Ash dieback in Ireland
A review of European management options and case studies in remedial silviculture

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Abstract

Ash dieback, caused by *Hymenoscyphus fraxineus*, is developing rapidly across the island of Ireland. Ireland's ash (*Fraxinus excelsior* L.) woodlands, particularly first rotation plantations, are quite unique and are at particular risk of very rapid decline. Urgent action is required in order to minimise the economic, ecological and social impact of the disease. However, for this to happen forest owners require guidance regarding potential positive management interventions. This article outlines the wider, mainly European, experience of remedial silviculture. It presents three case studies on existing remedial silviculture trials in Ireland. In the absence of silvicultural research data specific to the evolving situation with ash dieback, this article explores the potential benefits of positive practical actions which may minimise the impact of the disease. Despite the seriousness of the situation, such silvicultural activity may even result in a positive economic outcome. It is hoped that by beginning to document potential mitigatory management options, this paper may bring some reassurance to owners and managers of ash-dominated woodlands.

Keywords: *Fraxinus excelsior*, *Hymenoscyphus fraxineus*, underplanting, management guidelines, stand restructuring, mitigation.

Ash woodland in Ireland

According to the 2017 National Forest Inventory (DAFM 2018c), ash accounts for 25,280 ha or 3.8% of the total forest estate in the Republic of Ireland. Approximately 60% of this area is under 30 years of age (DAFM 2018c) as much of it was established with state aid under the Afforestation Programme. Since the early nineties broadleaved planting has increased dramatically and ash has been the single most prevalent species (DAFM 2018a). The most recent national forest inventory reports that 17,000 ha have been afforested with ash since 1990 (DAFM 2018a). The vast majority of this new plantation resource has been established in single species blocks. Its monocultural composition, relatively young age and possible sub-optimal site selection, puts the ash plantation resource in Ireland in a "high risk" category (Alsop and Goldberg 2018)

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with regard to the severity of the impact from ash dieback. This fungal disease is caused by *Hymenoscyphus fraxineus* (T. Kowal) (Baral and Bemmann 2014).

The reasons for the upsurge in the popularity of ash planting may have been a perception that it is a relatively vigorous species and easy to grow, it attracted a higher premium than conifer species and/or commanded a high sale value in the lucrative hurley market. In today's terms, the equivalent establishment costs for an area of 17,000 ha of ash would exceed €60 million and represent €123 million in premium payments to landowners over a twenty-year period (O'Leary 2013). State investment in this resource is ongoing through the Forest Improvement Scheme (FIS). Of a total area of 5,429 ha funded for first thinning under the FIS (2009-16), ash has been by far the most widely funded species at over 3,300 ha in this scheme (DAFM 2018a). In March 2013 DAFM introduced a Reconstitution Scheme (Chalara Ash Dieback) to restore forests planted under the afforestation scheme which had suffered from or were associated with plants affected by disease. By July 2017, approximately €3.4 million had been paid out under the Scheme and over 967 ha of infected and associated ash plantations have been cleared (DAFM 2018b). Were an eradication policy to continue, based solely on the Reconstitution Scheme, we can make the very general extrapolation that the total cost of establishing and subsequently removing the ash plantation resource in Ireland would likely exceed a quarter of a billion euro. This scenario however, is highly unlikely given that the complete removal of all infected stands is in no way in keeping with accepted guidelines (see following sections) and the subsequent section of this article outlines the changing policy responses to the development of the disease.

Ash is one of the most important native tree species in Ireland. Woodlands dominated by ash have a rich shrub and herb flora as a result of their relatively open canopy and are the most species-rich of all Irish woodland types in terms of numbers of associated vascular plants (Cahalane 2013, Cross 2013). The 2003-2008 *National Survey of Native Woodlands in Ireland* shows ash was the second most common maturing tree (DBH ≥7 cm) surveyed or 18.5% of the total, after downy birch, *Betula pubescens* Ehrh. at just over 21% (Perrin et al. 2008). Ash was also considerably the most abundant naturally regenerating native tree (DBH <7 cm), at 69% of the total regeneration recorded (Perrin et al. 2008) and therefore plays a fundamental role in the perpetuation of the national native woodland resource. It is probably the most widespread tree, occurring in almost every 10 km grid square (NBDC 2018) and has been recorded in 91% of native woodlands (Perrin et al. 2008). Ash forms the canopy in about 30% of Ireland's native woodlands. At a European level, ash-dominated woodlands have a highly restricted distribution. They are situated primarily in Ireland and Britain with outliers in Northern Spain/SW France and locally on the coast of Norway. They are therefore extremely important in a European context (Cahalane 2013, Cross 2013).

