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September 2008

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Citation

Hein S, Collet C, Ammer C, Le Goff N, Skovsgaard JP, Savill P (2008) *A review of growth and stand dynamics of Acer pseudoplatanus L. in Europe: implications for silviculture.* 52 pp.
http://www.valbro.uni-freiburg.de/

A review of growth and stand dynamics of *Acer pseudoplatanus* L. in Europe: implications for silviculture

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Abstract

Sycamore (*Acer pseudoplatanus* L.) is a widespread but minor species throughout Europe but there is a growing interest in using it more widely because of its potentially high economic and ecological values. Silvicultural recommendations for exploiting the potential of the species to the full should aim at producing high quality timber on short rotations. This can be achieved in a number of ways including the creation of mixed-species and structurally diverse stands that will simultaneously increase ecological values. This review synthesises existing knowledge on growth and development of sycamore that may be used as a basis for developing silvicultural recommendations. Sycamore regenerates easily, although competing ground vegetation, damage by browsers and bark stripping by grey squirrels may endanger production of valuable timber. Existing yield models show that sycamore grows rapidly for the first 20-25 years and then slows considerably. Because of its relative scarcity, there has been limited interest in the species for growth model development and this has restricted its inclusion in forest growth simulators. This review shows that there is currently a lack of detailed knowledge about the responses of sycamore to various environmental, ecological and silvicultural factors and this hinders the understanding and management of this valuable broadleaved tree.

Introduction

Sycamore (*Acer pseudoplatanus* L.), the most common European maple, is a valuable species in many European forests (Spiecker *et al.*, 2008). Interest in sycamore arises from both its economic and ecological characteristics. It produces potentially valuable timber with a very hard, fine, even-textured grain and brightly coloured wood (Moltesen, 1958; Grosser, 1998). It is used widely in the manufacture of furniture, marquetry, veneer, and plywood and, in some countries, for sawn timber, pulp and fuel (Aaron and Richards, 1990; Nunez-Regueira *et al.*, 1997; DGFH, 1998). The desirable qualities and numerous uses of sycamore wood are reasons for the high market prices that can be achieved (e.g. Thill and Mathy, 1980; Whiteman *et al.*, 1991; Soulères, 1997). Sycamore is also one of the fastest growing broadleaved species when grown on suitable sites. Its rapid growth and potentially high timber prices make it economically attractive.

In ecological terms, sycamore supports a wide range of epiphytes, herbivores and ground flora (Bingelli, 1993). Its litter improves humus formation and nutrient cycling (Wittich, 1961; Weber *et al.*, 1993; Heitz and Rehfuess, 1999). Maintaining or promoting sycamore may therefore enhance the ecological values of a stand and contribute to habitat and landscape diversity (Stern, 1989; Pommerening, 1997; Bell, 2008). Sycamore is also often regarded as a species that is well adapted to current and also to predicted future climatic conditions in Central Europe (Kölling and Zimmermann, 2007, Kölling, 2007). For instance in the case of Germany it is expected to adapt to elevated temperatures and reduced precipitation. The area suited to sycamore growth is projected to reduce by only 4% as a result of climate change. Thus, its vulnerability to climate change, at least in Germany, should be minor (Kölling and Zimmermann, 2007).

Sycamore is either native to, or has been introduced to most biogeographic zones within Europe, with the exception of the Mediterranean, Boreal and Alpine. It is found at high elevations in southern and central Europe, but much lower in more northerly and more maritime regions (Röhrig and Ulrich 1991). The species has become naturalized far beyond its native range. Its current distribution extends from Turkey and Spain to Ireland and Sweden (Fremstad and Elven, 1996; Rusanen and Myking, 2003) and even to North America, South America, New Zealand, and India (Binggeli, 1992). However, despite its economic and ecological advantages and its adaptability to a wide range of site conditions, sycamore only occupies a small proportion of the forest area of Europe. In most European countries, national inventories indicate that it rarely exceeds 3% of the forest area (Hein, 2008a). Like many other valuable broadleaves, sycamore could be used more widely in European forestry and in the timber industry (Spiecker *et al.*, 2008).

Throughout Europe, many recommendations on how to grow sycamore exist (e.g. Thill, 1970; Kerr and Evans, 1993; Allegrini *et al.*, 1998; Joyce *et al.*, 1998; Tillisch, 2001). They are usually based partly on expert opinion and partly on professional experience. Though the recommendations normally produce reliable results in local silviculture, they are often based on assertions and hypotheses that have not been objectively tested and their successful extension to wider geographical areas is questionable.

Important shifts in management objectives have occurred in response to an increasing interest in ecosystem services and reductions in the net incomes from forestry (e.g. Puettmann and Ammer, 2007; Spiecker *et al.*, 2004). These factors require the development of new silvicultural methods. For valuable broadleaved species such as sycamore, these methods should aim at producing high quality timber within a short period, which should ensure high final return, and simultaneously create mixed-species and structurally complex stands, which should increase the ecological services of the forest (Spiecker *et al.*, 2008). However, the extent to which current silvicultural recommendations can be used to guide silviculture in this new context is unclear.

In order to develop silvicultural recommendations for growing sycamore in different geographical or silvicultural contexts, it is necessary to know (1) key features about the growth and development of the species that are relevant to silvicultural practice, including regeneration, survival, growth and wood quality, (2) the effects of factors that influence growth and development, including site, climate, and stand characteristics, and (3) the silvicultural methods to apply in order, where possible, to control these factors.

The objective of this review is to synthesise existing knowledge about different aspects of sycamore growth and development, in order to provide a basis for determining local, regional or national silvicultural guidelines for the species. The establishment and growth patterns of sycamore are described and the various factors that control their variability are identified. Though the focus is not on a particular silvicultural system, special emphasis is given to (1) the identification of factors that result in rapid growth while producing high quality timber and the analysis of possible trade-offs between fast growth and final wood quality and (2) specific problems that occur when growing sycamore in mixture with other species. The content of the paper therefore moves from consideration of the biological characteristics of sycamore towards conclusions for forest management.

Regeneration and early growth

In most of Europe, natural regeneration of sycamore is common when potential seed trees are available. Natural regeneration is used in a wide range of silvicultural systems, from regular systems where the seedlings grow rapidly in full light on cleared sites to irregular ones where the seedlings may be maintained for long periods under canopies.

