Broadleaf thinning in Ireland – a review of European silvicultural best practice

Jerry Hawe[a] and Ian Short[b*]

Abstract
A substantial first-rotation broadleaf plantation resource in Ireland is progressively entering a thinning phase. Silvicultural best practice in support of such a management intervention needs to be developed for this new woodland resource to achieve its maximum commercial potential. National research trials are key to the provision of information for the development of best practice. Determining the current state-of-the-art is a prerequisite to the design and implementation of appropriate research trials. This study reviews the literature concerning the fundamental principles of broadleaf thinning with particular regard to timing, intensity and impacts on crop tree growth response, focussing on a range of commonly planted broadleaf species in Ireland. The overall aim of this review is to gain a fuller understanding of the most effective thinning methodology to be employed to maximise the production of high quality hardwood timber. In doing so it is intended that the information presented may support ongoing and future research trials with regard to potential silvicultural treatments to apply, data types and analysis and the likely results of practical application to commercial forestry.

Keywords: *Silviculture, selective thinning, thinning intensity, thinning control*.

Introduction
Ireland has a stocked forest area of 637,140 ha (DAFM 2013); of this area, broadleaved species account for 164,310 ha. Of those broadleaves, 33.9% are effectively non-commercial species (both long and short living), of which over half are willow (*Salix* spp.). The next largest broadleaf species group comprises birch (*Betula* spp.; 22.7%), followed by ash (*Fraxinus excelsior* L.; 12.5%) and oak (*Quercus* spp.; 10.2%) (DAFM 2015). Just over 74% (c. 122,246 ha) of the broadleaved area is under 30 years of age. The vast majority of this new, first rotation, plantation resource was established with State aid under the Afforestation Scheme. Since state support for forestry development in the private sector began, about 60,000 ha of new broadleaved plantation have been established in Ireland (Hendrick and Nevins 2003, DAFM 2012). Broadleaved planting has increased dramatically since 1993, with ash as the single most prevalent species (DAFM 2013, 2015). The most recent figures place ash afforestation at 17,000 ha since 1990 (DAFM 2015). The stand configuration of the four main commercial hardwood species tends to be in either single species blocks (ash and sycamore (*Acer pseudoplatanus* L.)) or intimate line mixtures (oak and beech (*Fagus sylvatica* L.)) (DCMNR 2000).

[a] Forestry Consultancy and Research, Belfast Co. Antrim.
[b] Teagasc Forestry Development Dept., Ashtown Food Research Centre,
[*] Corresponding author: Ian.Short@teagasc.ie

The silviculture of these new forests now comprises not only establishment and tending phases, but increasingly, as the resource matures, an early thinning phase. Thinning should aim to add value to the initial State investment by maximising the production of high quality hardwood timber. In 2009 a tending and thinning element of the Forest Improvement Scheme was introduced. This provides grant aid for the first thinning of broadleaved plantations. Of the new broadleaf plantation resource, 4,760 ha has been thinned up to the end of 2014 and ash has been the main species treated (DAFM 2015). Given the overall figures outlined above, it would appear that only a proportion of those crops requiring first thinning are actually being treated.

Much remains to be understood concerning the most appropriate silvicultural thinning practices in first rotation Irish broadleaf plantations. Even-aged, greenfield plantations comprised, at least initially, of single main crop species, may be an appropriate foundation in the development of a new broadleaf woodland resource. However, they do present quite unique management challenges (Hawe and Short 2012) and opportunities, which require that existing technical guidelines and academic knowledge be reviewed against the particular environmental and structural context specific to Irish plantations. For example, similar to the coniferous forest resource, Irish broadleaved stands, under certain favourable growing conditions, have proved to be very vigorous - perhaps more so than the same species in the UK or continental Europe. This has implications with regard to the timing and intensity of thinning treatments, as well as how they might be adapted from UK or European standard practice in order to take advantage of this opportunity to harvest an increased yield. European, British and Irish forests in general face an increased risk from pests and disease (Pautasso et al. 2015), not least young, even-aged, monocultural plantations of ash in Ireland. This may also drive the need to maintain crop trees in the best possible health and vigour and grow them as quickly as possible to maximise yield for securing returns on the initial capital investment. This situation may also require the development of adapted thinning treatments. Adapted thinning treatments may form the basis of structural and species diversification in order to build resilience and secure ecological objectives for our broadleaf woodland resource. However, for any such adapted thinning treatments to be designed and applied, first an appropriate baseline for conventional thinning in Irish broadleaf plantations needs to be established. This study seeks to inform that process. As and when the most effective and practical early thinning prescriptions are established, they can be disseminated to Irish forest owners and managers. This may help to facilitate the transition from the “farmer who owns a forestry plantation” to “farm forester,” who is actively involved in the management of their plantation. Engaging and informing forest owners should help to address the apparent shortfall in the timely first thinning of existing broadleaved crops in Ireland.

This paper reviews established UK and Irish broadleaved silviculture texts, being based on similar environmental and stand conditions, in an attempt to synthesise best-practice relating to the early thinning of pole-stage plantations. The paper also reviews the findings from contemporary European, UK and Irish silvicultural research trials on selected broadleaf species that are of relevance to Irish plantation forestry. The overall aim of this review is to establish silvicultural best practice with regard to the early thinning treatments applied to the new broadleaf plantation resource in Ireland, with particular regard to the timing of interventions, thinning intensity and impacts on tree crop growth response.

Broadleaf thinning – a general overview

Thinning reduces stand density, competition and affords the remaining trees more space to grow. The primary crop response to thinning relates to the distribution of volume within the stand (Savill et al. 1997). Total volume production per unit area does not differ greatly between thinned and unthinned stands. Provided the site is fully occupied, with a reasonably intact canopy, whereby trees can fully utilise available resources, a stand will produce approximately the same amount of wood at various stocking densities (Zeide 2006). Thinning concentrates this volume on fewer trees, meaning that they produce greater individual volume increment than stands with higher stocking densities (Hamilton 1976, 1981). Different management objectives concerning diameter and mean radial increment result in differences in rotation length, and in the desired number of crop trees per ha at the end of the rotation (Dobrowolska et al. 2011). "Thinning control" seeks to manage the redistribution of volume increment so that selected trees can produce target stem diameters and log lengths within a given timeframe. Thinning control is supported by various data, including crop age, top height, basal area and stocking (stems ha^{-1}). These data inform decisions on timing and intensity of thinning interventions (Rollinson 1988, Edwards and Christie 1981). Achieving a specific top height or basal area threshold is often used as a determinant of the timing for first and subsequent thinnings. Basal area or number of stems per ha may be used to control the proportion of volume or stocking removed (Table 1).

In broadleaved stands thinning generally seeks to improve the quality of the final crop (Savill et al. 1997). Potential crop trees (PCTs) should have good stem form, good vigour, be disease- and damage-free and should be relatively evenly distributed throughout the stand (Short and Radford 2008). PCTs should be selected early, usually at the time of first commercial thinning (Hart 1991) and subsequent thinning operations seek to favour these trees. This represents a fundamental difference to conifer crops where highly systematic thinning generally seeks to maximise stand volume production. In broadleaved stands the overriding importance of stem quality may dictate that some stand volume production be sacrificed to favour the development of selected PCTs, which should maintain well balanced, even crowns (Kerr and Evans

1993). Most broadleaved species, and particularly ash, cherry (*Prunus avium* L.) and birch (*Betula* spp.), require that the crowns are kept free from competition to maintain good form and vigour (Savill 2013), and therefore PCT volume increment. Thinning too heavily however, may have negative effects on both overall volume production and PCT stem quality such as epicormic shoot growth or heavy low side branching (Savill 2003). Broadleaved thinning should therefore seek to achieve a balance whereby the diameter growth of PCTs is maximised without negatively impacting on stem quality. Evans (1984) identifies five silvicultural objectives for broadleaved thinning:

1. to improve stand quality by removing poorly formed and defective trees;
2. to ensure that future increment is concentrated on the best formed trees;
3. to provide more growing space for final crop trees and so to enhance their diameter increment;
4. to ensure satisfactory development of mixed stands and timely removal of nurse or secondary species;
5. to remove trees which are diseased or damaged in other ways.

The factors identified by selected authors as affecting the decision of how and when to first thin common ash are outlined in Table 1. In general, broadleaved crops should undergo first thinning when 8–10 m top height has been achieved. Crops let grow much beyond this stage may develop crown proportions which are too constricted to fully respond to thinning. Late thinning may also expose remaining stems to wind damage. Initial PCT numbers should be two to four times the required number of final crop trees, which is generally between 60–190 stems ha^{-1} (Kerr and Evans 1993).

Given that the overall aim of broadleaved thinning is to favour PCTs, the principal thinning method recommended in Ireland is "selective", whereby a number of co-dominant competitors are removed to free up PCT crowns in a crown thinning. Some systematic early thinning may also be appropriate such as the opening up of access racks, which may involve the removal of between 1 in 7 to 1 in 10 planting lines (Short and Radford 2008). Wolf trees and diseased trees should also be removed in early thinning.

Whether removed systematically (lines/racks) or selectively in terms of PCT competitors, wolves etc., stocking reduction provides a very practical means of thinning control. Stocking reduction can focus on the removal of specific groups or individual trees required to deliver the silvicultural objectives of the operation. The disadvantage of stocking as a control, particularly if trees are removed in the wrong strata (suppressed/sub-dominants), is that stocking density may not correlate closely with required basal area/volume reduction or with reduced competition.

A more objective method to determine both the timing and intensity of thinnings is through the measurement of basal area, which for most broadleaves should be between 20 and 30 m^2 ha^{-1} prior to thinning (Kerr and Evans 1993). Rollinson (1988) provides threshold basal areas by species (for given top heights). Edwards and Christie (1981) provide post-thin target basal areas by species (for given Yield Classes (YC)). Ultimately a range of crop data, such as age, top height, basal area, volume and stocking, may be utilised with a visual assessment of crown and canopy structure to comprehensively control thinning practice.

Particularly in continental Europe, where there is a long history of broadleaved silviculture, target diameter and log quality over a specified rotation length, dictate the timing and intensity of thinning interventions (Hein and Spiecker 2009). Experience combined with contemporary research has created a body of knowledge concerning quite exacting management inputs with known or expected outcomes, and has facilitated the development of quite precise allometric and yield models. Broadleaved plantations in Ireland on the other hand are effectively a "brand new", first rotation resource with no history of silvicultural management. Nevertheless, Irish forestry can aspire to the development of effective broadleaved silviculture best-practice guidelines and sophisticated management objectives. In doing so, Ireland can begin to assess the fundamentals of best-practice based on the European and UK experience.

Review of individual species literature – timing of initial thinning interventions, intensity and impacts on growth

Thinning of ash

Since the inception of the afforestation programme, ash has been the most widely planted broadleaved species (DAFM 2011). Regardless of stem quality issues (Hawe and Short 2012), good vigour is not uncommon. First rotation ash plantations often achieve YC 8–10, resulting in many stands established in the 1990's now requiring first thinning.

Table 1 summarises the factors that affect the decision to implement first thinning in an ash stand. The "trigger" includes stand attributes which may be monitored to a point in the rotation where they reach a threshold which initiates first thinning. "Intensity control" then provides a guideline for the proportion of the standing crop to be removed.

Table 1 shows that:

- first thinning should commence before the crop reaches 10 m top height (albeit Rollinson (1988) provides no threshold basal area at this height);
- threshold basal area should be 18–20 m^2 ha^{-1}; these conditions may be expected before the crop is 15 years old; and
- the height of live crown should not be allowed fall below 33% of overall tree height or 50% of stem height.

