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(*Fraxinus excelsior* L.)

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Abstract:

The natural range of European ash (*Fraxinus excelsior* L.) includes almost entire Europe except central and southern parts of the Iberian Peninsula, southeast Turkey, northern Scandinavia, Iceland and the northernmost parts of the British Isles. European ash is one of the most important tree species in Europe. Like many other valuable broadleaved species, ash should be used more widely in European forestry and in the timber industry. This article reviews essential ash characteristics relevant to the further development of silvicultural practices. The review emphasizes aspects of site requirements, regeneration and growth dynamics, and recent developments in ash dieback. In the context of silviculture the review specifically addresses (1) the identification of factors allowing rapid growth while producing high quality timber, (2) the analysis of possible trade-offs between fast growth and timber quality, and (3) the specific challenges when growing ash in mixture with other species.

Key words: silviculture, site requirements, regeneration, growth dynamics, timber quality, ash dieback

Introduction

The natural range of European ash (*Fraxinus excelsior* L.) includes almost entire Europe except central and southern parts of the Iberian Peninsula, southeast Turkey, northern Scandinavia, Iceland and the northernmost parts of the British Isles. The eastern limits of ash stretch towards the Volga River in Russia and further south to the Caspian Sea. In northern and western parts of its natural range ash occurs in lowland forests while in central and southern Europe it occurs in mountain regions up to altitudes of 1,600 m above sea level.

Like many other valuable broadleaved species, ash should be used more widely in European forestry and in the timber industry. The objective of this review is to synthesise essential ash characteristics relevant to the further development of silvicultural practices. The review includes site requirements, regeneration and stand establishment, growth dynamics, phytosanitary concerns, silvicultural experiments and critical analyses of experience from the forestry practice. Throughout, we aim to identify factors which influence one or more of these processes or issues. We do not focus on a particular silvicultural system, but emphasise specifically (1) the identification of factors allowing rapid growth while producing high final quality timber and the analysis of possible trade-offs existing between fast growth and final quality, and (2) specific challenges when growing ash in mixture with other species.

Site requirements

Ash often occurs in mixed broadleaved forest or as a groupwise admixture to forests of oak, beech or alder. Mesophytic oak and ash forests occurring on base-rich soils (pH usually between 6 and 7) derived from calcareous, marl or sedimentary parent material. Soils are often rich in clay or silt and have a rich invertebrate fauna, especially lumbricid worms (Loidi, 2004). Site conditions may have hampered the growth of ash, as well as wild cherry *(Prunus avium*) (Löf et al., 2007).

Soil and water

In eastern parts of its natural range, ash may become a dominant species in floodplain forests and on moist clay-loam lowland sites. In central parts of Europe 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 the so-called *chalk ash* adapted to dry calcareous sites (Münch and Dietrich, 1925). Subsequent research (Herre, 1928; Leibundgut, 1956; Schönborn, 1965; Knorr, 1987; Weiser, 1995) could not substantiate this theory. Consequently, the natural occurrence of ash on such a wide range of site types is due to a general, high tolerance in relation to the supply of water and nutrients. Its occurrence on sites which are marginal or less optimal (for example, gley, chalk or peat soils) is probably due to competition from other species on better sites, more or less mediated by the influence of foresters.

Ash generally grows well on soils with a pH above 5-6. Toxicity of Al-ions is supposed to prevent growth and even establishment of planted ash on soils with a pH lower than 4.0 (Zollner and Kölling, 1994). Soils which are fertile, pH-neutral, deep, moist and freely draining create optimal conditions for the growth of ash. Only optimal site types provide the fast growth rates which are needed to produce high quality ash timber. Pure ash should only be grown on the best sites. Generally, any other site is not likely to be successful for the production of fast grown, high quality ash. On infertile and dry sites ash depends highly on water supply from rainfall.

Ash belongs, like elm (*Ulmus* sp.) and sycamore (*Acer pseudoplatanus*), to the most demanding tree species of soil richness and humidity. The sensitivity of ash to mobile surface and ground water is manifested in its rapid occurrence in communities where it does not occur as a rule (Bugala, 1995). It tolerates short-term flooding, while stagnant water is unfavourable for the species because of oxygen lack.. The negative effects of flooding were stronger for *F. excelsior* than for *Q. robur* (Vreugdenhil et al., 2006). The growth of *F. excelsior* is closely correlated with physical properties of the soil on which it grows (Gordon, 1964; von Gadow, 1975; Knorr, 1987; Franc and Ruchaud, 1996; Fraxigen, 2006). Ash is intolerant to compacted soils. Two favourable characteristics of soil are the alkalinity of the substratum that increases downwards and a very well developed humus layer. Ash height growth increases in active and acid mull humus types, compared with moder mull. Good sites for ash growth are where the climate is 'warm' (>1376 day – Celsius degrees > 5.6), soil moisture is 'fresh' to 'very moist' (generally meaning that depth to the winter water table is between 40 and 100 cm) and soil nutrient status is 'rich' and 'very rich' (generally soil pH in the range of 5.0-7.5) (Kerr and Calahan, 2004).