Seed production and dispersal

Sycamore normally starts bearing fertile seed between about ages 25 and 30 (Burschel and Huss, 1997) but the largest quantities are usually produced between the ages of 40 and 60 (El Kateb, 1992). The tree produces seeds annually but there are commonly two or three years between good seed crops. The regular and prolific seed production and the high germination rate of the seeds (Jones, 1945; El Kateb, 1992) ensure successful regeneration in most forest areas (Ammer, 1996a). As with many other European forest trees, sycamore has a short-lived seed bank and the regeneration process is consequently driven by seed rain (Deiller *et al.*, 2003; Hérault *et al.*, 2004). Sycamore seeds are wind-dispersed and follow the usual log-normal pattern of seed distribution of wind-dispersed tree species (Wagner, 1997). Seeds are dispersed further than those of the oaks (*Quercus robur* L and *Q. petraea* (Mattuschka) Liebl.), beech (*Fagus sylvatica* L.) or lime (*Tilia* spp.), but not as far as ash (*Fraxinus excelsior* L.) or the birches (*Betula* spp.) (Johnson, 1998; Degen, 2006). Its dispersal capabilities allow sycamore to colonize adjacent stands by regularly providing a small number of new seedlings, which may establish themselves successfully if conditions are suitable. Natural regeneration may be efficiently used for converting conifer plantations into broadleaved stands, provided there are some stands with mature sycamore trees near the conifer plantation (Diaci, 2002; Hérault *et al.*, 2004). In Denmark, for instance, the invasiveness of sycamore has been widely used since the late 1960s for reliable, fast, and inexpensive establishment of a new generation of trees following windthrow of conifers (Jensen, 1983a, b; Tillisch, 2001)

Though very little seed is dispersed more than 50 m from parent trees (Degen, 2006) it is usually enough to colonize neighbouring stands with dense canopies and low understorey competition. It will not, however, be sufficient to colonize large canopy gaps where a well developed ground flora exists, such as a grass sward, and where competition is intense. In large canopy gaps (>30 m diameter), if sycamore seedlings are not present before canopy opening, the seeds are less likely to stock the centre of the gap fully and regeneration will therefore be found closer to the gap edges (Mosandl, 1984; Ammer 1996a).

Response to canopy density

In full light and on suitable sites, sycamore seedlings will grow rapidly and out-compete species such as beech and the oaks (*Quercus robur* and *Q. petraea*). When light availability is reduced to below 25% of full intensity (PAR), seedling diameter and height growth are strongly reduced (Dreyer *et al.*, 2005; Delagrange *et al.*, 2006). However, small sycamore seedlings (<50 cm tall) can survive for long periods (>15 years) under dense canopies where the light intensity is as low as 1% of full light (Hättenschwiler and Körner, 2000). In a 17-year-long experiment, Ammer (1996a) demonstrated that sycamore has a high survival rate even in low light conditions of around 5% of full light. At these, annual height increment is very small (typically around 1-2 cm per year for 0.2 to 1.0 m tall seedlings) (Gardère, 1995; Ammer, 1996a). The regular seed production by mature trees combined with the good shade tolerance of small seedlings leads to the formation of an abundant and persistent seedling bank under the closed canopy. Small suppressed sycamore seedlings are able to recover vigorous height and diameter growth immediately after canopy opening (Caquet *et al.*, 2005). On fertile soils, advance regeneration of 0.2 to 1-m-high seedlings competes strongly with newly germinating seedlings and its rapid development may preclude the establishment of other tree species (Wohlgemuth *et al.*, 2002; Collet *et al.*, 2008).

In the early stages of development, sycamore exhibits several life and physiological traits that usually characterize shade tolerant species: high survival and slow growth at low light intensities, a low photosynthetic rate at maximum irradiance, and low light compensation point (Hättenschwiler and Körner, 2000; Kazda *et al.*, 1998, 2000, 2004). As is normal with most species (Messier et al. 1999), light requirements increase as seedlings develop: 2-3 m tall seedlings are less shade tolerant than smaller ones established on the same site (Collet, 2008 unpublished results) and adult trees clearly exhibit leaf gas exchange characteristics typical of moderately shade tolerant species (Hölscher, 2004). Sycamore seedlings are able to germinate and establish under deep shade but, as with most species, canopy opening is required if they are to advance to the canopy layer (Helliwell and Harrison, 1979). Although the general pattern of change in shade tolerance with increasing size is well established, more investigation is needed to analyze these changes and quantify the light levels required to allow active growth at the different developmental stages.

Sycamore seedlings that grow under closed canopies develop a characteristic morphology: the apical meristem of the leading shoot has a high probability of dying each year, which leads to the formation of a stem with multiple forks (Gardère, 1995). In addition, the stem has a low mechanical strength and, in large seedlings (>1 m tall), it is often not rigid enough to prevent bending under its own weight. Large sycamore seedlings that have developed under deep shade are often not able to take advantage of canopy openings because they cannot recover the mechanical stability necessary to start rapid height growth (Grisard, 2008). The size threshold above which the seedlings have stability problems is variable and depends largely on local environmental conditions.

To summarize, under closed canopies sycamore produces an abundant seedling bank. Small seedlings respond to canopy openings and may easily be used for natural regeneration.

However large seedlings that have grown and developed in closed stands may not be as responsive to canopy opening.

Responses to competition from ground vegetation

A second major factor that may affect the establishment, survival, and growth of sycamore seedlings is competition from ground vegetation. Sycamore seedlings are very sensitive to competitive herbs (Ammer 1996a; Diaci, 2002; Modrý *et al.*, 2004; Vandenberghe *et al.*, 2007). In natural regeneration, a canopy opening often induces development of luxuriant vegetation that rapidly forms a dense layer and competes with young tree seedlings. After canopy opening there is a short period, usually of no more than one or two years, during which the vegetation has only a small detrimental effect on seedling establishment (Diaci, 2002; Wohlgemuth *et al.*, 2002). After this, it hinders the growth and survival of sycamore seedlings seriously. Based on a survey of 2,791 sycamore seedlings, Ammer and Weber (1999) found that the main factors that influence height growth on relatively poor calcareous soils in the Alps are (in this order) initial seedling height, light availability above the seedlings (determined by the overstorey density) and interactions (between light and intraspecific competition and between light and competition by the ground vegetation). These factors explained 41% of the variation in the data. They emphasised the importance of competing ground vegetation in impeding the early growth of sycamore. The silviculturist's skill lies in ensuring reasonable growth of young sycamore trees by appropriate manipulation of the light so that tree growth is adequate but weed growth is minimised.

Responses to late frosts

Sycamore is relatively tolerant to late spring frosts in terms of establishment, survival, and growth. This frost resistance also explains the success of the species after the formation of large canopy gaps (Piovesan *et al.*, 2005). Frost tolerance and the species' capacity for vigorous growth in early development are reasons for forest managers' preference of sycamore in regions where stand establishment may be slow or made difficult by harsh climatic conditions (e.g. Skovsgaard and Jørgensen, 2004).

Responses to coppicing

Sycamore coppices quickly after cutting, which partly explains its presence in forest stands after clear felling. The rapid coppice regrowth on clearfelled sites has often been exploited to restock stands and archive good quality sprouts (Bryndum and Henriksen, 1988; Henriksen and Bryndum, 1989; Tillisch, 2001).