The European project FRAXIGEN (2005) recommends thinning from 6–7 m in height. This represents a pre-commercial thinning, which may include stands derived from natural regeneration that are likely to have a much higher initial stocking than plantations. Early, high intensity interventions in highly stocked, naturally regenerated stands are essential for the development of quality PCTs (Rytter and Werner 2007). While such recommendations on naturally regenerated stands are useful, ash stands in Ireland are derived primarily from plantations with very specific and relatively low initial stocking rates (2,500–3,300 stems ha^{-1}). Joyce et al. (1998) also recommend a pre-commercial thinning or tending for ash plantations at a top height of 7–8 m. Aside from the removal of wolves, this is primarily a low thinning with little or no impact on PCT development. The data from Joyce et al. (1998) in Table 1 reflects a first crown thinning.

Thinning intensity is the rate at which volume is removed, e.g. 10 m^3 ha^{-1} $year^{-1}$ (Rollinson 1988). Marginal Intensity represents the upper limit of volume that can be removed in a single intervention without causing a loss of cumulative volume production. Marginal intensity is defined as 70% of the YC × the thinning cycle (in years). Thinning control may therefore be based on inventory data using volume and/or basal area. While "stems ha^{-1}" is not recommended as a formal means of control, it does represent a useful guide, assuming the correct type of thinning has been carried out (Rollinson 1988).

A highly systematic use of inventory data to guide thinning control may however, detract from the forester's observation of PCT crown development requirements. As stated previously, broadleaves must maintain well-balanced, even crowns. This is particularly true for ash, which requires crowns continually free from competition and growing quickly from an early age to produce quality timber (Kerr and Evans 1993, Savill 2003, FRAXIGEN 2005). Applied at a practical management level, i.e. during the marking of the thinning, intensity control may therefore, be based to a large extent on the number of stems removed in order to free up PCT crowns. Apparently, only Short and Radford (2008) and Hein and Spiecker (2009) provide intensity guidelines based on selectively removing a specific number of trees which are in direct competition with any given PCT.

The principal silvicultural texts (Table 1) generally agree that ash thinning should be "early," "heavy" and "frequent". These are highly subjective terms which require further clarification with regard to timing, rate of removal, resultant effects on growth and schedule of subsequent interventions. Short and Radfords' (2008) guidelines on thinning intensity in Irish broadleaf plantations are highly practical in their application. However, the effects of the prescribed systems on stand growth and dynamics are as yet relatively unknown. Ongoing research into thinning intensity, the structural distribution of removals, the related impacts on PCT crown development, stem quality and volume increment is required to inform and update future management guidelines.

Knowledge of the dynamics of even-aged stands of ash is poor; for example, there is not yet any explanation for the belief that the window for a response to thinning is smaller for ash than for some other broadleaved species (Kerr and Cahalan 2004). Investigating the relationship between crown development and stem volume increment could ultimately lead to a better understanding of the stand dynamics of ash, although few experiments have explored the impact of thinning on this relationship (Dobrowolska et al. 2011).

Some of the most comprehensive modelling experiments on the relationship between crown characteristics and stem development in *F. excelsior* were carried out by Ottorini et al. (1996). Based on the coniferous crown modelling work of Mitchell (1975) and Ottorini (1991), a wide range of crown attributes were recorded for dominant and co-dominant sample trees including: crown height, crown projection area (CPA), "competitive status", foliar volume and foliar biomass. Competitive status is measured by ratio of crown length to total height of the tree (Le Goff and Ottorini 1996). Crown height was positively correlated with foliar volume, which in turn was positively correlated with stem volume increment. Competitive status was positively correlated with stem volume increment (and to a lesser extent tree height). As a key determinant of PCT volume increment, competitive status provides a useful management tool, which is easily observed/measured, described and monitored. According to Table 1 for example, the competitive status of an ash PCT should be maintained at ≥0.33.

Thinning of oak

Next to ash, oak (*Quercus robur* Liebl. and *Q. petraea* Matt.) are collectively the second most widely planted species within the Irish afforestation programme (DAFM 2011). Being slower growing than ash, oak generally requires a much later first thinning intervention (Edwards and Christie 1981, Rollinson 1988), often around 25 years of age for typical yield classes. Top height at first intervention would still be around 10 m at this stage. Traditionally, thinning interventions in oak aim to provide frequent, relatively low impact inputs that avoid sudden structural changes within the stand (Kerr and Evans 1993) on thinning cycles of 5–10 years (dependent on YC).

In contrast to the traditional "gradualist" approach outlined above, some continental systems favour a "dynamic" approach to early thinning in oak. Everard (1985) states that:

> Nothing more than thinning highlights the differences between classical and progressive silviculture. The classical approach involves a late start to thinning, and a very gradual opening of the stand from below. Denmark can be regarded as leading in progressive thinning, and here broadleaved crops are thinned early, often and in the crowns.

Table 1: *Main factors that affect the timing and intensity of first thinning in ash.*

Publication	Trigger for first thin				No of PCTs selected	Intensity control of thinning			Cycle
	Top height (m)	Basal area[a] ($m^2 ha^{-1}$)	Age (yr)	Other		Stems removed	Basal area[b] ($m^2 ha^{-1}$)	Target stocking (stems ha^{-1})	
Edwards and Christie 1981[c]	11.3	18	15				9	1,121	5 yrs
Evans 1984	8-10	20-30		Live crown 50% stem height	350				5-7 yrs
Forestry Commission 1955	7.6-9.1							2,717	3-4 yrs
FRAXIGEN 2005	6-7[e]			Live crown >33% tree height					
Hart 1991	10			Live crown 50% stem height	270-540				
Horgan et al. 2003	10				350-400				
Joyce et al. 1998	10				1,000[d]			1,000	+3 m TH[f]
Kerr and Evans 1993	8-10	20-30		Live crown >33% tree height	350				
Rollinson 1988[c]	12	18	15						
Short and Radford 2008	>8				300	Racks 1 line in 7, 2-3 competitors per PCT		≈ 1,300	+4 m TH

[a] Threshold basal area; [b] Target basal area; [c] Yield Class 10; [d] All remaining stems treated as PCTs prior to selection of 150 PCTs at Top Height 15 m;
[e] Includes pre-commercial thinning of naturally regenerated stands with potentially high initial stocking; [f] TH = top height

Sevrin (1997) outlines two French approaches that illustrate the change in classical and progressive silviculture. A traditional approach whereby first thinning begins when trees reach 8–15 m top height, depending on intensity of previous management, and removes one or two badly formed stems and impeding trees per high quality stem, the subsequent thinning occurring 12–15 years later. A "dynamic" system is also outlined where first thinning begins at 8–12 m top height and all crown competitors of 70 selected high quality stems ha^{-1} are removed, the subsequent thinning occurring 6–8 years later. Modelled on a French system, Joyce et al. (1998) promote earlier "tending" operations in Irish plantation oak (from a top height of 6 m) whereby wolves and defective stems are removed in one or two interventions before systematic crown thinning commences at a top height of about 14 m. This reflects traditional oak silviculture in the north of France whereby successive/frequent early cleaning or tending operations remove unwanted poor quality trees, albeit from stands derived from natural regeneration and potentially with initial stockings in the tens of thousands. Formal crown thinning in traditional oak silviculture in France is initiated much later in the rotation (age 30–50 years) than in British systems, although tending does blend somewhat into the crown thinning stage (Evans 1982). The dynamic approach aims to take advantage of distinct phases early in the rotation, i.e. close spacing in youth to assist natural pruning and maximise clean bole length, but also facilitating "early crown thinning to optimise the potential of the juvenile growth phase for crown development" (Joyce et al. 1998). A similar phased approach with an early natural pruning followed by a second PCT crown release phase has also been promoted within oak silviculture in Germany. In this system it is accepted that the promotion of crown development decelerates natural pruning, therefore the development of the desired clear bole length is achieved in closed stand conditions in the early rotation, which is followed by selective crown thinning of PCTs (Spiecker 1991, Hein and Spiecker 2009), predicated on the finding that stem diameter is closely correlated with crown width.

Facilitating early and ongoing crown development in order to maximise stem increment production has become an increasingly popular concept. Hemery et al. (2005) demonstrate the linear (r^2>0.8) relationship between crown and stem diameter in 11 common UK broadleaves. If this ratio is maintained, through thinning, PCT crowns (and therefore stems) may accrue their maximum increment. Modelling optimum crown space at a given DBH can be used to indicate desired basal area or stocking (Hemery et al. 2005). In north-western Spain, stand density tables were produced for pedunculate oak (*Q. robur*) that aim to provide dynamic thinning models based on desired stand attributes of height, diameter and volume (Barrio Anta and Álvarez González 2005). Recent Swedish research promotes crown / stem ratio modelling in pedunculate oak as the basis for silvicultural management and suggests that early, heavy thinning combined with high pruning, initiated early and repeated at regular intervals, may maintain timber quality, accelerate achievement of target diameter and therefore help shorten rotation length (Attocchi 2015).

A system which stimulates vigorous crown development of selected trees, in order to achieve maximum radial stem increment (Jobling and Pearce 1977) is commonly referred to as "free growth." It has also been called "free-thinning" and is associated with "crown release" thinning. In contrast to the aforementioned, relatively regular and gradual oak silvicultural systems, the free growth system can be viewed as an intense form of selective crown thinning in which a limited number of the best dominants are freed from crown competition from the first thinning onwards by felling any tree that touches the crown of a selected tree. The Forestry Commission (1955) suggested that about 100 dominants per acre (250 ha^{-1}) are selected. Research in Britain on free growth of broadleaves did not begin until 1950. Several hundred hedgerow and parkland oak were examined in the first study and showed that these free-grown trees had markedly greater radial stem increment than trees in forest stands (Hummel 1951), leading to the suggestion that a relatively small number of well-formed trees, selected early in the rotation and pruned to encourage clean boles, could result in a complete stocking of valuable trees at maturity. After a free-growth treatment was applied to a 19-year-old oak plantation (*Q. robur* and *Q. petraea*), stem volume and DBH increased compared with control and light crown thinning treatments (Kerr 1996), but pruning was required to ensure stem quality was maintained. It may be thought that the free-growth system is not suitable for oak, due to the requirement for pruning of epicormics and the additional expense of this action. Indeed, Kerr (1996) did wonder whether this was the reason that free-growth of oak was not common in Britain, and that it may be more applicable to cherry (*Prunus avium*), sycamore (*Acer pseudoplatanus*), ash (*Fraxinus excelsior*) and mixed stands of such species. However, Beinhofer (2010) modelled the free-growth system, with and without pruning, and compared it with conventional management of oak. Results showed that oak grown using the free-growth system and pruned provided a better financial return than conventionally grown oak or unpruned free-grown oak. Whether pruning was carried out or not, the free-growth system was still financially more attractive than the conventional method (Beinhofer 2010). Pruning of epicormics is one of the silvicultural operations recommended by Jobling and Pearce (1977) for free grown oak where the objective was to produce veneer-quality timber in a rotation of less than 100 years. They recommended that 60–80 well-formed dominant trees ha^{-1} be selected when mean height was >8 m and that they should be evenly spread through the stand. All trees whose crowns were within one quarter of the mean crown width of the chosen trees were then removed by thinning. Pruning of epicormics and side branches of the chosen trees, to an ultimate height of 6 m, had to be carried out.

The crowns of the chosen trees were subsequently maintained free from competition by successive thinnings carried out every 3–5 years. A similar system was described by Lemaire (2010). The French "sylviculture dynamique" system similarly aimed to produce high quality oak in a rotation of less than 100 years. In this system 70 stems ha^{-1} were selected before dominant tree height reached 16 m and stems that were competing in the canopy with them, as well as those <2 m distance from their canopy, were removed. Suppressed stems and those not directly competing with the selected stems remained to help prevent epicormics but pruning was also carried out on the selected stems as required.