In addition to the national forest area of 770,020 ha (DAFM 2018c), a further 482,000 ha of hedges, trees and scrub were identified by Green (2011) in a hedgerow mapping project, where ash was the most common tree species at c. 50% occurrence (O'Leary 2013). Clearly ash is a critical feature in this substantial element of the natural landscape.

Ash also plays a central role in Irish culture, most notably in its specialist use within Gaelic games such as hurling and camogie (O'Leary 2013). Approximately 350,000 hurleys are manufactured in Ireland each year (O'Riordan 2012), the preferred material being Irish-grown ash due to its strong, flexible and good shock absorbency properties (Culleton 2006). While the Gaelic Athletic Association (GAA) had planned to be self-sufficient in hurley ash production by 2017 (O'Riordan 2012), the imminent threat from ash dieback not only renders this a virtual impossibility, it threatens both the cultural and technical integrity of Gaelic games, and the livelihood of the indigenous wood processing industry which supports this national sporting sector.

Considering the state investment and promotion of ash as our principal commercial hardwood species, the relatively young age and monocultural composition of the plantation resource, and the species' core function within our native woodland ecology, ash dieback has the potential to be most devastating forest pathogen ever seen on the island of Ireland.

The development of ash dieback in Ireland and policy resources

The first confirmed finding of the disease in Ireland was made on the 12th of October 2012 at an afforestation site in Co. Leitrim which had been planted in 2009 with trees imported from continental Europe (DAFM 2018b). This batch of plants was traced to 11 sites in total and the entire batch was destroyed by burning. Since the first finding, Department staff have carried out surveys focussed initially on young ash plantations and adjacent hedgerows. Surveys were also extended to non-forestry sites such as roadside plantings, Agri-Environment Options Scheme (AEOS) farm plantings, horticultural nurseries, garden centres, etc. Two hedgerows adjacent to young ash plantations were found to be infected in 2013 and eradication measures were carried out (Cahalane 2013). Ash dieback has followed a similar path in Northern Ireland (NI). The first finding was in mid-November 2012 in a forestry plantation established with imported stock (Finlay 2014). By the end of December 2016 there were a total of 176 premises with recently planted ash confirmed as infected in NI (DAERA 2018).

Authorities north and south of the border work together under the auspices of the North South Ministerial Council, which resulted in the publication of the *All-Ireland Chalara Control Strategy* in July 2013. The first objective of this strategy was to "reduce the risk of the disease becoming established in the wider environment" and until April 2017, this involved the eradication of all confirmed infected material.

However, more recent surveys have tended to focus on the wider environment and the increasing number of infections therein. South of the border, 17 counties had hedgerow infections by 31st July 2017 (DAFM 2018b). In NI, wider environment cases were found in a total of 31 10-km grid squares (as of 3rd November 2017) (DAERA 2018). This represents an increase of almost 100% compared to the 2016 data.

While an eradication policy may have slowed the rate of infection, both authorities (DAFM (ROI) and DAERA (NI)) are currently reviewing their policies about mandatory eradication and are focussing more on the management of infected stands.

The ash dieback policy review by DAFM, relating to the predominately young, plantation-based resource, has resulted in a categorisation relating primarily to top height, and sets out broad management options, and grant-aided funding mechanisms for each category. This has been a change to a more management-based approach, where pole stage stands, particularly those with a good proportion of healthy trees, receive a thinning grant in order to remove infected trees and favour healthy, vigorous individuals, particularly those of good form, which may be grown on in order to add value and maintain the woodland ecosystem.

In late 2017/early 2018, DAERA held a public consultation on a proposal to "discontinue the issuing of Statutory Notices requiring the destruction of ash trees affected by ash dieback" in favour of "managing" the disease. In keeping with an all-Ireland strategy, this also represents a fundamental move from eradication towards a management approach by DAERA. The following section considers such management approaches in continental Europe and Great Britain, where eradication measures have been largely ineffective against the windborne pathogen.

Remedial silviculture – research and management guidelines from Great Britain and continental Europe

Clearly the ash-dominated woodland resource in Ireland varies greatly in age, structural complexity, overall species diversity, commercial and ecological value, and therefore any pre-emptive or remedial silvicultural treatments designed to alleviate the threat from ash dieback are also likely to vary quite considerably according to individual stand conditions and management objectives.

