further area to explore is the capacity of trees grown quickly in their youth to maintain diameter growth rate as they mature.

In several countries of Europe, ash is dying due to a fungal disease, the pathogenesis of which is poorly understood, while at the same time in some parts of its natural range ash can become invasive. As so little is known about ash dieback and the dynamics of ash in relation to climate change, uncertainty arises as to what constitutes best practice. Clearly, there is an urgent need to understand and quantify relationships with silviculture and other factors that influence the health and growth of ash in pure as well as mixed stands throughout the continent.

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