All of the principal texts on oak silviculture concur that epicormic or side branching can be a major problem in the production of quality timber. Thinning practice should avoid exacerbating this problem (Horgan et al. 2003). While one proposed benefit of the dynamic system outlined above is increased diameter increment leading to more rapid achievement of target diameter and the shortening of rotations, a further benefit may be that healthy vigorous PCTs are less susceptible to the development of epicormic branching. Although first interventions in oak are perceived as being relatively late (in terms of age), if crown size is allowed to deteriorate through very late and light thinning then the resultant stress may also promote epicormic development (Joyce et al. 1998). The dynamic system seeks to minimise any growing stress through the development of healthy PCT crowns. Albeit dedicated crown thinning does not appear to commence until relatively long clear boles (Hein and Spiecker 2009) or tall (Joyce et al. 1998) top heights have been achieved. Everard's (1985) observations on French and Danish oak silvicultural systems state that epicormics are best controlled through early and heavy thinning. Somewhat conversely, the traditional gradualist approach discourages epicormic development through frequent light thinning and the minimisation of stand structural changes (Evans 1984). In the case of late thinnings, a drastic return to the desired stocking may also promote epicormics (Shapland 1966). Timely intervention is therefore critical.

North American research on mixed-oak stem quality (Sonderman and Rast 1988) points out that while heavier thinnings increased the crown class (relative crown proportions) of dominant trees and PCTs potentially facilitating shorter rotations, light frequent interventions (akin to the traditional UK systems) resulted in fewer and smaller side branches throughout the stand, albeit with much slower diameter increment. Further US research trials on oak thinning intensity suggested that trees with higher crown class scores (the more dominant trees) continued to have fewer epicormics than trees with lower crown class scores across a range of intensity treatments (Dimov et al. 2006). One note of caution however, is that external environmental factors may promote epicormic development, therefore making the assessment of the outcomes of silvicultural practice more difficult (Lockhart et al. 2006). While these US observations restate the pros and cons of early vs. late and/or heavy vs. light thinning, they also reinforce the benefits of developing and maintaining healthy and balanced PCTs (as opposed to a stand based management approach), which should be the central focus in broadleaf silviculture.

In view of the large body of information and experience available, the thinning of oak is perhaps more complex than most other broadleaved species. This being the case it may be prudent, particularly from the low starting base of Irish plantation silviculture, to observe the fundamental principle of maintaining well-balanced PCT crowns. If this requires earlier or heavier thinning than some systems dictate, then the pruning of epicormics is likely to be a necessary, complimentary operation.

Thinning of beech

Like oak, beech (*Fagus sylvatica* L.) has traditionally a relatively late first thinning intervention (Edwards and Christie 1981). However, particularly when derived from natural regeneration, beech can have very high initial stocking rates requiring pre-commercial tending interventions (Joyce et al. 1998, Skovsgaard et al. 2006). These may be selective in terms of taking out poorly formed individuals (Joyce et al. 1998), which are common in young beech stands. However, in very densely stocked stands such operations may be costly and some form of systematic (mechanical) thinning, in terms of taking out lines or racks may be more practical (Evans 1984, Skovsgaard et al. 2006). Short and Radford (2008) recommended no initial tending intervention for Irish beech plantations (irrespective of initial stocking). For pure beech at a stocking of 6,600 stems ha^{-1} they recommended a combination of systematic and selection thinning commencing at a top height of 12–15 m. This contrasts with Joyce et al. (1998), who recommended an initial stocking reduction from 6,600 to 2,500–3,000 stems ha^{-1} at a top height of 5–8 m. This is a low thinning and they reached a similar position to Short and Radford (2008) that crown thinning should commence at 12–15 m. Given that many beech plantations in Ireland, up until 2011, were established with a conifer nurse; the removal of this nurse is likely to form the basis of the first thinning. Short and Radford (2008) make provision for this in a two phase tending/thinning prescription. However, as beech in Ireland is now (since 2011) planted pure at only 3,300 stems ha^{-1}, any new guideline related to this configuration is likely to retain the maximum stocking in an effort to achieve a desired clear bole length prior to a first crown thinning. (This general situation also applies to oak plantations in Ireland pre/post 2011.)

The general approach for the early treatment of beech is to retain high stocking until PCTs achieve a clear bole length of 6–8 m (Brumme and Khanna 2009), followed by heavy crown thinning to encourage rapid diameter increment (Kerr and Evans 1993), as fast-grown beech is preferred for nearly all end-uses over slow-grown (Evans 1982). Boncina et al. (2007) demonstrated that selective crown thinning in beech may result in dominant tree (PCT) increment 30–56% higher than that of the dominant trees in unthinned stands. Other studies in European beech stands have shown that, on favourable sites, accelerated increment can be related to increased thinning intensity (Pretzsch 2005, Štefančík 2013). It may therefore be that traditional yield models have underestimated the potential diameter increment in European beech (Hallenbarter et al. 2005) and more current dynamic growth models need to be developed (Álvarez-González et al. 2010).

It has also been shown that beech stands can cope better with climatic (moisture and temperature) fluctuations when intra-species competition is reduced, i.e. through thinning, resulting in positive growth outcomes for the remaining trees (Cescatti and Piutti 1998, Van der Maaten 2013).

Beech is the most shade tolerant broadleaf used in Irish forestry (Hill et al. 1999) and with high crown plasticity (Schröter et al. 2012), unlike ash for example, can respond well to thinning even after a period of neglect (Kerr and Evans 1993). However, Štefančík (2015) pointed out that delayed (and less intensive thinning) can result in lower quantitative production.

Most authors agree that beech thinning should focus on a desired clear bole length. This change of focus, somewhat away from the maintenance of PCT crown proportions, is facilitated by beech's shade tolerance and related crown plasticity. Brumme and Khanna (2009) leave first thinning relatively late – 40 to 60 years – to achieve the desired clear bole length. The reason for this disparity with other guidelines is unclear although it may be due to less vigorous growing conditions and they do specify a slightly longer bole. Most authors however, agree that once the target bole length is achieved, subsequent thinning should be moderately heavy and frequent in order to maximise PCT crown development and therefore volume increment.

Thinning of sycamore

Standard UK guidelines include the same early thinning criteria, top height, threshold basal area, etc., for sycamore (*Acer pseudoplatanus* L.) as for ash (Edwards and Christie 1981, Rollinson 1988). More applied guidelines relating to Irish plantation silviculture also make the same prescriptions for the initial thinning of the two species (Short and Radford 2008). Hein and Spiecker (2009) treat the two species growth habits and silvicultural requirements as very similar in their allometric models linking target diameter, rotation length and stocking.

Certainly the need for early and heavy thinning to maintain vigorous crowns in sycamore has been well documented in Irish and UK forestry (Bolton 1949, Hiley 1955, Stevenson 1985, Stern 1989, Kerr and Evans 1993, Horgan et al. 2003). Evans (1984) promotes early and frequent interventions, particularly on fertile sites, and heavy crown thinning, to the point of free-growth in order to drive rapid diameter increment, on more sheltered sites. Horgan et al. (2003) concur with the recommendation for a first heavy

Table 2: *Main factors that affect the timing and intensity of first thinning in oak.*

Publication	Trigger for first thin				No of PCTs selected	Intensity control of thinning			Cycle
	Top height (m)	Basal area[a] (m^2 ha^{-1})	Age (yr)	Other		Stems removed	Basal area[b] (m^2 ha^{-1})	Target stocking (stems ha^{-1})	
Edwards and Christie 1981[c]	10.4	24	25				20	3,529[d]	5 yrs
Evans 1984	8-10	20-30			200				5-7 yrs
Forestry Commission 1955: 1st thinning	9-10.5			Work to a light grade. Eliminate wolf and whip trees.				2,700-3,460	5 yrs
Forestry Commission 1955: 2nd thinning				Work to a moderate grade. Eliminate whips.					5 yrs
Hochbichler 1993	13-15		30	Start of selective thinning	60-70	1 – 2 competitors per selected stem			
Horgan et al. 2003					300-400				
Joyce et al. 1998: 1st tending	6-7							3,600[d]	
Joyce et al. 1998: 2nd tending	10-11							1,900-2,100	
Joyce et al. 1998: crown thinning	13-15			Target clear bole length achieved.	100			1,000-1,300	+ 1.5-2 m TH[e]
Kerr and Evans 1993	8-10	20-30			200				

Publication	Trigger for first thin				No of PCTs selected	Intensity control of thinning			Cycle
	Top height (m)	Basal area[a] ($m^2 ha^{-1}$)	Age (yr)	Other		Stems removed	Basal area[b] ($m^2 ha^{-1}$)	Target stocking (stems ha^{-1})	
Lemaire 2010	9-12			Prune selected trees and halo thin the following year.	70				
Rollinson 1988[c]	12	26	28						
Sevrin 1997	8-15			In favour of the best trees, gradually remove 1 or 2 trees that impede or have poor form or a defect.	Not yet selected				12-15 yrs
Sevrin 1997	8-12			Remove all trees that interfere with the PCT crowns.	70				6-8 yrs
Short and Radford 2008	10-12				340	Racks 1 line in 7, 1-2 competitors per PCT		≈4900[d]	

[a] Threshold basal area; [b] Target basal area; [c] Yield Class 6; [d] Initial stocking >6,000 stems ha^{-1}; [e] TH = top height

Table 3: *Main factors that affect the timing and intensity of first thinning of beech.*

Publication	Trigger for first thin				No of PCTs selected	Intensity control of thinning			Cycle
	Top height (m)	Basal area[a] ($m^2 ha^{-1}$)	Age (yr)	Other		Stems removed	Basal area[b] ($m^2 ha^{-1}$)	Target stocking (stems ha^{-1})	
Edwards and Christie 1981[c]	11.4	23	30				20	3,946[d]	5 yrs
Evans 1984	8-10	20-30			250				5-7 yrs
Forestry Commission 1955	9			If badly shaped trees are numerous remove the worst of these and favour good trees. In more normal crops employ a light grade thinning				3,459	
Horgan et al. 2003				Clean bole min 6 m	300-400				
Joyce et al. 1998 – 1st tending	5-8							2,500-3,000	
Joyce et al. 1998 – crown thinning	12-15			Target clear bole length achieved	150			1,500	+ 2-3 m TH[e]
Kerr and Evans 1993	8-10	20-30		Clean bole min 7 m	250				
Rollinson 1988[c]	12	24	30						
Short and Radford 2008	10-12				340	Racks 1 line in 7, 1-2 competitors per PCT		≈ 4,900[d]	
Brumme and Khanna 2009	15		40 – 60	Clean bole 6 – 8 m	80-160				4-6 yrs

[a] Threshold basal area; [b] Target basal area; [c] Yield Class 6; [d] Initial stocking >6,000 stems ha^{-1}; [e] TH = top height

crown thinning followed by ongoing selection thinning aimed at the continual release of PCT crowns. They also recommend the retention of the middle and understorey (where possible) in order to control the development of epicormics in PCTs.