Ash is deeply rooting in both pure and mixed stands, but more exclusively in the latter, owing to competition from shallow-rooted species. The roots penetrate over 2 m deep in fresh, loamy grey-forest soils and chernozems, whereas on gleyed meadow soils of heavy clay roots do not penetrate beneath the gley horizon. (Shparik and Polataichuk, 1988).

European ash is sensitive to drought. Decrease in ground water table causes high damages in stands (top declining). Drought tolerance in European ash is related to a reduction in osmotic potential (osmotic adjustment) but also to an increase of the elastic modulus (elastic adjustment). The first mechanism involves maintenance of turgor pressure, the second is thought to facilitate continued water uptake from drying soils (Peltier and Marigo, 1996). Water supply has a dominant influence on growth. High growth rates can be achieved on sites with >110 days of easily available water during the growing season. Growth was poor on sites with >30 days waterlogging in the upper half of the main rooting horizon at the beginning of the growing season.

Temperature

European ash is not a high temperature demanding tree species. However, it is sensitive to severe winter frosts and late spring frosts. During very severe winters ash stems can crack. Young ash is susceptible to late spring frost which may harm the foliage. Consequently, frost hollows is best avoided for planting of ash. Healthy plants will usually recover gradually with canopy closure,. On some sites the admixture of other species or the planting of ash among stump regrowth or insufficient natural regeneration of ash, alder or birch may alleviate the problem (Savill,1991; Fraxigen, 2006)

Light demand

Growth that may be exhibited by European ash, depending upon ecological conditions in which its populations are supposed to exist, is the most important biological feature of the species. European ash is a light demanding tree and does not even tolerate side shadow. In improper light conditions it quickly stops development (Jaworski, 1995). Its light demand is close to pedunculate oak (*Q. robur*) and black alder (*Alnus glutinosa*). On appropriate sites (e.g. limestone) and under moderate shade (≥3.0% relative light intensity RLI) ash has the ability to establish a seedling bank by which the species is permanently present in the regeneration stratum of a stand. However, young seedlings tolerate shaded circumstances, but become more light demanding when getting older, so regular treatments are necessary to ensure better light conditions in a stand (Wardle, 1959; Okali, 1966; van Miegroet and Lust, 1972; von Lüpke, 1989; Wagner, 1996; Franc and Ruchaud, 1996). In a dynamic classification of trees, ash, together with oak, elm, lime, hornbeam and pine, were included in a group of post-pioneers (Bugala, 1995).

Survival of seedlings is higher when they grow under semi-closed canopy (10, 18, and 28%) and also outside the forest at a 92% light intensity level, compared with those under the closed canopy (2.5%) (Bugala, 1995). Ash regeneration does not survive at relative light intensity below 2%. At RLI above 3%, regeneration of ash developed successfully. Successful establishment and development of ash regeneration typically occurred in gaps (Emborg, 1998). Ash had a lower survival rate at low light than beech and a higher growth rate at high light. Maple showed a weaker trade-off with the lowest survival rate but a growth rate inferior to ash. At low light, beech showed the lowest mortality, maple the highest and ash in between on both sites (Petritan el al., 2007).

Regeneration

Ash stands can be established by (1) natural regeneration, which can be prolific on good sites, (2) planting or (3) a combination of the two, for example by enrichment planting in between patches of natural regeneration.

Ad 1) European ash can regenerate naturally, but seedlings often die because of competition with weeds. Natural regeneration can be achieved by using group shelterwood system (in ash-oak stands), strip shelterwood system (in ash-dominated stands) and improved Swiss irregular shelterwood system (in multilayered stands with the composition of ash and oak). Götmark et al. (2005) found that seedling density is higher in hardwood forests. The natural regeneration was very poor and species diversity low, in particular where the humus layer was more acidic and the litter layer thick. No regeneration phase older than the seedling stage (height <40 cm) developed on the different humus types (Tabari and Lust, 1999). In areas of older stands (60 yr old) that have been harvested at irregular intervals, competition between maple and ash in this case appeared to favour ash (Urbinati and Cillia, 1995). The expansion of ash natural regeneration depends on soil and exposition conditions and relates to the water balance gradient. Ash reached the highest densities (up to 6,000 individuals/400 m^2) on medium-deep, heavy-textured decarbonized soils. The lowest expansion (508 individuals/400 m^2) was found on slopes fully exposed to south (S) with water retention capacity lower than 20 mm. Ash natural regeneration reached the highest average heights (around 210 cm) on *Fageto-Quercetum illimerosum mesotrophicum*, the smallest heights on *Carpineto-Aceretum saxatile*. On less favourable sites it is capable to use the protection of other tree species and as a low growing tree it can eventually dominate the site. (Střeštil and Šammonil, 2006). The development of natural regeneration is limited in principle by trophic preferences of game. It is necessary to consider the present game stock to be contradictory with objectives of area protection and preservation (Čermak and Mrkva, 2006).