Responses to damage by mammals

Sycamore seedlings are highly palatable to deer (roe [*Capreolus capreolus* L.], red [*Cervus elaphus* L.*]*, sika [*Cervus nippon* Temminck], and fallow [*Dama dama* L.]) which feed on the leaves, buds, and young shoots (Gill, 1992). Seedlings <3-years old can be severely browsed and show low survival rates after damage (Eiberle and Nigg, 1987) or much reduced height growth in subsequent unbrowsed years (Kupferschmid and Bugmann, 2008). Older seedlings are more resilient to repeated browsing. Though it rarely leads to death, it can induce the formation of multiple forked stems (Ammer, 1996 b; Harmer, 2001; Modrý *et al.*, 2004) and keep seedlings at browsing height or below for many years. This prevents them from growing into the understorey (Ammer, 1996 b). In all situations where the initial number of seedlings is low (as in conifer plantations undergoing conversion, Diaci, 2002) or where the number of seedlings is high but the browsing pressure strong (Burschel *et al.*, 1985; Mosandl and El Kateb, 1988; Ammer, 1996b), control of damage by animals is required to ensure sufficient stocking and growth.

In mixed stands, differences in both palatability and in resilience between species strongly affect the species composition of the regeneration. Only sparse data exist that compare the palatability and resilience of sycamore and its associated tree species. The sensitivity of sycamore to browsing is comparable to that of ash (Kupferschmid and Bugmann, 2008) and much higher than that of beech (Modrý et al, 2004), and in many stands where the three species grow in mixture, a high browsing pressure on sycamore leads to the dominance of beech in regeneration. In contrast, when browsing is controlled, sycamore and ash may dominate beech (Modrý et al, 2004). In mixed mountain forests where sycamore grows in mixture with silver fir, sycamore seedlings are less damaged by browsing than silver fir seedlings. Therefore sycamore dominates silver fir seedlings for many years (Ammer, 1996b). Thus, even on sites where sycamore has a strong competitive advantage over other species, it may be overtopped by a less palatable species if the browsing pressure is high.

Damage due to bark stripping

Bark stripping of sycamore by the American grey squirrel (*Sciurus carolinensis* Gmelin) has repeatedly been reported from Great Britain and Ireland (O'Teangana *et al.*, 2000; Lawton, 2003; Mayle *et al.*, 2004; Mountford, 2006) and more recently from northern Italy (Bertolino and Genovesi, 2002; Signorile and Evans, 2007). According to an assessment by Rayden and Savill (2004) sycamore and beech are the most susceptible broadleaves. Stems below 30 cm DBH are the most vulnerable to debarking by the grey squirrel, and the fastest growing individuals seem to be the most affected (Harris, 2005). When the lower parts of a trunk are affected, debarking leads to staining of the wood close to exposed parts. Bark stripping within the crown also leads to a reduction of annual increment by up to 4 $m^3ha^{-1}year^{-1}$ and to severe crown dieback (Mayle *et al.*, 2004). The long-term prospects for growing sycamore for high quality wood production are much reduced (Rayden and Savill, 2004). No silvicultural measures have been found to decrease the risk of bark stripping of sycamore apart from sustained shooting, trapping or poisoning the squirrels.

Interactions between environmental effects

Browsing, shading, late frost, and competition from ground vegetation may interact in many ways and, when combined, the effects on survival and growth of sycamore seedlings can be extremely variable, depending on local environment (e.g. Skovsgaard and Jørgensen, 2004). For example, Diaci (2002) observed that roe deer may feed on herbaceous vegetation, which strongly reduces the competitive effect of that vegetation on the establishment and survival of sycamore seedlings. The authors concluded that in fenced exclosures where deer browsing is not possible, seedling densities can be significantly lower than outside the fence. In an experiment performed in an agro-sylvo-pastoral system, Vandenberghe *et al.* (2007) showed that taller vegetation surrounding sycamore seedlings may also provide protection from browsing. In other studies, it has been demonstrated that browsing has an overwhelmingly negative effect on sycamore seedling establishment, compared to competition from ground vegetation (Ammer, 1996b; Harmer, 2001), and that the effects of the two may be additive (Modrý *et al.*, 2004). It is therefore difficult to indicate the relative importance of browsing, competition by vegetation, late frosts, and their possible interactions on sycamore seedlings and associated species. Additional studies are needed to understand the interactions among these different factors and to quantify their combined effects on the development of regeneration. The results could then be used to formulate silvicultural means of controlling them.

Growth at later stages of stand development

Height growth

Few investigations into height growth of sycamore have been reported in the literature compared to the more common European broadleaves like *oak* and beech (Table 1). The early quantitative research approaches date back only to the 1950s. Lessel (1950) graphically constructed the first height growth curve using 77 trees from a limited geographical area in Germany (cf. table 1). Kjølby (1958) in Denmark was the first to create polymorphic height growth curves followed by Hamilton and Christie (1971) in Great Britain and more recently by Lockow (2004) in Germany. Kjølby's model was based on a large number of temporary and permanent growth and yield plots, but lacked a clear definition of stand mean height. Similarly for Romanian forests, only sparse information was given on how the height growth curves were constructed (Anon., 1984).

The height growth curves for sycamore all share one common characteristic (Figure 1 A-D): rapid height growth at early ages (<20 – 25 years) which then slows. On sites where growth is best, sycamore reaches up to 19.5 m by age 20 (Claessens *et al.* 1999); on the poorest sites the lowest height is 6.5 m (Anon., 1984). Compared to beech (Figure 2A), sycamores are taller between ages of about 20 – 40 and similar to ash (Figure 2B). This height advantage when young enables sycamore to survive and even to grow well in mixture with other species. However, stand heights at greater ages are variable (Figure 1A).

Many studies show that genetic origin influences height growth of sycamore. Cundall *et al.* (1998), for example, found significant differences in early height growth between British and continental European provenances. However, at 6, 10, 15, 21 and 31 years after the start of a German experiment with eight provenances from the states of Saxony-Anhalt and Thuringia, no significant differences in height growth were found (Weiser 1971, 1981, 1996). Recently, the European Forest Genetic Resources Programme (EUFORGEN, Eriksson, 2001) established a European database on provenances, which will offer further opportunities for research on this topic (Turok *et al.*, 1996).

Even though some common characteristics are clear from these height growth models, there is still some variability that cannot be explained. Possible reasons for it are changes in growth due to changing site conditions or changing silvicultural prescriptions. In addition unbalanced datasets (e.g. no observations for old sycamore trees on the best sites), biased sampling techniques, and inefficient smoothing techniques can cause biased predictions when setting up height growth equations. These sources of variability are potential causes of uncertainty for the silviculture of sycamore as real height growth may diverge from the model output.