Perhaps the most comprehensive recent review on sycamore silviculture in Europe was carried out by Hein et al. (2009a), who questioned the widespread applicability of historical guidelines which are based on assertions and observations that have not been objectively tested. They highlight a lack of published research material on sycamore silviculture which takes into account modern management objectives, e.g. the production of high quality timber over short rotations. Traditional diameter increment predictions based on yield tables may be based on "average" crops that have been subjected to moderate, un-quantified thinnings and do not necessarily reflect modern thinning regimes. Hein et al. (2009a) outline the current requirement to improve stand economics and achieve merchantable stem dimensions and target diameter in the shortest possible rotation. In this scenario they reflect on the potential gains which may be made by heavier thinnings, up to a given threshold (Plauborg 2004), particularly during the vigorous early rotation phase (Nagel 1985) up to about 20–25 years. Various models which aim to maximise stem quality, and crown and diameter increment, are considered. Knowledge gaps are identified and the need for further research highlighted. In general terms however, early and heavy thinning in sycamore, in support of positive economics, would appear to remain the focus of most authors, from the reflections of Lord Bolton (1949), who favoured increasingly early interventions in his high quality sycamore stands, through to more contemporary literature. Any apparent change of focus relates more to modelling growth and treatment outcomes as opposed to silvicultural practice by experience and observation. Both approaches may inform practical management guidelines.

Thinning of cherry

Little debate surrounds the thinning of cherry where "early, heavy and frequent" is the common recommendation (Pryor 1985, Kerr and Evans 1993, Joyce et al. 1998, Horgan et al. 2003). Cherry is highly sensitive to crown competition, particularly after its fast growing phase up to about 20 years (Joyce et al. 1998), and under-thinning is likely to result in loss of increment and possibly crown dieback (Pryor 1985). As cherry is best grown as a minor component in mixed broadleaved stands (Evans 1984, Kerr and Evans 1993, Loewe et al. 2013), PCTs cannot be allowed to lose their place in the canopy as they are unlikely to recover it (Stojecová and Kupka 2009). Crown thinning should commence when around 8 m top height is attained (Horgan et al. 2003) and should focus on removing PCT competitors to allow adequate growing space throughout the thinning cycle (Kerr and Evans 1993). Subsequent thinnings should be frequent and heavy, to the point of free-growth (Horgan et al. 2003), in order to achieve large diameter timber in the shortest possible rotation (Kerr and

Table 4: *Main factors that affect the timing and intensity of first thinning in sycamore.*

Publication	Trigger for first thin				No of PCTs selected	Intensity control of thinning			Cycle
	Top height (m)	Basal area[a] ($m^2 ha^{-1}$)	Age (yr)	Other		Stems removed	Basal area[b] ($m^2 ha^{-1}$)	Target stocking (stems ha^{-1})	
Edwards and Christie 1981[c]	11.3	18	15				9	1,121	5 yrs
Evans 1984	8-10[c]	20-30[c]		Maintain deep crown	350				≤6 yrs
Forestry Commission 1955				Similar to that of ash but more shade tolerant and can carry more stems ha^{-1}					
Horgan et al. 2003	12			Live crown >33% tree height	200-300				+ 2-3 m TH
Joyce et al. 1998	12-14				150			1,000	+ 2-3 m TH[d]
Kerr and Evans 1993	8-10	20-30			350				
Rollinson 1988[a]	12	18	15						
Short and Radford 2008	>8				300	Racks 1 line in 7, 2-3 competitors per PCT		≈ 1,300	+4 m TH[d]

[a] Threshold basal area; [b] Target basal area; [c] Yield Class 10; [d] TH = top height

Evans 1993). Joyce et al. (1998) recommend retaining half or even two thirds of the height of the tree in live crown. Such open growth will clearly entail lower stocking densities at a given top height compared to other commercial broadleaved species (Hein and Spiecker 2009) and PCTs will require judicious pruning (Pryor 1985, Pakenham 2005). An allometric equation is provided in Pryor (1988) relating stem and crown diameters (Equation 1).

$$\text{Crown diameter (m)} = 1.19 + 0.158 \times \text{DBH (cm)} \quad (R^2 = 0.88) \qquad (1)$$

There is a high correlation between the two, suggesting that if a tree's crown is impeded then its stem diameter will be correspondingly restricted. To obtain good stem diameter growth rates, Pryor (1988) suggests that stocking should never be allowed to rise above the values corresponding to 100% canopy closure in Table 5. Extended thinning cycles will require thinning to a much lower canopy closure percentage to prevent 100% closure being attained prior to the next thinning.

Duyck (1997) provides a model for the silviculture of cherry in the Normandy region of France (Table 6). Comparing the mean diameter of the main stand after thinning and the number of stems remaining with the data in Table 5, the stocking rate of Duyck (1997) closely resembles that of Pryor (1988) with 60% canopy closure, suggesting that 60% is a target canopy closure for thinning operations.

Thinning of alder

There is little literature regarding the thinning of alder (*Alnus glutinosa* or *A. cordata*). Nisbet (1893) says about alder:

> Its treatment in pure forest is as a rule rather as coppice than as high timber forest, after its growth has once been begun; the original formation of crops usually takes place by means of planting rather than by either natural or artificial sowing (Nisbet 1893, p. 228).

He goes on to describe coppicing of alder and its management but at no point discusses the management of alder as a high forest.

Recent proposals for the thinning of alder (e.g. Poulain 1991, Vaast and Billac 1996, Claessens 2005) suggest intensive and especially early thinning regimes beginning at age 10–15 years. Two methods are commonly used:

- stand thinning – a homogenous thinning of the whole stand, favouring more or less equally all the trees remaining after thinning;
- crop tree thinning – a crown thinning that concentrates on removing competitors of a small number of selected trees of high potential quality that will form the final stand, creating space around the crown of the future crop trees.

Savill (2013) recommends crop thinning. It should be started early and must be

Table 5: *Estimated number of cherry stems ha^{-1} for a range of mean stand diameters and degrees (percentage) of canopy closure (Pryor 1988).*

Mean stem diameter	Mean crown diameter	Numbers per ha. at % canopy closure of:				
(cm)	(m)	100%	90%	80%	70%	60%
10	2.8	1,624	1,462	1,299	1,137	974
15	3.6	982	884	786	687	589
20	4.3	689	620	551	482	413
25	5.1	490	441	392	343	294
30	5.9	366	329	293	256	220
35	6.7	284	256	227	199	170
40	7.5	226	203	181	158	136
45	8.3	185	167	148	130	111
50	9.1	154	139	123	108	92

Table 6: *Guide to silviculture of cherry in the Normandy region of France (Duyck 1997).*

Age	Main stand before thinning					Thinning				Main stand after thinning				
	No. stems ha^{-1}	Dominant height (m)	Mean diameter (cm)	Surface area (m^2 ha^{-1})	Total volume (m^3 ha^{-1})	No. stems	Mean diameter (cm)	Surface area (m^2 ha^{-1})	Total volume (m^3 ha^{-1})	No. stems	Dominant height (m)	Mean diameter (cm)	Surface area (m^2 ha^{-1})	Total volume (m^3 ha^{-1})
15	690	9.9	13.6	10.01	40	90	10.48	0.78	3	600	9.9	14.0	9.24	37
20	600	12.5	18.6	16.24	85	205	17.44	4.90	25	395	12.5	19.1	11.34	60
25	395	15.1	23.7	17.44	113	114	21.86	4.27	27	281	15.1	24.4	13.17	86
31	281	17.9	29.9	19.71	155	78	27.39	4.58	36	203	17.9	30.8	15.13	120
37	203	20.1	36.2	20.95	188	46	33.61	4.07	36	157	20.1	36.9	16.87	152
44	157	22.0	43.2	23.10	230	35	40.01	4.36	43	123	22.0	44.1	18.74	187
52	123	23.3	51.3	25.38	270	26	47.37	4.65	48	96	23.3	52.3	20.74	221
60	96	24.1	59.6	26.90	297	19	54.33	4.31	47	78	24.1	60.8	22.58	250
69	78	24.5	69.1	29.15	328						24.5			

heavy and frequent around the selected final crop trees to achieve marketable timber before heart rot sets in. He goes on to state that alder does not respond to delayed thinning. Claessens (2004) provides more detail of a crop thinning system, providing the minimum distance between future crop trees and their nearest neighbours as a function of their height and DBH (see Table 7).

Rytter and Werner (2007) report results of a replicated black alder (*A. glutinosa*) thinning trial in Sweden. The stand used was derived from natural regeneration with a stocking density of 20,000 stems ha^{-1}. Table 8 illustrates a standard tending/thinning regime for such a stand. Three replicates of two thinning treatments and a control were investigated. The two thinning treatments reduced stocking density to 1,433 and 1,067 stems ha^{-1} for the standard and strong thinning treatments, respectively. Both thinning treatments resulted in a significant increase in DBH after three years compared to the control treatment and both the thinning treatments were similar to each other. The mean crown diameter of the stems in the thinned treatments was significantly greater than those in the control treatment one year after thinning, implying that the crowns of the stems in the thinned treatments had expanded to utilise the additional space available to them.

Alder constitutes 9% of the Irish broadleaf forest estate (Government of Ireland 2013). Neither Horgan et al. (2003) nor Joyce et al. (1998) provide any advice on the thinning of alder in an Irish context except to say that it doesn't respond to delayed thinning. Short and Radford (2008) provide some recommendations, suggesting that more than 350 potential crop trees ha^{-1} should be selected when the stand top height is 8 m and then at least two competitors per PCT should be removed. The next thinning is recommended to take place when top height is 12–15 m and 2–3 competitors per PCT are thinned. Short and Radford (2008) provide no advice for later thinnings.

Table 7: *Minimum approximate distance between a future alder crop tree and its nearest neighbour (trunk to trunk) should be a function of total height and DBH of the future crop tree -all values in metres (recalculated from Claessens (2004)).*

Total height of the future crop tree (m)	Minimum distance between future crop tree and its nearest neighbour (m)
9	30 × DBH
12	27 × DBH
15	24 × DBH
18	21 × DBH

Note: Actual formula uses circumference at 1.3 m height. The above approximates the cited formula by substituting circumference with 3 × DBH (approximating π × DBH).

Table 8: *Recommended number of remaining* Alnus glutinosa *stems after thinning (Rytter and Werner 1998).*

Tree height (m)	**Stems remaining after thinning**
2–3	2,000–2,500
6–7	1,200–1,400

Thinning of birch

The interest in silver and downy birch (*Betula pendula* Roth. and *B. pubescens* Ehrh., respectively) as commercial broadleaf species has only recently begun to develop in Ireland (O'Dowd 2004, Renou et al. 2007). This same interest gained momentum some years previously in the UK, during the early nineties (Cameron 1996), and surprisingly, 50 years prior to that birch was still considered a weed species in Scandinavian forestry (Lorrain-Smith and Worrell 1992). Following an extensive improvement programme launched in Finland in 1960 (O'Dowd 2004), birch timber is now a significant component of Northern and Eastern European commercial forestry output (Hynynen et al. 2009, Liepiņš et al. 2011). This being the case, much of the literature on the silvicultural management of birch originates in Scandinavia and may therefore be difficult to transfer to Irish plantation forestry conditions. For example, many Scandinavian stands are derived from highly stocked (mixed species) natural regeneration origin (Hynynen et al. 2009), requiring timely (before reaching 5–7 m height) pre-commercial thinning interventions in order to maintain the crown proportions and vigour of the dominant trees (Fällman et al. 2003, Rytter and Werner 2007). In Finland however, pure birch plantations generally require no pre-commercial thinning (Hynynen and Niemistö 2009). Certain fundamental silvicultural characteristics of the species may be applied to birch stands in general. "Birch requires ample head room, and when once the chief un-wanted classes (whips and wolves) have been eliminated the grade of thinning adopted should be moderate to heavy" (Forestry Commission 1955).