The number of oak and ash seedlings was positively related to the number and proximity of parent trees. There were no consistent relationships between decreases in the sizes of the seedling populations and the type, amount and height of vegetation. The size of seedling populations generally declined with time; ash populations fell by 40-50 per cent each year (Harmer et al. 2005).

F. excelsior natural regeneration is often so prolific that the species becomes invasive (Fraxigen, 2006). Ash can regenerate vegetative but it does not play an important role in its life, oppositely to lime, alder or willow. The most popular form of vegetative regeneration is layering. Layering is especially present in very shadow forests (Polatayčuk and Šparik, 1993). Frosts are very dangerous for ash seedlings. Late spring frosts can cause forking, one of the major potential defects in ash (Savill, 1991).

Ad 2) Across the European countries the recommendations on planting density are varying: Some states of Germany recommend a planting density of 4,000 to 5,000 plants per hectare (HE-MIN, 1999), whereas British or French authors recommend considerably lower densities: 300 - 1,200 plants per hectare or 1,600 to 2,500 plants per hectare (Kerr and Evans, 1993; Duflot, 1995; Armand, 1995; Kerr, 1995).

In Poland two-year-old seedlings are usually planted; one-year-old and three-year-old seedlings are rarely planted. The spacing is from 1.3 x 1.3 to 1.6 x 1.6 m. Soil is prepared in spots. Height, stem diameter and stem volume of trees decreases with increasing spacing. These results suggest that better growth at closer spacing may be a silvicultural characteristic of ash (Kerr, 2003). The greatest percentage of survival was observed at wide spacing (2.5 x 2.5 m) and ash monoculture (98%) (Espahbodi et al., 2003).

Generally speaking ash regeneration can be very abundant during early phases of stand establishment. 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 a very low vitality of beech seedlings and saplings has been described in connection with abundant and vigorously growing ash regeneration leading to the term “Fraxinisation” (“Vereschung”) which has been discussed intensely in German literature (Leibundgut, 1954, Leibundgut, 1956; Faust, 1963; Röhrig, 1966; Freist, 1990; Wagner, 1990; Börth, 1990a; Börth, 1990b, see also Fraxigen, 2006). However, the high competitiveness of ash in mixed species regenerations seems to be part of its ecological strategy of being an intermediate species which takes advantage of disturbances in stands. Advantageous elements of an ecological strategy of ash as an intermediate species compared to beech as a late successional species are (according to Wagner, 1999):

- Fruiting in short intervals but with high density;
- Building up seedling banks;
- Ability to respond with large height increment as soon as resource availability (light!) increases by gap establishment;
- Very effective leaf positioning which avoids self shading within a single sapling but casts deep shade underneath when combined with high seedling densities.

Rysavy and Roloff (1994) found that the dominance of ash over other broadleaves was not linked to allelopathic effects, but to the high tolerance of ash against drought in its youth. However, Horn (2002) suggested that ash is not able to dominate beech regeneration in the rooting zone and drought tolerance of ash seedlings is not significantly higher than in beech seedlings.

Shoots, bark, flowers and fruits of ash are intensively utilized by animals as fodder (Bugala, 1995). The presence of these food resources in a forest may have a marked importance for the existence of herbivore populations; however the pressure from animals may modify local ash population features and affect the reproduction success of this species or even decide its occurrence in given ecological conditions (Latham and Blackstock, 1998).

Mixed use and high grazing intensity are directly preventing ash seedlings establishment, when low grazing intensity is allowing ash seedlings establishment indirectly through herbaceous vegetation neglected by livestock. Ash possesses the ability of compensatory growth and therefore under a high grazing intensity develops a subterranean vegetative reproduction (Marie-Pierre et al., 2006).