Diameter growth

Estimates of diameter growth at breast height (DBH) are traditionally obtained from yield tables. However these estimates simply mirror growth in "average" conditions (e.g. moderate thinning) that are often not quantified and do not necessarily reflect modern thinning regimes. Furthermore they do not give production objectives nor do they offer paths towards specific goals. Nagel (1985) set up a polymorphic model modifying a potential maximum stem diameter growth for open-grown trees by a competition index. Following his findings, diameter increment of sycamore reaches its highest values at a tree age of less than 10 years when growing without competition. These results are in agreement with investigations on height growth: sycamore reaches high values of both height and diameter increment at an early age. It then slows with increasing age (<20 – 25 years). As with height, it thus exhibits a growth pattern different from beech and oak, but similar to ash. Case studies from Thuringia, Germany, and the Lorraine region of France on growth of ash, sycamore, and beech on the same sites underlines these findings derived from separate height and diameter growth models (Erteld, 1959; Le Goff *et al.*, 1985).

Crown diameter – stem diameter relationships

To describe diameter growth, authors often refer to the allometric relationship between crown width and DBH (for broadleaves e.g. Savill, 1991). For instance Hemery *et al.* (2005) used this relationship to define desirable spacings or stocking rates for ash, cherry*,* and sycamore. This relationship can help explain differences between species with regard to diameter development.

Recently Hein and Spiecker (2008a) proposed a more general description of this allometric relationship for sycamore, similar to one previously proposed for oaks by Spiecker (1991) and ash by Hein (2004). The inclusion of age as an independent variable in the relationship between crown width and DBH can explain the observed differences in crown width between fast and slow growing trees. Trees growing rapidly in diameter (i.e. those with a high mean radial increment) reach a given DBH earlier than those that grow more slowly. When slower growing trees reach this DBH, their crown is significantly larger than faster growing trees of the same DBH. This agrees with the results of investigations by Hasenauer (1997), Condés and Sterba (2005), and Hein and Spiecker (2008b) on open grown trees: trees grown without competition have larger crown diameters for any DBH than those in densely stocked stands.

However, the relationship for sycamore differs from those for ash, oak and cherry (Hein and Spiecker, 2008a). At the same DBH and tree age, dominant sycamores have the smallest crown diameters. Apparently the crowns of dominant trees are more efficient in the use of space. Thus when considering the upper canopy, a slightly more trees can be grown per hectare, a finding relevant for crop tree selection and thinning intensity.

Size-density relationships have been a topic of intense forest research for many decades (Reinecke, 1933; Yoda *et al.*, 1963; Pretzsch, 2005). However, so far no relationships have been established for sycamore. Provisional results have been obtained in France, comparing self-thinning curves for sycamore, beech, ash, sessile and pedunculate oak (Le Goff, 2007, unpublished results): data for sycamore are scarce, but the size-density relationship seems to have a slightly steeper slope than the relationships established for beech (Le Goff and Ottorini, 1999) and ash but similar to that for oak. Thus, a pure even-aged stand of sycamore would have a smaller maximum number of live trees per unit area for a given mean diameter than pure beech or ash, but the same number as oak. These findings contradict the results studies on the crown width, DBH and tree age relationship mentioned previously. Possible explanations are that the self-thinning curves are based upon mean diameter of all trees in the stand whereas the crown width measurements focus merely on dominant trees from the upper canopy. Furthermore tree age also has an influence on tree diameter development and could thus modify the self-thinning lines. Finally the results of the size-density relationship studies are preliminary. To describe the sycamore self-thinning line more accurately data from unthinned permanent plots would be necessary. An approach towards unifying both findings is yet to be found.

Volume growth and productivity

Volume growth is a function of changes in tree diameter, height, and the number of trees per hectare. A general indication of it is given in yield tables such as those of Kjølby (1958) which display the range of volume productivity found for sycamore (see Fig. 1). The current annual volume increment (CAI) culminates at 19.5 $m^3\ ha^{-1}$ at age 21. The mean annual volume increment (MAI) culminates at 15 $m^3\ ha^{-1}$ at age 27 for the best yield class. Kjølby's (1958) MAI-graph allows estimates to be made of the productivity of sycamore in Denmark: the cumulative volume production at 80 years is 1050 $m^3\ ha^{-1}$ for the best and 700 $m^3\ ha^{-1}$ for the poorest yield class (all values given for volume over bark >5 cm in diameter and halfway between thinnings).

As with all species, stand volume productivity is affected by thinning intensity and thinning grade. Unfortunately few results are available for sycamore. In Danish experimental plots thinned between ages 17 and 44 (Jensen, 1983a,b; Bryndum and Henriksen, 1988; Henriksen and Bryndum, 1989; Jørgensen, 1992, 1998; Plauborg *et al.*, 2001; Plauborg, 2004), heavy thinning beyond a relative basal area of approximately 60% has been shown to reduce stand volume growth by more than 10%, while extremely heavy thinning to a basal area of 31% reduced stand volume growth by as much as 50-60% compared to the unthinned controls. Diameter growth of large, potential crop trees responded only marginally or not at all to these thinnings. This latter finding is in contrast to a statement by Stern (1989) to the effect that sycamore has the ability to respond positively to delayed thinnings compared to species such as cherry or even ash. The possible inaccuracy of Stern's assertion is supported by the fact that sycamore shows an early culmination of both height and diameter increment, which are good indicators of the crown's ability to respond to thinnings.

Comparing the volume production of sycamore and beech over time, two main characteristics are apparent: firstly, the cumulative volume production of sycamore (at about 1050 m^3 ha^{-1}) is considerably higher than that of beech which reaches only 546 m^3 ha^{-1} at age 80 in the best yield class (Schober, 1995). Henriksen and Bryndum (1989) stated for Danish thinning trials with sycamore and beech on similar sites that sycamore has a higher or equivalent cumulative volume production to beech only up to age 40. CAI and MAI culminate earlier than in beech. Interestingly, even if height growth of ash and sycamore were similar, the cumulative volume production of ash would be considerably lower (555 m^3 ha^{-1} at age 80 for the best yield class, Volquardts, 1958). A comparison by Lockow (2004) of the effects of dominant stand heights on cumulative volume production of sycamore, ash and beech in northern Germany revealed another pattern for the best site class of each species: at a dominant height of 30 m the volume of sycamore exceeds that of ash by 180 m^3 ha^{-1} with respect to its cumulative volume production, whereas beech exceeds sycamore only at heights greater than 30 m having been the same earlier in the rotation.

Thus, although volume increment (CAI and MAI) can reach high values, it culminates early and it is influenced by thinning intensity. Its growth response to thinnings is most rapid in youth but then slows down considerably. Trade-offs between losses of volume growth per unit area and height and diameter increment of crop trees also have to be considered when deciding on whether to thin heavily or lightly. In addition, compared to ash, the productivity of sycamore is sufficiently high to consider it an alternative species on appropriate sites.

Yield tables

Most of the early information on height, diameter, and volume growth of sycamore (see previous section) has been structured in yield tables. There are some interesting facts about European yield tables, only a few of which are available for sycamore (Table 1). The first to be developed was that of Kjølby (1958) who graphically displayed all classical dendrometrical measures, including selected tree dimensions and stand attributes both before thinning, and of the trees removed, and the thinning yield. Although it was the first yield table and constructed from trees in a limited geographical area, it reflects the same growth pattern outlined in previous sections: all measures of increment peak early having reached high values, and cumulative volume production is high.