To further qualify the above statement; birch is a strong light demander and requires heavy thinning to ensure minimal competition from surrounding trees (Cameron 1996). Birch PCTs only maintain their vigour and diameter increment when growing as dominant trees at relatively wide spacing with a low degree of competition. First commercial thinning should be carried out before the crown ratio of the dominant trees fall below 50% (Horgan et al. 2003, Hynynen et al. 2009, Hynynen and Niemistö 2009). If, through neglect, crown proportions are allowed to fall much below this figure, birch stands rarely recover (Cameron 1996). The "two-phase," which is an early close spacing followed by crown release, a concept described by Hein and Spiecker (2009) for oak, ash, sycamore and cherry is not appropriate for birch (Hynynen et al. 2009). The birch requires early and heavy thinning (Rytter and Werner 2007), until full and permanent crown release is achieved in order to grow large dimensioned, high value timber. Various authors put the top height threshold for first thinning in birch between 10–15 m however, maintaining the appropriate live crown ration should take precedent over top height as a first thin trigger, and it is notable that UK and Irish guidelines (Worrell 1999 and Horgan et al. 2003) put the top height threshold closer to 10 m.

In Scandinavia commercial thinning is carried out when dominant height is between 12–15 m with stocking reduced from 1,600–3,000 stems ha^{-1} to 600–700 stems ha^{-1} (Raulo 1987, Mielikäinen et al. 2007). In Latvian birch silviculture the pre-commercial thinning phase in natural stands begins at 3–6 m stand height, leaving 1,500–2,000 stems ha^{-1} (Zālītis and Zālītis, 2007). Commercial thinnings are carried out twice during the rotation: the first at an average height of 14–15 m, leaving about 1,200 stems ha^{-1}, the second at a height of 21–24 m, leaving 500–600 stems ha^{-1} (Liepiņš et al. 2011). Thinning from below is the conventional silvicultural method practiced in Latvia. Birch rotations in northern Europe are generally between 40–60 years depending on site productivity (Mielikäinen et al. 2007, Hynynen et al. 2009).

Based on trials in Silver birch in southwest Germany, Hein et al. (2009b) point out that natural pruning is poor as even dead lower branches are slow to shed. In keeping with the above, they recommend an early intensive release of PCTs combined with pruning to 5 m stem height in order to minimise wood defects. Hein et al. (2009b) also advise growing to target diameter no greater than 45–50 cm as birch diameter increment drops off rapidly after about 25 years, even with continued PCT crown release. Furthermore rotation lengths in excess of 50–55 years (95-120 final crop trees ha^{-1}) are likely to result in discolouration of the timber.

Worrell (1999) provides some useful practical guidelines on birch thinning in UK forestry conditions (based partly on Scandinavian silvicultural practice):

- respacing of naturally regenerated stands, ideally when 1.5–2 m tall and before 6 m, to about 2 m spacing or 2,500–3,000 stems ha^{-1}. Planted material should also be at this initial stocking.
- in pre-commercial thinning remove suppressed and poorly formed trees – misshapen stems and small crowns; favour silver birch over downy; favour seedlings over coppice shoots, but where coppice shoots are retained they should be singled to one or two stems per stool; retain the best co-dominants and dominants of exceptional form.
- two broad thinning options: "Heavy" commercial thinning – 2 to 3 thinnings over a 45–60 year rotation; *or*, "frequent" commercial thinning – cycles of 5–10 years.
- thin from a top height of 10 m in "frequent" thinning to 1,400–1,600 stems ha^{-1}; 5 to 7-year cycles early in the rotation and 8 to10-year cycles later in the rotation.

Worrell (1999) also suggests that the heavy thinning interventions, as detailed in Table 10, are appropriate to Britain.

Worrell (1999) suggests slightly shorter rotation lengths for British birch than for birch in Scandinavia – 35 to 40 years on better sites with adequate thinning, to 65 years

Table 9: *Main factors that affect the timing and intensity of first thinning in birch.*

Publication	Trigger for first thin				No of PCTs selected	Intensity control of thinning			Cycle
	Top height (m)	Basal area[a] (m^2 ha^{-1})	Age (yr)	Other		Stems removed	Basal area[b] (m^2 ha^{-1})	Target stocking (stems ha^{-1})	
Edwards and Christie 1981[c]	11.3	18	15				9	1,121	5
Worrell 1999: frequent thin	10			Live crown 50% tree height		≈ 1,000		≈ 1,500	5–7
Worrell 1999: 2 thin total	11 – 14		16+	Live crown 50% tree height		≈ 1,600		≈ 900	c. 13
Worrell 1999: 3 thin total	10 – 12		15+	Live crown 50% tree height		≈ 1,250		≈ 1,250	c. 10
Horgan et al. 2003	10			Live crown 50% tree height	700			1,500	
Raulo 1987	12 – 14					≈ 1,000–2,000		700–900	
Rollinson 1988[c]	12	18	15						

[a] Threshold basal area; [b] Target basal area; [c] Yield Class 10.

on poorer sites with lighter thinning. Average DBH at felling should be 25–35 cm, which assuming YC 10 was attained in well managed Irish birch stands, as suggested by Nieuwenhuis and Barrett (2002) for Irish-grown downy birch, could mean rotations as short as 30–35 years (Edwards and Christie 1981). It is encouraging that as improved birch material becomes available for use in Irish forestry, outline thinning prescriptions are already well advanced.

Thinning intensity trials and residual stand growth responses

One of the most prominent studies to quantify the effects of thinning intensity on the residual (post-thinning) broadleaf stand was carried out by Juodvalkis et al. (2005). They published the results of thinning experiments of six species in Lithuania, covering five broadleaves: pedunculate oak, silver and downy birch, aspen (*Populus tremula* L.) and common ash. The study was conducted over a 35-year period on 256 permanent sample plots in pure or nearly pure even-aged natural stands of high YC that were 10–60 years old when the study commenced. European studies on common ash show average YCs of 4–6 with a maximum of about 10 (FRAXIGEN 2005). Based on volume removed, low thinning intensity included 10, 15 and 20% volume removed; moderate intensity 25, 30 and 35%; and high intensity 40, 45 and 50%. No-thin controls were also included. Standard single tree and stand inventory data were recorded as height, DBH, volume, stocking, etc. "Crown surface area was estimated by measuring crown diameter in 8 different directions" (Juodvalkis et al. 2005).

The results (for all species) showed that:

Table 10: *Heavy thinning regimes for silver birch on a 45- to 60-year rotation (Worrell 1999).*

	2 thinnings	3 thinnings
First thinning		
Top height (m)	11 – 14	10 – 12
Age (yr)	16 – 28	15 – 25
Thinning volume ($m^3 ha^{-1}$)	30 – 40	20 – 30
Stocking after thinning (ha^{-1})	800 – 1,000	1,200 – 1,300
Second thinning		
Top height (m)	18 – 20	15 – 16
Age (yr)	29 – 48	24 – 40
Thinning volume ($m^3 ha^{-1}$)	40 – 50	35 – 40
Stocking after thinning (ha^{-1})	400 – 500	800
Third thinning		
Top height (m)	-	20 – 21
Age (yr)	-	34 – 60
Thinning volume ($m^3 ha^{-1}$)	-	60 – 70
Stocking after thinning (ha^{-1})	-	400 – 500

Note: the decision on when to thin should be based on the *height* of the crop, rather than age. Age is included in this table for general planning purposes.

- residual trees occupied available space and enhanced their crown increment, and faster expansion of crowns was recorded in stands thinned to a larger degree;
- in older stands crown increment was lower than in younger stands;
- tree crowns started to react one year after thinning and reached maximum growth after 2–3 years, though different species reacted at different growth rates;
- the strongest reaction was in aspen and birch, crowns of which expanded up to three times faster than those grown in unthinned stands. Ash and oak more than doubled their crown surface area increment;
- after 3–4 years, rates of crown expansion started to decrease. However, due to the extensive crown growth of all four broadleaved species, total crown area in thinned stands became greater or equal to that in unthinned controls after 4–7 years;
- thinning promotes DBH increment, especially in younger stands, and the rate of increase in DBH is positively correlated with thinning intensity. This was true for all four broadleaf species, showing an increase already one year after thinning and reaching a maximum 2–3 years later;
- in general, DBH increment following thinning was greater in younger stands and heavier thinnings. However, there was an intensity threshold beyond which the increase of DBH increment was not further enhanced –this is defined as minimal stocking. Thus, in 10–20 year-old stands, minimal stocking comprised 30–40% canopy coverage and in 50–60 year-old stands 50–60%. In terms of basal area for broadleaves, this roughly corresponded to 3.5–8 $m^2 ha^{-1}$ at a mean height of 7–12 m, and 14–20 m^2 ha^{-1} at a height of 20–24 m;
- overall, stand volume increment was only maximised in light or moderate intensity thinnings, varying between 15–25% of volume even in the youngest stands. The thinning effect on volume increment was largest in 10 to 20-year-old stands and declined sharply in older stands and in 50 to 60 year-old stands further increase in volume was negligible (Juodvalkis et al. 2005).

The Juodvalkis et al. (2005) study covered a wide range of age classes, in naturally derived stands, in northern central Europe, therefore the practical applications for plantation silviculture in different geographic areas may be somewhat limited. However, the trends illustrated by the study may be able to inform broader silvicultural practice. The positive impact of thinning in relation to PCT growth response is clear, specifically the correlation between crown development and stem volume increment. The higher relative gains in early thinning also provides a general lesson in broadleaved silviculture. Juodvalkis et al. (2005) also indicate the importance of maintaining relatively short thinning cycles. Their findings on the positive growth implications of higher thinning intensities broadly concur with the other authors in this review and the concept of "minimal stocking" is one which can inform other studies in different geographical areas with different environmental and stand conditions.

Starting in 2005, Çicek et al. (2013) carried out a thinning intensity trial on narrow-leaved ash (*F. angustifolia* Vhal.) in north western Turkey. Two thinning treatments were applied in two separate experiments. The first on a 36-year-old plantation established at 1,666 stems ha^{-1}, the second on a 22-year-old plantation established at 730 stems ha^{-1}. Intensity regimes in the respective sites were controlled by basal area: 0% removal as controls; 19% and 22% removal, respectively as moderate intensity thinnings; and 28% and 39% removal, respectively as heavy thinnings. Standard measurements over a 6-year period included: DBH, height and basal area. While this trial involved a different species from common ash, and it was carried out in somewhat different environmental and silvicultural conditions than those found/employed in northwestern Europe, the treatments and results are nonetheless interesting and broadly concur with the previously reported findings with regard to the impact of thinning on diameter increment. Both experiments showed that thinning significantly increased residual diameter increment, in comparison to the controls, and the rate of increase in diameter increment was positively correlated with thinning intensity. Thinning intensity did not significantly affect height increment. Stand basal area and stand volume had not recovered to the levels of the control after six growing seasons. Volume increments were higher in the second site, with a heavier thinning on a younger crop than in the first site. Çicek et al. (2013) concluded with recommendations for ash thinning including common ash, which supports the view that the selection of PCTs should occur early in the rotation. Crown thinning should favour these trees, with "heavier" thinning early in the rotation to keep PCTs entirely free of competition.

The COFORD-funded Teagasc/UCD Broadleaf Silviculture Research and Development (B-SilvRD) programme included a thinning intensity trial which explored the effects of conventional rack and selective first thinning practice, as recommended by Short and Radford (2008), on PCT development in plantation ash over three growing seasons (Teagasc 2015). The B-SilvRD trial applied this general rack and selective prescription in two separate plots – one involving the removal two competitors per PCT and another with the removal of three competitors. The trial assessed any relative growth advantage for PCTs over the remaining stand matrix. It also aimed to discern any significant difference between 2- and 3-tree selection, with a particular emphasis on DBH and BA increment (Hawe 2014).