Growth dynamics

Among valuable broadleaved trees ash has always attracted special attention. Outstanding wood properties, aesthetics, myths, a high economic value or simply its rareness has often led to an increased attraction of this species. Thus the earliest publications with an emphasis on quantitative growth and yield aspects are already from the early twentieth century (for illustration see table 1 and 2). However, the degree of how precise they describe data sampling, methods for data treatment and, more important, what their objectives in the investigations were varied widely (table 1).

Height

Considering differences in height growth due to varying site conditions in different European regions, some general guidelines to describe height growth of ash are apparent. Height growth culminates depending on site conditions between 10 and 25 years (Faliński and Pawlaczyk, 1995). As a consequence ash responds quickly to thinning only at young ages. The following Polish and Slovenian experience exemplifies a typical height growth pattern. In this geographical area during the first 10 years ash grows slowly, then faster and growth lasts for a long time (till 60 years (Fraxigen, 2006). At age 11 it archives about 300 cm in height. It can reach 27-28 m in height and 30 cm in diameter by age 70-80. In Bialowieza National Park (Poland), in moist forests, ash achieves 130-200 cm in diameter and 45 m in height and volume of stands 702 m^3/ha (Faliński and Pawlaczyk, 1995). In Slovenia the fastest height growth was observed in ash trees growing on hornbeam sites; however, above age 70, the height growth was fastest on ash sites (Kadunc, 2004). With respect to beech, height growth of ash has its maximum 30–40 years earlier illustrating the contrasting differences between ash and beech with respect to their capacity to respond to thinning.

When comparing height growth from different yield tables across Europe significant differences appear (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: between 80 and 100y: 0.25m/y) even at higher ages whereas others expect ash to slow down height growth at higher ages (for instance Hamilton and Christie, 1971 between 60 and 80y: 0.06m/ y). This may indicate species-specific differences in height growth, but most probably 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”, poor graphical or mathematical smoothing techniques or real differences in site conditions.

Ash trees on mountainous limy beech (*F. sylvatica*) sites recorded the slowest height growth. On the same sites, however, the diameter growth of ash is moderate, but very persistent and does not decline with age. At the age of 80-90 years, the diameter growth of ash on limy beech sites exceeds the growth curves of ash from the other site groups. In fact, the diameter growth of ash on ash, hornbeam and beech sites of mixed or silicated bedrock continues to rise until the age of 50, and after that it starts decreasing, the decrease being slowest on ash sites. The current annual height increment most often culminates before the tree is 10 years old but the mean annual height increment reaches the peak before the age of 20 years. The current annual diameter increment culminates between the age of 6 and 67 years, mostly between the age of 11 and 30 years. The mean annual diameter growth increment (MAI) culminates over a wider period than the CAI. It reaches the peak between the age of 12 and 99 years, but very rarely before the tree is 30 years old (Kadunc, 2004).

Volume

Volume growth of ash stands is exemplified by two selected yield tables in Europe: Volquardts (1958) or Hamilton and Christie (1971). In the yield tables prepared by Volquardts (1958) the current annual volume increment (CAI) culminates at 35 yr and achieves 12.2 m^3ha^{-1} (mean annual volume increment (MAI): 8.6 m^3ha^{-1}, 50 yr) for the first yield class, and with 8.6 m^3ha^{-1} at 45 yr (MAI: 6.2 m^3ha^{-1}, 60 yr) for the second yield class. His table allows an estimate of the productivity of ash in northern Germany: the cumulative volume production (CVP) at 80 yr is 504 m^3 ha^{-1} for the best and 352 m^3 ha^{-1} for the poorest yield class (all values given for volume over bark > 7 cm at moderate thinning from below as displayed in the original publication).

The yield table of Hamilton and Christie (1971) was set up as a joint table for ash, maple and birch. The growth pattern differs slightly from the yield table previously mentioned. The CAI peaks at 25 yr for the best (10) site class (14.6 m³ ha^{-1}) or 7.6 m³ ha^{-1} (20 yr) for the poorest (4). The respective values for the MAI are 10.0 m³ ha^{-1} at 45 yr (best) and 4.0 m³ ha^{-1} at 50 yr (poorest). There is a great difference in the CVP values: the productivity amounts to 647 m³ ha^{-1} for the best and 274 m³ ha^{-1} for the poorest yield class (both at 80 yr).

Generally speaking the yield table for ash shows one particular characteristic. Volume increment, either CAI or MAI and independent from the site, can reach significant values and has its maximum early in tree life especially when compared to European beech. The observed differences in the two tables selected in the previous section exemplifies a general finding typical when comparing yield tables across Europe: there are large differences in all classical growth and yield measures, indicating potential differences in growth but also differences in data sampling and techniques of table construction.