There are only some slight age-related growth pattern differences between the yield tables of Kjølby (1958), Nagel (1985), Lockow (2004) and Hamilton and Christie (1971). However, when compared to Kjølby's tables, cumulative volume production of the latter tables is much lower amounting to 766 m^3 ha^{-1} for the best and 274 m^3 ha^{-1} for the poorest yield class (both at 80 years). This clearly shows that their application of should be confined to the regions where the data used for their construction were collected.

To deal with yield estimates for sycamore for forest management in regions where no yield tables for it exists, the use of tables for other similar species is often recommended. The instructions for the use of yield tables in southern Germany, for instance (BY-FE, 1990; BW-FE, 1993), assign sycamore to the ash tables. For Austria, Marschal (1975) recommends that beech tables are used. However, where tables for sycamore and comparable species are available there are significant regional variations in rates of growth and production, indicating that the use of tables constructed for other species to estimate sycamore growth will most likely give unreliable results.

Some yield tables should be treated with caution, because data were sampled at the beginning of the 20th century and most likely growth patterns have changed since then (e.g. Spiecker *et al.*, 1996). Data on the growth of sycamore is sparse and existing yield tables do not cover the whole range of the species in Europe. Thus, information for predicting the growth of sycamore is less reliable than that for the more important European broadleaves. In addition yield tables summarise growth of pure stands, while sycamore is much more commonly found in mixtures. This indicates potential difficulties in silvicultural practice, especially where single tree silviculture is applied.

Forest growth simulators

Only a few forest growth simulators have been parameterised for sycamore and are thus available for decision making in forest management. Kjølby's (1958) classical yield table has been transformed into mathematical models which are currently in use for forest management planning in Denmark. Nagel's (1985) models have been integrated into the forest growth simulator BwinPro (Nagel *et al.*, 2003), a forest ecosystem management model (*sensu* Hasenauer *et al.*, 2000) widely used in northern Germany.

Another tree growth simulation system with species-specific parameterisation is SimCAP (Ottorini and Le Goff, 2002), a single tree, spatially explicit growth simulator (*sensu* Porté and Bartelink, 2002; Robinson and Ek, 2003) based on tree crown development. The program is adapted to pure and mixed even-aged stands of ash and beech, and will be modified to work with sycamore data as well. Specific tree growth and development equations are under construction for sycamore, based on stem and branch analysis of sampled felled trees.

Some parameters of the single tree, distance-dependent growth simulator SILVA (Pretzsch *et al.*, 2002) have been estimated for sycamore using "expert opinion" (Dursky, 2000), others adapted from the ash yield table set up by Wimmenauer (1919), and yet others from the beech yield table by Wiedemann (1932) and Nagel (1985). Apart from the simulators mentioned above, sycamore has been included into other large scale forest-related decision tools (e.g. Bugmann *et al.*, 1997; Lasch *et al.*, 2002). However, as they do not aim at simulating the effect of contrasting silvicultural regimes on classical growth and yield characteristics at tree or stand level, they are not discussed further here.

Summarising the section, there is ample evidence that sycamore is, so far, not of primary interest when setting up growth simulators. However a species-specific parameterisation could improve yield estimates and contribute to sustainable forest management planning.

Growth of sycamore in mixed-species stands

For both ecological and anthropogenic reasons that are difficult to disentangle (Merton, 1970), sycamore is rarely found in pure stands (Jones, 1945). It more often constitutes a component of mixed broadleaved or conifer-broadleaved stands, where it may be found in small groups or in intimate mixtures with other species. Such stand types are often managed by silvicultural systems that include some sort of selection or group-selection thinning, or they are a result of selection-like thinning practices (e.g. Sabroe, 1958, 1959, 1973).

The ability of sycamore to grow in mixture with other species arises from two main characteristics: it can easily regenerate naturally and can achieve temporal dominance through its rapid early height growth. These two features enable sycamore to develop successfully under silvicultural regimes that have been optimised for other species, and they explain its ability to grow in mixture with species that may have different silvicultural requirements.

On the most productive sites, an important issue when growing sycamore in mixture with, or adjacent to other species is its potential invasiveness (Henriksen, 1988; Skovsgaard and Henriksen, 2006; Skovsgaard and Jørgensen, 2004; Waters and Savill, 1992). This is due to the fact that sycamore is very competitive in youth on these sites. There is a widely held belief that if its development is not controlled, the stand may evolve into a pure sycamore within one or two rotations. Sycamore can easily be grown in mixture with other species, and can also easily be controlled by intensive early thinning.

On limestone plateaux of western and central Europe, sycamore is usually found as a secondary species in stands dominated by beech or oak (e.g. Erteld, 1959). These stands are characterized by a potential for significant species diversity, due to a high spatial heterogeneity in soil conditions. The main species found in association with sycamore, besides beech and oak, are: Norway maple (*Acer platanoides* L.), *field maple* (*Acer campestre* L.), hornbeam (*Carpinus betulus* L.), ash, cherry, various *Sorbus* species and limes. (Decocq *et al.*, 2005). On sites with good water availability, sycamore may represent a major proportion of the total stand basal area. By contrast, on drought-prone sites it is widely scattered. On slightly acidic sites with deep and well-drained soils, sycamore may also be found in mixture with the same set of species.

Beech is the species most commonly found in European forests in association with sycamore (Jones, 1945; Bartelink and Olsthoorn, 1999; Piovesan *et al.* 2005). At the regeneration stage the two species are often seen in intimate mixture. Their seedlings have similar light requirements and, in shaded or partially shaded conditions, they show similar growth in the first few years after establishment. However, once the canopy is removed and the seedlings are in full light, sycamore grows much more quickly and rapidly suppresses beech on good quality sites (Beck and Göttsche 1976). This growth advantage persists until an age of 60 to 80 years (Figure 2A, e.g. Hein, 2004; Schober 1995) when beech catches up (Erteld, 1959). After that age, it is necessary to remove the beech that may overshadow sycamore and keep them free from any competing beech in order to maintain good diameter growth. Alternatively, an alternating rotation-long dominance of either beech or sycamore may be anticipated or managed for (Skovsgaard and Henriksen, 2006).

In naturally regenerated stands, sycamore is also often mixed with ash. The two species show very close ecological requirements and growth dynamics (Binggeli, 1992; Waters and Savill, 1992). The light requirement for both species increases after the seedling stage. Similar ecological requirements are reflected in their similar height-growth curves (Figure 2B, e.g. Le Goff, 1982; Hein, 2004), which makes controlling their growth in mixed stands easy. However, when mature, sycamore casts a deeper shade than ash, which may give it a small competitive advantage on moist sites. On drier sites sycamore often grows more slowly than ash (Morecroft *et al.*, 2008). A survey of ash and sycamore regeneration patterns conducted by Waters and Savill (1992) in southern parts of Great Britain indicated that canopy tree replacement in stands of the two species may proceed in cyclic rather than serial fashion, although this is not a general pattern observed in all stands (Morecroft *et al.*, 2008).