Given that individual PCTs subjected to a rack with 2- to 3-tree selective thinning are afforded varying levels of crown space, particularly where adjacent lines, additional diseased trees, etc. are removed, the actual crown space afforded to individual PCTs in the B-SilvRD trial was assessed both by recording their actual number of immediate neighbours remaining post-thinning and by recording whether a PCT was adjacent to a rack. PCTs in each intensity treatment showed significant DBH increment gains over the remaining stand matrix ($p \leq 0.0001$ at each measurement period). There was no significant difference in DBH and BA increment on the PCTs between the two thinning intensity treatments. The number of neighbours remaining was negatively correlated with PCT diameter increment. However, overall PCT increment gains in relation to the remaining number of neighbours was only significant at the first measurement period ($p = 0.0462$). Only those PCTs with the greatest individual canopy space continued to show significant growth increments throughout the trial, i.e. the number of neighbours effect combined with a rackside situation showed significant DBH increment gains at each measurement period ($p = 0.0124$, $p = 0.0069$ and $p = 0.0061$).

The three trials described above (viz. Juodvalkis et al. (2005), Çicek et al. (2013) and the B-SilvRD trial (Hawe 2014) cover quite different geographic areas and stand configurations. However, a common theme is the maximisation of PCT growth increment through increased thinning intensity, to the point of minimal stocking (Juodvalkis et al. 2005). Clearly the maximisation of PCT growth increment cannot be at the expense of timber quality and, for some species, is likely to require a complementary pruning treatment(s). This concept may however, be explored through further trials and is potentially of great interest to the silviculture of the most widely planted commercial broadleaf species in Ireland.

Modelling PCT growth responses to provide management guidelines

Gaining a better understanding of stand growth responses to thinning may ultimately lead to more effective management prescriptions to facilitate desired production objectives, i.e. target log length/diameter within a given timeframe.

Hein and Spiecker (2009) described the allometric modelling of crown width for common ash, sycamore and wild cherry, which in turn provides some practical silvicultural management guidelines for certain production objectives. The models are based primarily on crown width (not defined), which is correlated with DBH, and consider production objectives such as clear bole length, target diameter and rotation length. Having demonstrated the strong link between crown width and DBH ($r^2 = 0.88$), the models predict the rotation lengths required to produce various target harvesting diameters, across a range of mean radial increments and clear bole lengths and with different numbers of crop trees per ha. Hein and Speicker (2009) also promote PCT-based thinning, identifying future crop trees early and thinning to favour their development. Their numbers of final crop trees for ash range from 61 ha^{-1} to 124 ha^{-1}. Tables are provided that show the number of competitors that should be removed per future crop tree; the number of final crop trees per ha; target diameter; crop tree/competitor breast height ratio; and competitor removal data according to crop tree DBH and age. As such, Hein and Spiecker's tables represent one of the most comprehensive attempts since the UK Forestry Commission yield models (Edwards and Christie 1981) to model complete rotations for individual broadleaved species, showing critical crop data over time. In addition, complete rotation tree spacing tables across an increasing DBH range and for different target mean radial increments are provided.

For example, Hein and Spiecker (2009) provide early thinning guidelines for ash which include the removal of between 3 and 5 competitors per PCT. This compares with Irish guidelines for early ash thinning (Short and Radford 2008), which recommend the removal of 2–3 competitors per PCT. However, certain difficulties exist with regard to extrapolating Hein and Spiecker's (2009) models to plantation forestry silviculture outside of their experimental area. Hein and Spiecker base their silvicultural practice for common ash on a "two phase management system", developed by Spiecker (1991) for oak. The pre-thinning first phase involves only natural and intervention pruning until the desired clear bole length is achieved. Phase two then involves successive thinning interventions. The pre-thinning clear-bole lengths for ash considered in the model range from 12–20.3 m. Delaying first thinning to such an extent in Irish ash plantations may compromise the PCT's "competitive status" (as described by Le Goff and Ottorini 1996), i.e. the crown depth as a proportion of overall tree height and therefore the tree's ability to respond to thinning (Kerr and Evans 1993).

Discussion

The principal aim of silvicultural thinning in broadleaf plantations is to ensure satisfactory crown and stem development, and therefore volume increment, of selected PCTs. From an early stage in the rotation, PCT crowns must be kept free from competition to maintain high growth rates and therefore maximise volume increment on the best stems (Kerr and Evans 1993, Savill 2003). This ongoing release of PCT growth is controlled via thinning intensity.

The systems and units employed to control thinning intensity include: basal area (BA) reduction (Çicek et al. 2013), volume removal (Juodvalkis et al. 2005), canopy coverage (Juodvalkis et al. 2005), live crown height as a proportion of stem or tree height (Evans 1984, Le Goff and Ottorini 1996, FRAXIGEN 2005) and stocking or stem removals (Hein and Spiecker 2009). Historically in Irish and UK forestry, publications such as *Thinning Control* (Rollinson 1988) and the *Forestry Commission Yield Models* (Edwards and Christie 1981) provided intensity guidelines based on number of stems per ha, basal area and/or volume removal. In two Irish publications, Joyce et al. (1998) and Short and Radford (2008) provide intensity guidelines based on a reduction of number of stems per ha. Short and Radford (2008) outline the methodology to reduce stocking, including the systematic removal of entire lines of trees (racks), primarily to facilitate access, combined with the selection of PCTs and related competitor removals.

Short and Radford's (2008) recommendations may be contrasted with Hein and Spieker's (2009) thinning control tables, which attach detailed production objectives to the number of competitors removed. In a 15-year-old ash stand, with a PCT DBH of 15 cm, where the DBH of the competitor equates with 90% of the PCT DBH on a 65-year rotation with a target diameter of 60 cm, Hein and Spieker (2009) recommend the removal of 4.3 competitors per PCT ("within the next 5 years" or presumably in a single intervention on a 5-year cycle). This is somewhat heavier than current Irish guidelines suggest. The difficulty in comparison exists in the disparities between geographically distinct silvicultural conditions and practice. Hein and Spieker's (2009) work encompasses a wide range of data and allometric modelling, from a country with a long history of broadleaf silviculture and related research. Within Irish forestry very little allometric data have been available in relation to broadleaf plantations. Therefore, it is difficult to predict how current thinning guidelines will impact PCT development with regard to maintained crown release (in the period to the next thinning). The B-SilvRD programme includes thinning intensity trials, which aim to explore the effects of conventional rack and selective first thinning practice (as recommended by Short and Radford 2008) on PCT development. The early results of these trials would appear to indicate that the volume increment of Irish plantation ash PCTs may be accelerated through heavier selective thinning than was previously thought.

Strong common threads run through all of the reviewed material. Broadleaf thinning should focus on the development of selected individuals. This represents the highest quality stems within the stand, the PCTs. These should be identified early in the rotation. While some highly systematic thinning, such as the removal of lines to facilitate access is accepted, silvicultural thinning should primarily involve the removal of PCT competitors. Crown proportions are closely related to diameter, basal area and volume increment. While different broadleaf species have different rates of crown plasticity, in general PCT crowns should be continually kept free of competition so they can maintain proportions which are able to respond to successive interventions and therefore drive stem and stand volume production.

Thinning intensity is closely related to PCT diameter, basal area and volume increment. Heavier thinnings tend to produce greater/more rapid volume increment. Early thinnings also produce greater/more rapid volume increment. However, Hein and Spiecker (2009) and Juodvalkis et al. (2005) demonstrated there is an upper limit to thinning intensity above, which thinning no longer increasingly benefits PCT development. Heavy thinning may also have a deleterious effect on stem quality, e.g. the production of epicormics in oak, and it may reduce total stand volume production.

The studies reported in this review covered a large geographical area, over which considerable variation in climatic and other environmental conditions, stand dynamics, silvicultural systems etc., might be expected. The research information collected in particular trials may only apply to the provenances used and also the climatic and site conditions of the study area. It may be risky to extrapolate to other sites, especially if located in a different country with different environmental conditions. Such extrapolation requires a degree of speculation possibly not supported by local research; e.g. the minimal stocking thresholds presented by Juodvalkis et al. (2005) may be an underestimate for relatively high YC Irish broadleaf plantations.

Juodvalkis et al. (2005) results do however, provide some very useful observations on the overall effects of thinning broadleaves and therefore may be useful in providing some direction for further thinning intensity trials in different geographic regions. For example, the minimal stocking thresholds outlined may be related to the number of post thinning stems per ha in these trials, which in turn may affect the numbers of PCT competitors removed during thinning. For example, the 30–40% canopy cover minimum stocking figure proposed by Juodvalkis et al. (2005) may correspond to greater than 4 competitors removed per PCT (in a plantation with initial stocking of 2,500 stems ha^{-1} and 1 in 7 lines removed as racks). This is a higher intensity than current Irish guidelines recommend in crop conditions with potentially greater vigour than the continental stands of northern central Europe.

Juodvalkis et al. (2005) state that the "annual increment of the mean DBH was regularly higher, the younger the stand and the larger the spacing," indicating that thinning to favour selected PCTs should be relatively heavy to ensure necessary crown development and rapid DBH increment. While the recommendations of Edwards and Christie (1981) and Rollinson (1988) reflect thinning to marginal intensity, there may be very good silvicultural reasons to thin more heavily and earlier than these thresholds dictate. Indeed, Rollinson (1988) points out certain positive silvicultural and economic aspects of thinning beyond marginal intensity, which will not only produce more rapid diameter increment on good quality PCTs, but it may also make early thinning interventions more profitable through increased thinning yields.

Strong common themes have emerged from recent research into broadleaf thinning. Particularly where the most vigorous, strong light demanding species are concerned, the strongest of these are easily described: "earlier and heavier", i.e. the indications are that these crops may benefit from earlier and heavier thinning than was previously reported. These common themes may therefore be considered, not only in relation to broadleaf thinning guidelines, but also as the basis for further local research trials.

Çicek et al. (2013) demonstrated how a relatively narrow range of treatments, which generally reflects the parameters of normal silvicultural practice, can generate long term results. When expressed in common management units (in this case basal area reduction), it can easily inform practical guidelines.

The literature suggests that top height, threshold BA and proportion of live crown should all be monitored until one or more factors indicate the optimum timing of first (and subsequent) thinning, bearing in mind early is better than late. Competitive status as described by Le Goff and Ottorini (1996) provides an indicative, discernable, formal and recordable description of live crown proportion (in relation to height). Its use is recommended in monitoring broadleaf stands with regard to the timing of thinning interventions. This is particularly true for species such as ash, cherry and birch where successful performance relies on maintaining good live crown proportions relies.

In thinning control, stocking reduction is perhaps the most straightforward means to control thinning operations on the ground, while quantitative PCT selection and appropriate competitor removals can be accurately judged by an experienced eye. Stocking reduction should also be monitored together with a more formal crop inventory descriptor, e.g. basal area.

Conclusions and recommendations

In general, the literature would appear to support the view that relatively high YC broadleaf plantations in Ireland may be thinned more heavily than current guidelines suggest. This is particularly true where the objective is to maximise PCT diameter increment. The upper limit for effective high intensity thinning remains unknown. The intensity regimes employed in international trials (Juodvalkis et al. 2005 and Çicek et al. 2013) were sufficiently broad to fully bracket the expected response to thinning. Future thinning intensity trials in Ireland need to be located primarily in larger, homogenous blocks of vigorous broadleaf plantation. This would facilitate the full replication of a broader range of treatments. Future trials must include significantly heavier thinnings than those included in current guidelines, up to the removal of the entire adjacent eight neighbours. This could be compared with conventional 2–3 competitor removal and begin to identify minimum stocking thresholds as described by Juodvalkis et al. (2005), i.e. the point of maximum acceleration of PCT volume increment.