The productivity of the ash is conditioned by the quantity of solar energy penetrating into the stand, the effectiveness of its use in trees and storeys, by the quality (class) and productivity of trees forming the stand, by its optimal number and their distribution on an area unit. The more the surface of a storey resembles the stairs, solar energy has a greater possibility of penetrating into the stand (Kairiuksis and Juodvalkis, 2005).

Diameter and branch free bole

In a recent survey experts of valuable broadleaves in Europe have been asked which silvicultural strategies for ash are currently being applied in their area (Thies and Hein, 2000; Thies and Hein, 2008). Their answer showed significantly varying production objectives across Europe. Besides a different perception of the growth potential of ash, differences in the silvicultural traditions between the countries may also be apparent.

Some additional examples drawn from literature are shown in table 3. Some authors do not clearly describe the production time (rotation) as part of their production objectives. As diameter growth is linked to crown width, some references also indicate the number of crop trees per hectare expected at the end of rotation. But only a few authors give quantitative information on wood quality aspects as for instance the targeted clear bole length. We interpret these differences also as an indicator of a significant degree of uncertainty concerning production objectives: especially concerning the relation between harvesting (target) diameter, production time (rotation) and other elements like quality aspects or risk of production objectives.

Growing ash at wide spacing increases the bole volume and does not involve a reduction in wood quality. The increased mean ring width (and thus the increased latewood percentage) associated with wide spacing results in a reduction in heartwood percentage (because the target diameters are reached more quickly) and an increase in wood density, elasticity and strength. The only disadvantage with wide spacing is the increased shrinkage and swelling of the wood (drying anisotropy) and hindering of self-pruning (Oliver-Villanueva and Becker, 1993). Ash should be grown at faster rates by increasing the growing space per tree from youth onwards (Oliver-Villanueva and Becker, 1993).

There are differing objectives for diameter growth between forest owners. Thus, adjustable growth models are needed for controlling diameter growth for a wide range of possible objectives. The following aspects of production objectives are derived from simple allometric models describing the relation between crown width, diameter at breast height and tree age, or from allometric models describing the relation between clear bole length, diameter at breast height, tree height and tree age (for further literature reviews see Hein, 2004; Hemery et al., 2005; Hein, 2008; Hein and Spiecker, 2008, for a similar study in the Ukraine see Lavny, 2000). The relation between these aspects of a production objective can be used as a basis for controlling diameter growth and for defining production aims (e.g. Hein, 2008; Hein and Spiecker, 2008). These relationships are also translated into thinning guidelines.

Different management objectives concerning diameter at breast height and mean radial increment result in differences in total production time (rotation) and in the number of crop trees per hectare at production end (rotation age). The length of the branch free bole is also affected. Table 4 presents a variety of production aims for European ash. For the calculation of production objectives it is assumed that the crown coverage of ash is similar to the oak coverage which amounts (Spiecker, 1991) on average to about 70 %. 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 hectare (and thus dominant layer trees) are expected at the end of production time (rotation). If trees should grow at a mean radial increment of 3 mm per year, the production time is extended by 25 years and 71 European ash trees per one hectare. 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-diameter at breast height-tree age relation has been shown to be almost independent form site indices (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 production time (rotation).

As the production objectives in table 4 are based on models, other objectives can be calculated according to the needs of the forest owner.

Branch development

Thinning affects branchiness, branch occlusion and thus knottiness. A bole with no dead or living branches visible from the outside can have a large knotty core. Using species-specific taper functions (Dagnelie et al., 1999) for ash the width of the knotty core can be simulated and simple rules for controlling knottiness can be derived from the allometric model mentioned above. Quality of ash trees can be improved by formative shaping (Bulfin and Radford, 1998ab). It should be commence as early as possible in the rotation, ideally when trees are 1-1.6 m in height. Formative shaping had a significant positive effect on the height growth and significant negative effect on diameter growth of ash.

A moderate intensity of formative pruning that removed forks and large branches did not improve the form ash. Attempting to produce the quality of timber required by management objectives by minimizing the number of trees planted and applying formative pruning is risky and likely to fail. A more secure way of obtaining quality improvement is to use traditional pruning after a period of canopy closure (Kerr and Morgan, 2006).