A third broadleaved species often grown in mixture with sycamore is oak. Sycamore clearly has a competitive superiority over oak, due to its more rapid early height growth and its greater shade tolerance. If sycamores are scattered as individual dominant trees in a stand dominated by oak, there is no need to control development of sycamore. But if sycamore occupies a larger proportion, it is necessary to prevent the competing sycamore from overcrowding the target oak.

In mountain forests, sycamore may be found in mixed stands on a broad range of sites (Piovesan *et al.*, 2005; Walentowski *et al.*, 2006). It is often found as a secondary species in stands dominated by Norway spruce, silver fir, and beech, where it may grow very well (Ammer, 1996a). In the Bavarian Alps, the percentage of sycamore in these associations varies from 10 to 15% of stand basal area; Norway spruce, silver fir, and beech each represent between 20 and 40% (Ammer, 1996a). The high proportion of sycamore in these stands is said to be a consequence of the low ungulate populations that occurred for a short time in the mid 19th century. During this period, the establishment of sycamore was favoured and stands that originated then have a higher proportion of sycamore than more recently established stands. Sycamore may also be found on unstable steep rocky slopes in mixture with lime and ash, due to its deep, strong root system.

In mountainous areas, sycamore is often associated with silver fir. While both have a high shade tolerances in the regeneration phase, the two species otherwise have very different growth patterns. Sycamore responds quickly to improved resource availability, while fir increases growth much more slowly (Ammer, 1996a). In even-aged mixtures sycamore therefore often overtops fir in the thicket stage, but due to its ability to persist under shade, fir is rarely out competed. At later ages fir trees can grow into the sycamore canopy and suppress neighbouring sycamores. However, as fir in such stands is usually rather localised, forest management activities to control it are hardly ever necessary. According to Pretzsch (2005) it would not be surprising if the mixture of the light demanding sycamore and the shade tolerant fir were an example of positively interacting species, possibly caused by complementary resource utilisation.

A recent investigation into survival of broadleaves in mixed-species floodplain forests has added another facet to knowledge of the behaviour of sycamore in mixed stands. After extreme episodes of flooding along the Rhine between France and Germany, Hauschild and Hein (2008) found that survival of sycamore increased with increasing tree diameter and decreased with increasing duration of flooding and increasing flood level height. Flooding tolerance of sycamore is very low compared to ash*, Populus,* oak*, Salix,* and *Ulmus*, but slightly higher than beech and cherry. Similar results were reported by Späth (2002), who defined 30 days as the maximum tolerable flooding period for sycamore given the flood levels typical for the Upper Rhine. This is especially true for small sized trees up to 25 cm DBH. In mixed-species floodplain forests the high vulnerability restricts silvicultural options for sycamore and, unsurprisingly, leads to the dominance of species native to floodplain forests (ash, poplar, red oak, willow and elm).

In conclusion, we currently have a good general knowledge about the growth of sycamore relative to that of its main associates. However, there is a lack of more detailed information about the relative sensitivity of sycamore to various growth factors (site fertility, drought, climatic events, herbivory, etc.) and to the main silvicultural operations and their interactions with the growth factors mentioned previously. This hinders our understanding of the dynamics of sycamore in mixed-species stands and precludes the development of silvicultural guidelines adapted to these stands.

Aspects of wood quality

Basic wood properties

The wood density of sycamore is similar to that of oak, at 0.63-0.64 g cm^{-3} at 12-17% moisture content (e.g. Aaron and Richards, 1990; Mmolotsi and Teklehaimanot, 2006). For potential silvicultural options it is important to note that ring width has little influence on wood density, as the wood is diffuse porous (Mmolotsi and Teklehaimanot 2006). This means that growth rate will not affect strength properties. Furthermore, wood density is independent of site characteristics (Von Wedel, 1964; Nepveu and Madesclaire, 1986). In addition, no differences in density have been found between white and coloured timber (Achterberg, 1963).

A white or a creamy colour of sycamore timber is a prerequisite for high prices (Achterberg, 1963; Von Wedel, 1964; Sachs, 1966; Keller, 1992). Brown coloured heartwood has occasionally been observed in logs of more than 50 cm in diameter (Von Wedel, 1964). According to Kadunc (2007), the presence of discoloured heartwood in the first log is very likely if the DBH is greater than 45 cm. Moltesen (1958) and Achterberg (1963) hypothesised that heartwood discoloration is linked to the occurrence of dead branches and frost cracks. Additionally, only recently has the effect of forks on the probability of heartwood formation been investigated: the presence of forks increases the risk of discoloration. Discolouration increases along the stem up to a height of 6-8 m, and decreases in the higher parts of the tree (Kadunc, 2007). Heartwood discoloration in sycamore is somewhat similar to the pattern found in beech: with increasing age, relative crown length and average diameter, the formation of discoloured heartwood is more likely (Knoke, 2002 and 2003).

Growth and its relation to branchiness and knottiness

As with most species, branchiness and knottiness are key determinants of wood quality in sycamore as they affect the mechanical, chemical and, particularly, the aesthetic properties of both round wood and sawn timber (Achterberg, 1963; Von Wedel, 1964; Becker, 2008). Only wood and timber free of tight and loose knots is put into the highest grades (e.g. European pre-norms on round wood grading, NHM, 1997). Since both of these factors can be controlled by silvicultural operations, they are important when setting up silvicultural strategies for the species.

Natural pruning of sycamore is fast due to its rapid early height growth, but the occurrence of forks can reduce the length of clear bole significantly. On good sites, the height of clear bole is greater than on poor sites for trees of similar diameters. Rapid self-pruning is characteristic of sycamore and ash, whereas pruning of beech and oak is slower under similar conditions (Hein, 2008a; Nutto, 1999). For evaluation of contrasting silvicultural strategies, allometric models developed by Hein (2004) give quantitative information on the length of clear bole during tree development, as a factor of the competitive status of the tree.

A few models relating to branchiness and knottiness are available for sycamore (e.g. Hein, 2004; Hein and Spiecker, 2007). For forest management, information on the probability of forks occurring, the distribution of branches within the crown, and the pattern of branch mortality would be beneficial. There have been no investigations into natural pruning of sycamore grown in mixed stands. However it is likely that that an admixture of species with different crown transparencies or competitive abilities will alter branch mortality. These gaps in knowledge are remarkable as sycamore produces branches arranged similar to whorls as it grows in height, following a pattern similar to branching in conifers, for which many detailed models already exist (e.g. Mäkinen *et al.*, 2003; Hein *et al.*, 2006).