The concept of maximising volume increment on potentially high value stems is desirable not only for purely economic reasons but may increase resilience to future invasive pests and diseases. For example, the imminent threat to ash woodlands in

Ireland from dieback (Castle 2014) caused by *Hymenoscyphus fraxineus* (Baral et al. 2014) may now present a situation whereby heavy thinning and the securing of crop trees in the shortest possible timeframe may have a range of benefits. From an economic perspective, the window of opportunity for securing a viable return on the investment in Ireland's first rotation ash woodlands may be shortening, wherein the objective of producing high value timber as quickly as possible may be desirable. Thinning in general has been shown to reduce the severity of ash dieback (Bakys et al. 2013). While the impacts of heavier thinning require further research; heavy selective and perhaps more systematic thinning may help to facilitate transitional management objectives such as a change of species via underplanting. It will provide the woodland with a more robust silvicultural and ecological structural composition, to mitigate the impacts of dieback outbreak (Short and Campion 2014). Selection and thinning to favour the most vigorous individuals can also promote the maintenance of the strongest possible genetic population and may assist in the development of resistance (McKinney et al. 2011). Further research on an extensive range of thinning (intensity) treatments in ash must be a short-term priority within Irish broadleaf silviculture and similar research in the longer term is required for other broadleaf species.

Acknowledgements

This work was carried out as part of the Broadleaf Silviculture Research and Development (B-SilvRD) project, a 5-year project funded by CoFoRD, Department of Agriculture, Food and the Marine.

References

Álvarez-González, J.G., Zingg, A. and Gadow, K.V. 2010. Estimating growth in beech forests: a study based on long term experiments in Switzerland. *Annals of Forest Science* 67 (3): p. 307.

Attocchi, G. 2015. Silviculture of Oak for high-quality wood production. Effects of thinning on crown size, volume growth and stem quality in even-aged stands of pedunculate oak (*Quercus robur* L.) in Northern Europe. Doctoral Thesis. *Swedish University of Agricultural Sciences*. Alnarp.

Bakys, R., Vasaitis, R. and Skovsgaard, J.P. 2013. Patterns and severity of crown dieback in young even-aged stands of European ash (*Fraxinus excelsior* L.) in relation to stand density, bud flushing phenotype, and season. *Plant Protection Science* 49: 120–126.

Baral, H.O., Queloz, V.K. and Hosoya, T.S. 2014. *Hymenoscyphus fraxineus*, the correct scientific name for the fungus causing ash dieback in Europe. *IMA Fungus* 5: 79–80.

Barrio Anta, M. and Álvarez González, J.G. 2005. Development of a stand density management diagram for even-aged pedunculate oak stands and its use in designing thinning schedules. *Forestry* 78: 209–216.

Beinhofer, B. 2010. Comparing the financial performance of traditionally managed beech and oak stands with roomy established and pruned stands. *Forest Research* 129: 175–187.

Bolton, Lord 1949. The growth and treatment of sycamore in England. *Quarterly Journal of Forestry* 43: 161–167.

Boncina, A., Kadunc, A. and Dusan, R. 2007. Effects of selective thinning on growth and development of beech (*Fagus sylvatica* L.) forest stands in south-eastern Slovenia. *Annals of Forest Science* 64: 47–57.

Brumme, R., and Khanna, P.K. 2009. *Functioning and Management of European Beech Ecosystems*. Berlin Heidelberg: Springer.

Cameron, A.D. 1996. Managing birch woodlands for the production of quality timber. *Forestry* 69: 357–371.

Castle, M. 2014. Modelling the spread of ash dieback. In *All Ireland* Chalara *Conference – Where do we go From Here?* Proceedings of a conference, held 8th May 2014, Dundalk, Co. Louth. p. 13.

Cescatti, A. and Piutti, E. 1998. Silvicultural alternatives, competition regime and sensitivity to climate in a European beech forest. *Forest Ecology and Management* 102: 213–223.

Çicek, E., Yilmaz, F., Özbayram, A.K., Efe, M., Yilmaz, M. and Usta, A. 2013. Effects of thinning intensity on the growth of narrow-leaved ash (*Fraxinus angustifolia* subsp. *oxycarpa*) plantations. *Turkish Journal of Agriculture and Forestry* 37: 97–104.

Claessens, H. 2004. Réflexions sur le détourage des feuillus à croissance rapide. *Forêt Wallonne* 71: 3–11.

Claessens, H. 2005. L'aulne glutineux. Ses stations et sa sylviculture. *ASBL Forêt Wallonne*.

Department of Agriculture Food and the Marine. 2011. *2010 Annual Report*. Forest Service, Dublin.

Department of Agriculture Food and the Marine. 2012. *2011 Annual Report*. Forest Service, Dublin.

Department of Agriculture Food and the Marine. 2013. *The Second National Forest Inventory, Republic of Ireland, Results*. Forest Service, Johnstown Castle Estate, Co. Wexford.

Department of Agriculture Food and the Marine. 2015. *Ireland's Forests – Annual Statistics*. Forest Service, Johnstown Castle Estate, Co. Wexford.

Department of Communications, Marine and Natural Resources. 2000. *Code of Best Forest Practice - Ireland*. Forest Service, Johnstown Castle Estate, Co. Wexford.

Dimov, L.D., Stelzer, E., Wharton, K., Meadows, J.S., Chambers, J.L., Ribbeck, K. and Moser, E.B. 2006. Effects of thinning intensity and crown class on cherrybark oak epicormic branching five years after treatment. In *Proceedings of the 13th*

Biennial Southern Silvicultural Research Conference. Gen. Tech. Rep. SRS–92. Ed. Connor, K.F., Asheville, NC, U.S. Department of Agriculture, Forest Service, Southern Research Station, p. 640.

Dobrowolska, D., Hein, S., Oosterbaan, A., Wagner, S., Clark, J. and Skovsgaard, J.P. 2011. A review of European ash (*Fraxinus excelsior* L.): implications for silviculture. *Forestry* 84: 133–148.

Duyck, D. 1997. Guide de sylviculture merisier en region Normande. Cited in Boulet-Gercourt, B. 1997. *Le Merisier. Les Guides du Sylviculteur.* IDF.

Edwards, P.N. and Christie, J.M. 1981. *Yield Models for Forest Management*. Forestry Commission Booklet 48, HMSO, London.

Evans, J. 1982. Silviculture of oak and beech in northern France: observations and current trends. *Quarterly Journal of Forestry* 76: 75–81.

Evans, J. 1984. *Silviculture of Broadleaved Woodland*. Forestry Commission Bulletin 62. HMSO, London.

Everard, J.E. 1985. *Management of Broadleaved Forests in Western Europe*. Report of a three-month study visit to France, and four other countries. Forestry Commission, Edinburgh.

Fällman, K., Ligne, D., Karlsson, A. and Albrektson, A. 2003. Stem quality and height development in a *Betula*-dominated stand seven years after precommercial thinning at different stump heights. *Scandinavian Journal of Forest Research* 18: 145–154.

Forestry Commission. 1955. *The Thinning of Plantations*. Forestry Commission Forest Operations Series No. 1. HMSO, London.

FRAXIGEN. 2005. *Ash species in Europe: biological characteristics and practical guidelines for sustainable use*. Oxford Forestry Institute, University of Oxford, UK. p. 128.

Government of Ireland. 2013. *The Second National Forest Inventory, Republic of Ireland, Results*. Forest Service: Johnstown Castle Estate, Co. Wexford.

Hallenbarter, D., Hasenauer, H. and Zingg, A. 2005. Validierung des Waldwachstumsmodells MOSES für Schweizer Wälder. *Schweizerische Zeitschrift für Forstwesen* 156: 149–156. Cited in Álvarez-González, J.G., Zingg, A. and Gadow, K.V. 2010. Estimating growth in beech forests: a study based on long term experiments in Switzerland. *Annals of Forest Science* 67: p. 307.

Hamilton, G.J. 1976. The Bowmont Norway spruce thinning experiment 1930–1974. *Forestry* 49: 109–19.

Hamilton, G.J. 1981 The effects of high intensity thinning on yield. *Forestry* 54: 1–15.

Hart, C. 1991 *Practical Forestry for the Agent and Surveyor*. 3rd ed. Sutton Publishing, Stroud.

Hawe, J. 2014. *Early Thinning of Ash*, Fraxinus excelsior *L., Plantations in Ireland –*

Thinning Intensity and Crop Tree Growth Responses. Masters Thesis. University College Dublin.

Hawe, J. and Short, I. 2012. Poor performance of broadleaf plantations and possible remedial silvicultural systems - a review. *Irish Forestry* 69: 126–147.

Hein, S., Collet, C., Ammer, C., Le Goff, N., Skovsgaard, J.P. and Savill, P. 2009a. A review of growth and stand dynamics of *Acer pseudoplatanus* L. in Europe: implications for silviculture. *Forestry* 82: 361–385.

Hein, S. and Spiecker, H. 2009. Controlling diameter growth of common ash, sycamore maple and wild cherry. *European Journal of Forest Research* 22: 123–147.

Hein, S., Winterhalter, D., Wilhelm, G.J. and Kohnle, U. 2009b. Timber production with silver birch (*Betula pendula* Roth): Chances and silvicultural constraints. *Allgemeine Forst Und Jagdzeitung* 180: 206–219.

Hemery, G.E., Savill, P.S. and Pryor, S.N. 2005. Applications of the crown diameter-stem diameter relationship for different species of broadleaved trees. *Forest Ecology and Management* 215: 285–294.

Hendrick, E. and Nevins, D. 2003. Foreword to *Managing Our Broadleaf Resource to Produce Quality Hardwood Timber*. Eds. Fennessy, J. and MacLennan, L., Proceedings of the COFORD seminar 10 – 11th October 2002, Carrick-on-Shannon. COFORD, Dublin.

Hiley, W.E. 1955. The thinning of plantations. *Irish Forestry* 12: 3–11.

Hill, M.O., Mountford, J.O., Roy, D.B. and Bunce, R.G.H. 1999. *Ellenberg's Indicator Values for British Plants. ECOFACT Volume 2 Technical Annex*. Huntingdon, Institute of Terrestrial Ecology, p. 46.

Hochbichler, E. 1993. Methods of oak silviculture in Austria. *Annals of Forest Science* 50: 583–591.

Horgan, T., Keane, M., McCarthy, R., Lally, M. and Thompson, D. 2003. *A Guide to Forest Tree Species Selection and Silviculture in Ireland*. Ed. O'Carroll, J., COFORD, Dublin.

Hummel, F.D. 1951. Increment of "free-grown" oak. *Report on Forest Research*, Forestry Commission, London, p. 65–66. Cited in Evans, J. 1982. Free growth and control of epicormics. In *Broadleaves in Britain*. Eds. Malcolm, D.C., Evans, J. and Edwards, P.N., Proceedings of a symposium, Loughborough, Leicestershire, 7 – 9th July 1982. The Institute of Chartered Foresters, pp. 183–190.

Hynynen, J. and Niemistö, P. 2009. *Silviculture of Silver Birch in Finland*. http://www.waldwissen.net/lernen/weltforstwirtschaft/fva_birke_waldbau_finnland/index_EN [Retrieved May 2015].

Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A., Hein, S. and Velling, P. 2009. Silviculture of birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.) in northern Europe. *Forestry* 83: 103–119.

Jobling, J. and Pearce, M.L. 1977. *Free Growth of Oak*. Forestry Commission Forest Record 113: 1–17.