Thinning enhanced crown projection area increment of residual trees. The largest effect was observed in stands of aspen and birch (growth increase by 200%), followed by ash and oak (over 100%). Thinning also promoted diameter at breast height (dbh) increment, especially in younger stands, and the increase of dbh increment was positively correlated with the thinning intensity. Ash reacted to a lower extent. Low and moderate intensities of thinning stimulated volume production in younger stands while the opposite was observed in older stands with increasing removals. The effect on ash was intermediate. Significant increase in volume increment is achievable with thinning of only young forest stands, e.g. 10- to 20-year-old ash (Joudvalkis et al., 2005). Branch pruning, especially severe pruning, significantly improved the plumpness of stem form. Severe branch pruning leads to: (1) a reduction in foliage area which directly affects assimilation, and (2) indirect effects on internal physiological processes (Li Maihe et al., 2001)

Defects

Production objectives should also consider production risks. Unfortunately, ash trees are facing two major defects, forking (mainly due to late frosts) (Ningre et al., 1992) and blackheart (for a complete review on blackheart including all significant European literature see Kerr, 1998). These defects reduce their possible use for highly-valued wood assortments. Silvicultural methods are aimed to limit the negative effects of these defects. They include weeding, tending (thus favouring height growth and natural pruning) and thinning. At a young age the incidence of blackheart is rare and thus does not drastically affect timber quality. As black heart seems to be related to tree age, a short production time (rotation) is recommended. Late spring or early autumn frost injury, water stress, damage by deer or insect attack are all possible causes of terminal bud failure and the consequent development of stem forking (Ningre et al., 1992). Another aspect to be considered in silviculture is the difference of natural pruning from thinning. Artificial and formative pruning (especially in widely spaced plantations) may improve the amount of clear bole produced (Nicolescu and Simson, 2002).

Ability to grow in mixture

European ash can grow in pure stands, but it is a tree species typical of mixed forests. Thus tending has to account for species-specific growth pattern. Ash occurs in ash-alder swamp forests, rarely in moist forest site type. It grows in oak-lime-hornbeam communities (of alliance *Carpinion*) and fertile beech forests (of alliance *Fagion sylvaticae*) in all possible locations. The species occurs together with black alder on rich marshy soils, in moist forests with pedunculate oak, elm, black alder and sycamore. Ash also grows with white poplar, elm, lime and sycamore on marshy soils formed from clay and loess. In southern Poland it occurs with silver fir and mountain elm on brown soils, and in mountains with silver fir, sycamore and mountain elm on brown soils formed from sandstone and shale.

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). Growing ash in pure plantations on the middle and upper parts of slopes is not recommended because it grows vigorously for only 30-40 years and declines thereafter. Ash grows well as the main species in mixture with *Acer platanoides* or *A. pseudoplatanus* on lower slopes, producing a mean annual increment of 6-7 cu.mha^{-1} of stemwood at 45 years. Ash is particularly good as an associate (15-20%) of oak on lower slopes (Danilov, 1988).

In the ash-cherry stand, two rapidly growing species altered their stem form and showed a plastic response to interspecific competition, and both species maintained a position in the upper canopy. 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 1.78 for ash-cherry, 1.77 for ash-oak, and 1.44 for ash-beech, indicating that the mixtures studied may be more productive in their early phase of growth than equivalent areas of pure species (Kerr, 2004).

Ash dieback

Since 1990s, a large-scale ash dieback has been observed in countries around the Baltic Sea and recently spreading to other regions of Europe. The symptoms include wilting of leaves, cankers on young shoots and stem bark necroses (Barklund, 2005, 2006; Juodvalkis and Vasiliauskas, 2002; Przybyl, 2002; 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 discolouration of bark changing the visual impression of the stand. Eventually, diseased trees may die unless they are harvested to salvage the timber. The fungus *Chalara fraxinea* sp. nov. has been hypothesized as the primary cause of the ash dieback (Kowalski, 2006).

A recent analysis suggested that crown dieback of ash is a primary disease (Skovsgaard et al. 2008). Macroscopic symptoms of top-dry and canker in the crown was found to be statistically associated. Moreover, the disease was clearly associated with symptoms of *Armillaria lutea* as a secondary damaging agent, but not with symptoms of *Nectria galligena*, *Pseudomonas syringae* subsp. *savastanoi* pv. *fraxini*, *Hylesinus fraxini* or *H. varius* when considered collectively. Top-dry was more frequent on trees of average or below-average size, indicating that individual tree resistance decreases with decreasing growth potential or tree vigour. 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 phyto-sanitary prescriptions for silviculture should primarily be targeted towards young stands as these represent the most critical phases of stand development (Skovsgaard et al. 2008).

A range of fungi has been identified in ash cankers and on dead tops of shoots. The most frequent were: *Alternaria alternata, Chalara sp., Cytospora ambiens, Diplodia mutila, Fusarium laterithium, Gloeosporidiella turgida, Phomopsis controversa* and *Phomopsis scobina*. In sparsely found dead roots of living trees appeared mostly: *Cryptosporiopsis radicicola, Cylindrocarpon destructans* and *Phialocephala* sp. (Kowalski and Lukomska, 2005; Heydeck et al., 2006).