There are also only a few investigations describing aspects of artificial pruning of sycamore. Compared to natural pruning, branch occlusion is significantly faster with artificial pruning and the width of the knotty core is also reduced (Hein and Spiecker, 2007). Most fungal infections found after pruning do not degrade sycamore wood and remain within the knotty core (Soutrenon, 1991). Unfortunately, no significant quantitative research has been done into the risk of coloration or wood decay after artificial pruning in sycamore. However, some general rules, common to all species, like restricting pruning to smaller branches and not damaging the branch collar can be applied equally to sycamore (see Hubert and Courraud, 1994; Allegrini *et al.*, 1998; Boulet-Gercourt, 2000; Hein, 2008b; Hein and Spiecker, 2007). So far no results on the impact of artificial pruning on the incidence of epicormics, or the long term effect of pruning on height or stem diameter growth have been published.

Silviculture for growing high value timber

Although there is a demand from the veneer and sawmilling industries for attractive large diameter sycamore logs of high quality (i.e. knot free, straight and without coloration inside), there are few quantitative silvicultural suggestions about how to approach such objectives.

Throughout Europe many local recommendations exist for growing high quality sycamore timber (e.g. Thill, 1970; Kerr and Evans, 1993; Armand, 1995; Bartoli and Dall'Armi, 1996;

Allegrini *et al.*, 1998; Joyce *et al.*, 1998; BY-MIN, 1999; Tillisch, 2001). Some are based mostly upon local experience (e.g. Table 1), but the potential to transfer them to other situations needs further research. They all contribute to useful information on growing valuable sycamore. In the following sections we highlight some of the main results that are common to these investigations. In addition we point to aspects that need further work.

Silvicultural objectives for growing crop trees should deliver quantitative information at least on-target diameter and rotation length, clear bole length and density per ha during tree development. These four important aspects can easily be controlled by appropriate silviculture. However the interdependence of diameter growth and wood quality, especially through natural pruning, must not be neglected. Approaches in Europe to these aspects differ significantly between authors (Thies *et al.*, 2008); especially in respect of the number of final crop trees, even though their diameters at breast height may be similar (Table 2). The variation in silvicultural objectives across Europe also indicates a significant degree of variability concerning the growth patterns of sycamore.

Recently a model framework towards quantifying silvicultural objectives for sycamore has been proposed by Hein (2004) and Hein and Spiecker (2008a). A potential outcome based upon crown width development is demonstrated in Table 2 (see also Hein, 2004). It shows, for example that there would be 72 mature dominant crop trees per hectare of 60 cm diameter by the end of a rotation of 75 years, assuming a mean radial increment of 4 mm per year. The anticipated length of clear bole is 11.8 m for site index 30 at age 60 years. It should be noted that only the last column is affected by site conditions (adapted from Hein and Spiecker, 2008a).

Although models are available now, many silvicultural recommendations for forest practice remain vague and non-quantitative (e.g. Joyce *et al.*, 1998; BY-MIN, 1999). In addition it is still unclear how silvicultural objectives should be adapted in mixed stands. Lastly no investigation has so far been made into the potential trade-offs between silvicultural objectives focussing on a limited number of selected crop trees and those maximising per hectare productivity as is done, for example, for oak (Spiecker, 1991; Kerr, 1996). Furthermore there is still debate on the appropriate time to select crop trees: if selection takes place early, the crown will respond quickly to thinnings, but the clear bole length will be shorter compared to later selection. Finally, the criteria for crop tree selection are generally accepted and can be ranked in order of priority: vitality, quality, and distribution. However, quantitative information on minimum vigour, acceptable levels of failures of the stem and their dynamics in time are still missing.

Once these objectives are set, silvicultural prescriptions are needed to enable them to be achieved. The following three approaches for solutions are in the literature on sycamore. They differ in their assumptions and advantages. In addition for each of these approaches research is still needed to quantify the uncertainty involved. The following sections refer to examples of the corresponding guidelines and outline the major research needs.

1. Thinning guidelines based on number of trees per hectare

The number of dominant trees per hectare reflects stand density. Assuming a specific crown cover, crown width development can be taken as a measure of the tree diameter growth over time (e.g. Thill, 1975; Hein, 2004). However, such guides do not allow for decisions on how to converge the circumstances of an individual tree to what is recommended in the guide.

Problems of vigour and risks of epicormic growth after heavy thinnings are not considered in such guides. Research would therefore be needed on growth responses after thinning with respect to the appearance of epicormics, losses in vigour after heavy thinning, and the interactions of extreme climatic conditions and silvicultural measures. Furthermore in mixed stands with groups of species mixtures such guides cannot be applied.

2. Thinning guidelines based on mean distance to neighbouring trees from the crop tree

An interesting type of thinning guide has been proposed by Spiecker (1994) for cherry and by Armand (1995) for ash. A similar guide has also been developed by Hein and Spiecker (2008a) for sycamore. A simple rule of thumb, derived from the crown width-DBH relationship, assuming a crown cover of 70%, consists of a constant variable to be multiplied by stem diameter to yield the necessary thinning radius around the crop tree. For example, with a mean radial increment of 4 to 5 mm per year, the DBH of a crop tree of 30 cm should be multiplied by the constant 22. The result gives the required approximate distance (in cm) between the sycamore and its nearest competitor to reach or maintain a radial increment of 4 to 5 mm. In this case, within a circle of 6.6 m radius, all competitors have to be removed to ensure the desired level of diameter growth of the crop tree. In this rule thinning frequency is a result of the time the crowns of the crop tree and its neighbours need to occupy the free space between crowns.

A guide of this kind suffers from the same drawbacks as the previous one. It also necessitates the selection of crop trees. In mixed stands containing sycamore, trees in the understorey are also present. Cutting them ignores the minor effects they might have on the growth of dominants. Furthermore it is unclear how such heavy crown thinnings affect the per hectare productivity of sycamore. In addition in mixed stands there may be species interactions by neighbouring trees of other species, which is an aspect not considered in guides of this kind.

This omission is serious, as sycamore is a species that usually occurs in mixed stands, but no proper guides are designed for this situation.

3. Thinning guidelines based on preventing crown competition after a specified length of clear bole length has been achieved

An alternative thinning guide can be based upon a two phases concept for growth control (for broadleaves in general: Spiecker, 1991; Wilhelm and Raffel, 1993; Wilhelm et al., 1999a, b, c; for sycamore: Hein and Spiecker, 2008a). The first phase encompasses the stand establishment period up to the time when the desired length of clear bole has been reached. The silvicultural focus during this phase lies primarily with natural pruning (tending phase). Few silvicultural interventions are needed except for maintaining the desired species-mix and removing trees of poor quality if they compete with crop trees. Once the desired length of clear bole has been achieved, crop trees are marked and the second phase begins. If self-pruning is insufficient, artificial pruning (i.e. before branches reach 3cm diameter at the collar) may be appropriate to obtain clear timber. This focuses all forest operations on speeding diameter growth up to the time when final harvesting diameter is reached. No further crown competition is necessary and crop trees are given a heavy selective thinning. The diameter increment of the crop trees converges to its site-dependent maximum. This two-phase system keeps branches small on the lower parts of the stem which has been sufficiently cleaned of branches by self-pruning. The knotty core will then be small due to high branch mortality during the first phase. Towards the crown the knotty core expands abruptly where the first live branch is present.