Joyce, P., Huss. J., McCarthy, R., Pfeifer, A. and Hendrick, E. 1998. *Growing Broadleaves – Silvicultural Guidelines for Ash, Sycamore, Wild Cherry, Beech and Oak in Ireland*. COFORD, Dublin.

Juodvalkis, A.A., Kairiukstis, L. and Vasiliauskas, R. 2005. Effects of thinning on growth of six tree species in north-temperate forests of Lithuania. *European Journal of Forest Research* 124: 187–192.

Kerr, G. 1996. The effect of heavy or "free growth" thinning on oak (*Quercus petraea* and *Q. robur*). *Forestry* 69: 303–317.

Kerr, G. and Cahalan, C. 2004. A review of site factors affecting the early growth of ash (*Fraxinus excelsior* L.). *Forest Ecology and Management* 188: 225–234.

Kerr, G. and Evans, J. 1993. *Growing Broadleaves for Timber*. Forestry Commission Handbook 9. HMSO, London.

Le Goff, N. and Ottorini, J.M. 1996. Leaf development and stem growth of ash *(Fraxinus excelsior)* as affected by tree competitive status. *Journal of Applied Ecology* 33: 793-802.

Lemaire, J. 2010. *Le Chêne Autrement. Produire du Chêne de Qualité en Moins de 100 Ans en Futaie Régulière. Guide Technique*. Forêt Privée Françoise.

Liepiņš, K., Baumanis, I., Gailis, A. and Aļļis, J. 2011. *Management and Stand Dynamics of Birch Forests: a Reflection on Shifting Silvicultural Concepts in Latvia*. In Proceedings of the Fifth International Scientific Conference: Rural Development. 22–25th November, 2011. Aleksandras Stulginkis University, Kaunas, Lithuania, p. 69.

Lockhart, B.R., Michalek, A.J. and Lowe, M.W. 2006. *Epicormic Branching in Red Oak Crop Trees Five Years After Thinning and Fertilizer Application in a Bottomland Hardwood Stand*. In Proceedings of the 13th biennial southern silvicultural research conference. Ed. Connor, K.F. Gen. Tech. Rep. SRS–92. Asheville, NC, U.S. Department of Agriculture, Forest Service, Southern Research Station, p. 640.

Loewe, V.M., González, M.O. and Balzarini, M. 2013. Wild cherry tree (*Prunus avium* L.) growth in pure and mixed plantations in South America. *Forest Ecology and Management* 306: 31–41.

Lorrain-Smith, R. and Worrell, R. 1992. The commercial potential of birch in Scotland. *Scottish Forestry* 46: 48–55.

McKinney, L.V., Nielsen, L.R. Hansen, J.K. and Kjær, E.D. 2011. Presence of natural genetic resistance in *Fraxinus excelsior* (Oleraceae) to *Chalara fraxinea* (Ascomycota): an emerging infectious disease. *Heredity* 106: 788–797.

Mielikäinen, K., Hynynen, J., Niemistö, P., Viherä-Aarnio, A., Brunner, A. and Hein, S. 2007. *Ecology and Management of Silver Birch (*Betula pendula *Roth.)*. ValBro

– Growing Valuable Broadleaved Tree Species COST Action. Presentation given in Finland (10–14th June 2007).

Mitchell, K.J. 1975. Dynamics and simulated yield of Douglas-fir. *Forest Science* Monograph 17. Society of American Foresters.

Nagel, J. 1985. *Wachstumsmodell für Bergahorn in Schleswig-Holstein*. Dissertation. Universität Göttingen. Cited in Hein, S., Collet, C., Ammer, C., Le Goff, N., Skovsgaard, J.P. and Savill, P. 2009. A review of growth and stand dynamics of *Acer pseudoplatanus* L. in Europe: implications for silviculture. *Forestry* 82: 361–385.

Nieuwenhuis, M. and Barrett, F. 2002. The growth potential of downy birch (*Betula pubescens* (Ehrh.)) in Ireland. *Forestry* 75: 75–87.

Nisbet, J. 1893. *British Forestry Trees and their Sylvicultural Characteristics and Treatment*. Macmillan and Co., London.

O'Dowd, N. 2004. *The Improvement of Irish Birch. Phase 1: Selection of Individuals and Populations*. COFORD: Dublin.

Ottorini, J.-M. 1991. Growth and development of individual Douglas-fir in stands for applications to simulation in silviculture. *Annales des Sciences Forestieres* 48: 651–666.

Ottorini, J.M., Le Goff, N. and Cluzeau, C. 1996. Relationships between crown dimensions and stem development in *Fraxinus excelsior* L. *Canadian Journal of Forest Research* 26: 394–401.

Pakenham, R. 2005. *Growing Valuable Broadleaved Tree Species: Silvicultural Perspective*. ValBro – Growing Valuable Broadleaved Tree Species COST Action. Presentation given in Thessaloniki (18th - 21st May 2005).

Pautasso, M., Petter, F., Rortais, A. and Roy, A.S. 2015. Emerging risks to plant health: a European perspective. *CAB Reviews* 10.

Plauborg, K.U. 2004. Analysis of radial growth responses to changes in stand density for four tree species. *Forest Ecology and Management* 188: 65–75.

Poulain, G. 1991. Quelques examples de la sylviculture de l'aulne glutineux en Thiérache (Nord de l'Aisne). *Forêt Entreprise* 74: 26–28.

Pretzsch, H. 2005. Stand density and growth of Norway spruce (*Picea abies* (L.) Karst.) and European beech (*Fagus sylvatica* L.): evidence from long-term experimental plots. *European Journal of Forest Research* 124: 193–205.

Pryor, S.N. 1985. The silviculture of wild cherry or gean (*Prunus avium* L.). *Quarterly Journal of Forestry* 79: 95–109.

Pryor, S.N. 1988. *The Silviculture and Yield of Wild Cherry*. Forestry Commission Bulletin 75. HMSO, London.

Raulo, J. 1987. *Bojrkboken Oversatt av Fritz Bergman*. Skogsstyrelsen, Jonkoping. Cited in Cameron, A.D. 1996. Managing birch woodlands for the production of quality timber. *Forestry* 69: 357–371.

Renou, F., Scallan, Ú., Keane, M. and Farrell, E.P. 2007. Early performance of native birch (*Betula* spp.) planted on cutaway peatlands: influence of species, stock types and seedlings size. *European Journal of Forest Research* 126: 545–554.

Rollinson, T.J.D. 1988. *Thinning Control*. Forestry Commission Field Book 2. HMSO, London.

Rytter, L. and Werner, M. 1998. *Lönsam lövskog—Steg för steg* [Profitable broadleaved forests—Step by step]. Uppsala, Forestry Research Institute of Sweden (SkogForsk), Handledning. (In Swedish). Cited in Rytter, L. and Werner, M. 2007. Influence of early thinning in broadleaved stands on development of remaining stems. *Scandinavian Journal of Forest Research* 22: 198–210.

Rytter, L. and Werner, M. 2007. Influence of early thinning in broadleaved stands on development of remaining stems. *Scandinavian Journal of Forest Research* 22: 198–210.

Savill, P. 2003. *Growing Quality Broadleaves – the British Experience*. In Managing our broadleaf resource to produce quality hardwood timber. Eds. Fennessy, J. and MacLennan, L., Proceedings of the COFORD seminar 10–11th October 2002, Carrick-on-Shannon. COFORD, Dublin.

Savill, P.S. 2013. *The Silviculture of Trees Used in British Forestry*. CAB International, Wallingford.

Savill, P., Evans, J., Auclair, D. and Falck, J. 1997. *Plantation Silviculture in Europe*. Oxford University Press, Oxford.

Schröter, M., Härdtle, W. and von Oheimb, G. 2012. Crown plasticity and neighborhood interactions of European beech (*Fagus sylvatica* L.) in an old-growth forest. *European Journal of Forest Research* 131: 787–798.

Sevrin, É. 1997. *Les Chênes Sessile et Pédonculé*. Les Guides du Sylviculteur. Institut Pour Le Développement Forestier.

Shapland, R.E. 1966. Notes on the establishment and early thinnings in oak plantations. *Quarterly Journal of Forestry* 60: 55–57.

Short, I. and Campion, J. 2014. Management of ash in the light of chalara dieback. In *All Ireland* Chalara *Conference – Where do we go From Here?* Proceedings of a conference, held 8th May 2014, Dundalk, Co. Louth, p. 14.

Short, I. and Radford, T. 2008. *Silvicultural Guidelines for the Tending and Thinning of Broadleaves*. Teagasc.

Skovsgaard, J.P., Nordfjell, T. and Sørensen, I. H. 2006. Precommercial thinning of beech (*Fagus sylvatica* L.): Early effects of stump height on growth and natural pruning of potential crop trees. *Scandinavian Journal of Forest Research* 21: 380–387.

Sonderman, E.L. and Rast E.D. 1988. *Effect of Thinning on Mixed-Oak Stem Quality*. Res. Pap. NE-618. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, p. 6.

Spiecker, H. 1991. Zur Steuerung des Dickenwachstums und er Astreinigung von Trauben - und Stieleichen (*Quercus petrea* (Matt.) Liebl. und *Quercus robur* L.) [On the controlling of diameter growth and natural pruning of Sessile and Pedunculate Oak (*Quercus petrea* (Matt.) Liebl. and *Quercus robur* L.)]. Schriftenreihe der Landesforstverwaltung Baden-Wurttemberg 72. Stuttgart [original in German]. Cited in Hein, S. and Spiecker, H. 2009 Controlling diameter growth of common ash, sycamore maple and wild cherry. *European Forest Institute Research Report* 22: 123–147.

Štefančík, I. 2013. Development of target (crop) trees in beech (*Fagus sylvatica* L.) stand with delayed initial tending and managed by different thinning methods. *Journal of Forest Science* 56: 253–259.

Štefančík, I. 2015. The effect of different tending on stand structure and quantitative production of European beech (*Fagus sylvatica* L.) stand in a selected region of East Slovakia. *Journal of Forest Science* 61: 98–105.

Stern, R.C. 1989. Sycamore in Wessex. *Forestry* 62: 365–382.

Stevenson, G.F. 1985. *The Silviculture of Ash and Sycamore*. Proceedings of the National Hardwoods Programme. Commonwealth Forestry Institute, Oxford, pp. 25–31.

Stojecová, R. and Kupka, I. 2009. Growth of wild cherry (*Prunus avium* L.) in a mixture with other species in a demonstration forest. *Journal of Forest Science* 55: 264–269.

Teagasc. 2015. https://www.teagasc.ie/crops/forestry/research/broadleaf-silviculture-research-and-development/ [Accessed November 2016].

Vaast, V. and Billac, J.M. 1996. Quelle sylviculture pour l'aulne glutineux? *Forêt de France* 397: 22–27.

Van der Maaten, E. 2013. Thinning prolongs growth duration of European beech (*Fagus sylvatica* L.) across a valley in southwestern Germany. *Forest Ecology and Management* 306: 135–141.

Worrell, R. 1999. *The Birch Woodland Management Handbook*. Highland Birchwoods: Ross-shire.

Zālītis, T. and Zālītis, P. 2007. Growth of young stands of silver birch (*Betula pendula* Roth) depending on pre-commercial thinning intensity. *Baltic Forestry* 13: 61–67.

Zeide, B. 2006. Evolution of silvicultural thinning: from rejection to transcendence. In *Proceedings of the 13th Biennial Southern Silvicultural Research Conference*. *General Technical Report SRS-92*. Ed. Connor, K.F., Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station, pp. 322–327.