Often the ash dieback is initially detected in nurseries and young stands, but it appears to occur equally frequent on older trees. So far, the pathogenesis is poorly understood, and consequently silvicultural prescriptions have not been developed yet. A similar phenomenon was reported in the British Isles since 1950s (Hull, 1991; Hull and Gibbs, 1991). It still remains unclear whether this dieback was associated with *Chalara fraxinea* or due to other circumstances. It is well-known that repeated deviation of temperature and moisture from usual rates, as well as atmospheric pollution, radiation background and mechanical injury by animals, may weaken the resistance of ash (Skudiene et al., 2003). Initial hypotheses about dieback causes of ash concentrated around the issues mentioned in Table 6 (Stadler and Gebauer, 1992; Mikułowski, 1998; Szwałkiewicz, 1999; Stocki and Stocka, 1999; Stocki, 2001ab; Kowalski, 2001). In The Netherlands the soil-borne fungus *Verticillium dahliae* has been found to be involved in the dieback (Hiemstra, 1995). Any or more of these factors may influence the general health condition of individual trees and consequently influence the susceptibility of trees to attacks by *Chalara fraxinea*.

Conclusions

Ash is a general species in Europe but its abundance is restricted by its site requirements. For growing quality timber the site should not be danger by spring frost. Some diseases give uncertainty in silvicultural management of ash, especially the disease of tree dieback.

Ash trees can reach heights of 30-40 m in Europe but the growth rhythm depends on region and site quality. Within a certain site index, clear bole length of the future crop trees can be managed by the density of the stand or/combined with artificial pruning and diameter growth of the future crop trees can be controlled by thinning. This gives different opportunities to the silvicultural manager: get long clear boles by natural pruning and with late starting and weak thinning during a longer rotation or get shorter clear boles with early starting, artificial pruning and heavier thinning over a shorter rotation.

There is unfortunately no ideal decision tool for control of diameter growth and natural pruning. First, objectives concerning the target diameter depend very much on the growing conditions of the forest and preferences of the decision maker. Second, many decision tools could be established but probably none would satisfy all requirements of the forest owner, be appropriate to every type of stand structure or can be based on scientific analysis.

For European ash large radial increments do not compromise good mechanical properties. Thus, it seems to be appropriate to grow valuable timber in a short production time (rotation) with large tree rings. However, additional work needs to be done to explore the capacity of old trees grown quickly in their youth to maintain the diameter growth level at older ages and larger diameters. Besides production objectives, it should be noted that only sites appropriate for the ecological characteristics of ash should be selected for producing high valuable timber.

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Table 1 Publications on yield tables and other quantified decision tools on European ash in Europe (in chronological order). Note: (Volquardts 1958) was used for the Dutch collection of yield tables (ash) (Jansen et al. 1996). Sopp (1974) was used for the collection of yield tables (ash) of the Austrian Forest Service (Sterba 1976).

Authors	Growth Description	Description of objectives available	Material used
Wimmenauer 1919b	2 site index classes, classical yield table	no objective available in publication, as just description of growth and yield, typically for yield tables with thinning regimes from below or from above	Germany, 25 long term experimental plots
Oppermann & Bornebusch 1929	1 site class, mathematically formulated growth model and classical yield table		Denmark, 8 long-term experimental plots
Zimmerle 1942	2 site index classes, classical yield table		Germany, 12 long term experimental plots
Carbonnier 1947	2 site index classes, classical yield table		Sweden, 15 long term experimental plots
Møller & Nielsen 1959	4 site index classes, classical yield table		Denmark: 23 long term experimental plots and 142 temporary plots, Sweden: 4 plots see Carbonnier (1947)
Volquardts 1958	2 site index classes, classical yield table		Germany 49 long term experimental plots, 35 + 169 temporary plots
Hamilton & Christie 1971	5 site index classes, classical yield table		Great Britain ash, sycamore and birch
Sopp 1974	6 site index classes, classical yield table		Hungary
Thill 1975	general guidelines on how to control growth, it is the first to mention a target diameter for individual trees	objective on target circumference: $u_{1,3}$ = 220 cm	Belgium
Kovàcs 1986	6 site index classes, classical yield table	no objective available, see first row.	Hungary, 84 long term experimental plots
Scohy 1990b	he is the first to describe both an objective diameter for individual trees and a clear bole length	objective on target diameter: $u_{1,3}$ = 200 cm objective on clear bole length: 7 – 8 m, including formative pruning and pruning	Belgium
Pilard-Landeau & Le Goff 1996	2 site index classes	objective on target diameter: $d_{1,3}$ = 40-60 cm, or $d_{1,3}$ = 60-70 cm clear bole length 6 – 8 m	France
Hein 2004, Hein & Spiecker 2008	no yield table, but a detailed description of target diameter, clear bole length and their interdependence, several decision tools of different types	growth models designed for flexible objectives on target diameter and target clear bole length, including artificial pruning and knottiness	1501 ash trees measured on temporary plots from 13 different European countries plus open-grown trees.