Such guides require the application of crop tree silviculture. Even though it may be appealing because it is simple to apply, the following questions remain:

- How do sycamores react in terms of epicormic production and vigour to a sudden transition between the first and the second phases?
- When released at the start of the second phase, how do they respond in terms of diameter growth after a long period of intense competition?

During the second phase, when trees are almost open grown the species mixture is expected to have a minor influence.

Conclusions

Although sycamore is an attractive species in forestry there is a lack of peer reviewed, scientifically-based investigations into its silviculture, preventing foresters from improving silvicultural strategies and add up information to everyday and local experience. Although there is some “grey literature” published in national non peer-reviewed journals, leaflets and brochures (e.g. Allegrini *et al*., 1998), this does not compensate for valid scientific literature. Filling in gaps about the growth of sycamore could contribute to improved management of forests in Europe.

Acknowledgements

This review paper has been made possible through travel grants by COST Action E42 “Growing Valuable Broadleaved Tree Species” (www.valbro.com). The authors thank Robin Hillestad M.Sc. and Ginamarie Lopez B.Sc. for repeatedly checking the language of the manuscript, and Isabelle Vinkler for comments on earlier drafts of the manuscript.

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Figures and figure captions

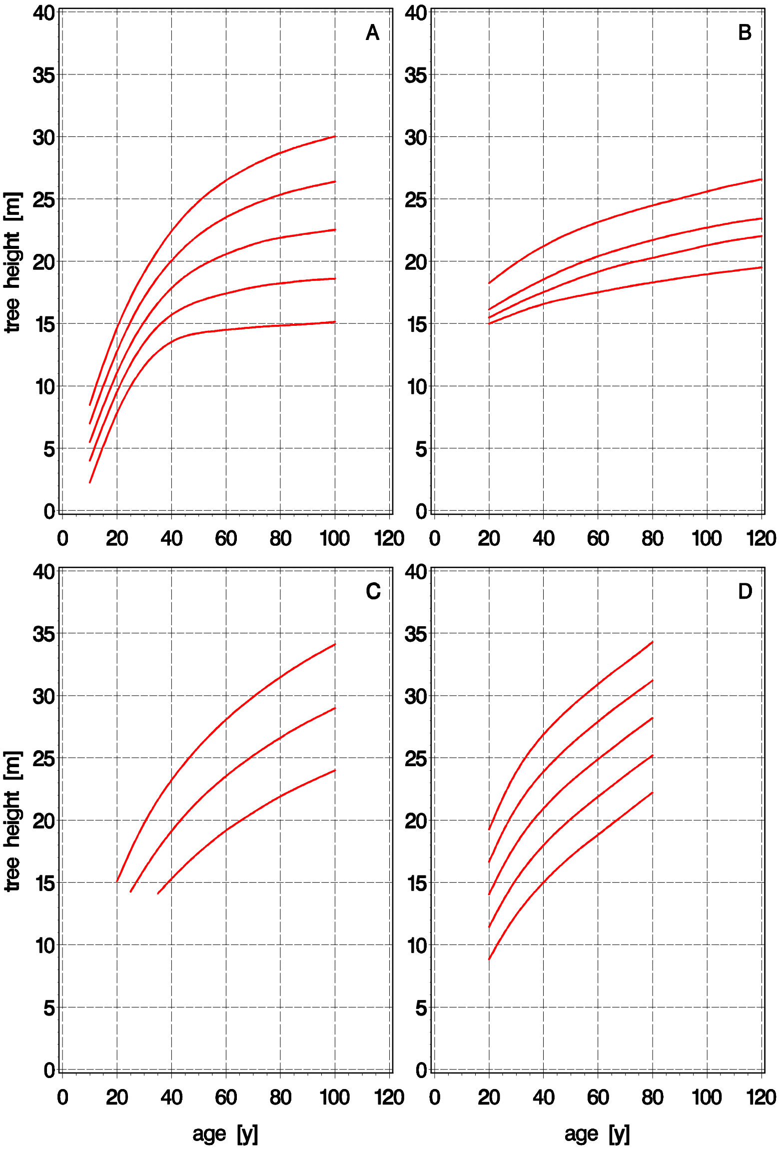

Fig. 1. A selection of height growth models for sycamore in Europe. (A): site classes I to V from Kjølby (1958) (Denmark), (B): site classes I to IV from Le Goff and Madesclaire (1985) (North-East France), (C): yield classes I to III from Nagel (1985) (Northern Germany), (D): site indexes 29 m, 26 m, ... – 17 m (base age = 50 years) from Claessens *et al.* (1999) (Belgium).

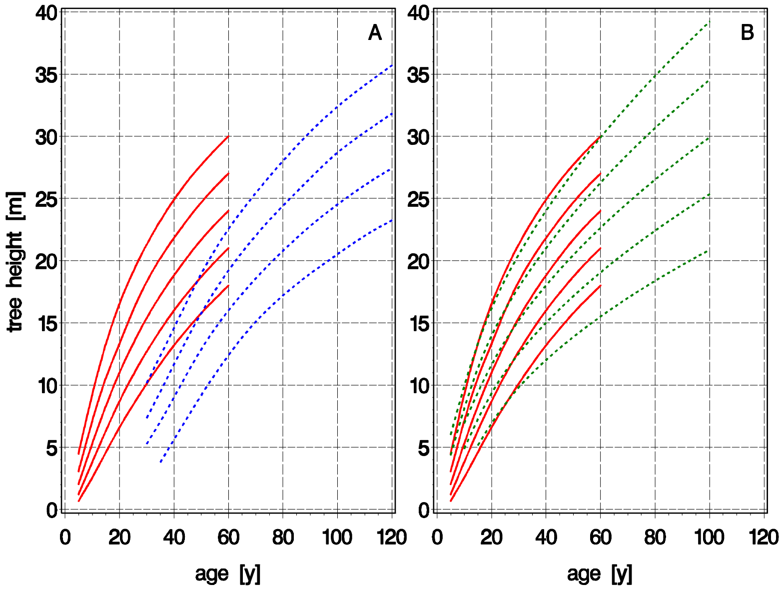

Fig. 2. Height growth of sycamore (solid lines, Hein 2004) compared to *Fagus* (left figure A, dashed line, Schober, 1995, site classes I – IV, dominant height of the 20% largest trees, moderate thinning) and *Fraxinus* (right figure B, dashed line, Le Goff, 1982, dominant height, site index 24 m, 21 m, ... – 12 m (base age = 40 years)).