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

Authors	Definition of height	Methods	Material
Wimmenauer 1918 Wimmenauer 1919a Wimmenauer 1919b	mean height	measurement of tree height graphical smoothing	Germany
Oppermann & Bornebusch 1929	mean height after thinning	measurement of tree height mathematical smoothing	Denmark
Zimmerle 1942	mean height	graphical smoothing	Germany
Carbonnier 1947	dominant height	combination of mathematical and graphical smoothing	Sweden
Volquardts 1958			Germany
Møller & Nielsen 1959	mean height of the quadratic mean diameter between two thinning	graphical smoothing	Denmark and Sweden,
Brüel 1969	mean height	graphical smoothing	Denmark
Hamilton & Christie 1971	h_{100}, i.e. top (dominant) height		Great Britain
Sopp 1974	dominant height		Hungary
Sterba 1976	h_{100}, i.e. top (dominant) height	based on Sopp (1974)	Hungary
Devauchelle & Levy 1977	mean height	stem analysis mathematical smoothing	France
Le Goff 1982	mean height of dominant trees	stem analysis mathematical smoothing according to Bailey & Clutter (1974)	France
Anonymus 1984 (in fact Tema 14.2/1978!)	mean height		Romania
Kovàcs 1986	dominant height	mathematical smoothing	Hungary
Knorr 1987	mean height	mathematical smoothing	Germany
ÚHÚL - BRANDÝS N.L.VÚHLM - ZBRASLAV STRNADY 1990	mean height of the main stand		Czech Republic
Thibaut et al. 1992	dominant height	measurement of tree height, stem analysis, mathematical smoothing according to Johnson (1935)/ Schumacher (1939)	Belgium
Jansen et al. 1996	dominant height	based on Volquardts (1958), Richards (1959) and Chapman (1961)	Germany
Hein 2004	dominant height	stem analysis, mathematical smoothing according to Sloboda (1971)	13 European countries

Table 3 Examples of different production objectives for European ash in Europe.

	harvesting (target) diameter [cm]	production time (rotation) [yr]	number of crop trees/ ha [-]	length of branch free bole [m]
Pilard-Landeau & Le Goff (1996) (France)	60 – 70	60	60	8 (h_0 = 30 m)
Kerr & Evans (1993) (Great Britain)	40 – 60	60 – 70	140 – 170	-
BW-MIN (1997) (Germany)	50	-	110	25 % of the final height

Table 4 Example of production objectives based on simple allometric models (from Hein 2004; Hein 2007b; Hein and Spiecker 2007) for ash. Site index: European ash: 33 m at age 60 yr (for site index calculation see Hein 2004).

harvesting (target) diameter [cm]	mean radial increment [mmyr^{-1}]	production time (rotation) [yr]	Number of crop trees/ha [-]	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

Table 5 Time [yr] and diameter at breast height (DBH) [cm], when a clear bole length of 25 % of the the final tree height (at the target diameter of 60 cm) is reached (SI = site index at base age of 60 yr, see Hein 2004).

Ø $ir_{1,3}$	SI = 33 m		SI = 30 m		SI = 27 m		SI = 24 m		SI = 21 m	
	time/ DBH [yr]/ [cm]		time/ DBH [yr]/ [cm]		time/ DBH [yr]/ [cm]		time/ DBH [yr]/ [cm]		time/ DBH [yr]/ [cm]	
2	-	-	-	-	-	-	-	-	-	-
3	28	16,8	33	19.8	39	23.4	47	28.2	57	34.2
4	28	22.4	33	26.4	40	32.0	50	40.0	66	52.8
5	28	28.0	34	34.0	44	44.0	63	63.0	-	-

Table 6 The causes of ash decline

- Unfavourable climatic conditions and weather anomalies in recent years
- Late frosts
- Lowering of the ground water level
- Droughts and excess of waters
- Improper soil pH
- Activity of *Armillaria* sp.
- Excessive concentrations of nitrogen compounds in the atmosphere
- Bacterial and fungal diseases
- Attacks of folivorous and secondary insects
- Damage caused by game.