Silviculture must act based on how the disease has developed for ash stands of variable genetic origin, under different site conditions, in different forest types, and for a range of observed treatment practices. Based on the circumstances, silvicultural practices should be modified and targeted to alleviate the immediate consequences of ash dieback, but also to ensure the retention of potentially disease resistant ash in the long term. Any remedial silvicultural strategy should depend on the original management objectives, site conditions, stand type, age and the level of infection (Skovsgaard et al. 2017).

In their management guidelines in relation to ash dieback, the Forestry Commission (FC) (2018a) set out some useful common principles, which may be considered in all management scenarios. These principles are:

- maintaining the values and benefits associated with ash woodlands and iconic trees;
- securing an economic return where timber production is an important objective;
- reducing the presence and rate of spread of Chalara dieback;
- maintaining as much genetic diversity in ash trees as possible with the aim of ensuring the presence of ash in the long term; and
- minimising impacts on associated species and wider biodiversity.

The most recent FC guidelines (updated September 2018) no longer include the third point above and indicate that there is no way to remove the risk of infection if spores are present. However, hygiene felling is still a fundamental element of positive management, particularly in relation to health and safety. "Managing the health and safety risk from dead and dying trees" now forms one of the five common principles (Forestry Commission 2018b). The determination of the impact of hygiene felling on in-stand spore loading and the rate of reinfection/residual stand longevity is likely to require further research.

Management interventions intended to mitigate the impact of ash dieback depend heavily on the age and composition of the stand, the stage of the infection and the overall objectives for the woodland. Various UK and European guidelines on the management of threatened stands reflect these variables. Alsop (2014) distinguishes simply between the management of stands prior to infection and the management of infected stands. Thomsen and Skovsgaard (2012) discuss silvicultural strategies for a series of categories: young stands with a high percentage of healthy trees; severely infected young stands; and older stands. Forestry Commission guidelines on *"Chalara dieback - Managing ash trees and woodland"* (Forestry Commission 2018a) make recommendations for younger stands (up to pole stage), depending on the proportion of ash in the stand, and for older stands. Numerous other publications discuss overall species composition and specific management objectives (Broome et al. 2014, Mitchell et al. 2014, Bladon et al. 2016, Mitchell et al. 2016, Reid et al. 2016). All of these variables are, and will become, increasingly relevant to the management of ash-dominated woodlands in Ireland and are discussed in the following sections. Silvicultural treatments do however, have strong common themes across the range of stand types, disease stage and management objectives. These tend to incorporate:

- thinning, both to secure a cohort of healthy, vigorous ash trees within the stand, and to promote species diversity; and
- the promotion of mixed species stands through restructuring (adapted thinning) followed by underplanting and/or the recruitment of mixed species through natural regeneration.

Thinning in younger stands

Skovsgaard et al. (2009) recommended that phytosanitary prescriptions for silviculture should primarily be targeted towards young stands as these represent the most critical phases of stand development and which are most vulnerable to the disease. Particularly in the relatively young (pole stage), pure, even-aged as well as the still largely uninfected ash stands which form a large part of the ash-dominated woodland resource in Ireland, timely and appropriate thinning is critical to ensure the general health and vigour of the stand (Hawe and Short 2016). This being the case, a number of publications deal with the thinning of these young stands in order to mitigate the effects of the disease. Bakys et al. (2013) outline the effects of four statistically designed thinning experiments in 12- to 15-year-old ash plantations in Denmark, with four contrasting residual stand densities: (1) 1,700–5,500 trees ha^{-1} (unthinned control plots); (2) 1,500 trees ha^{-1}; (3) 500 trees ha^{-1}; and (4) 100–150 trees ha^{-1}. Disease severity was worst in the unthinned control plots, but otherwise was unrelated to stand density. They suggested that the high degree of competition in the unthinned plots and subsequent loss of form and vigour positively contributed to the severity of the disease development. Very heavy thinning, such as that in scenarios (3) with 500 trees ha^{-1}, and (4) with 100–150 trees ha^{-1} residual stand density, is generally not recommended. With specific reference to thinning intensity, Ahlberg (2014) recommends thinnings of intermediate intensity (to around 1,500 trees ha^{-1} residual density) in stands with a good proportion of healthy trees. This should benefit both wood production and conservation objectives whereby the growth of the potential crop trees (PCTs) is maximised and a good population spread remains from which resistant individuals could be identified. Very heavy thinnings (<500 trees ha^{-1}) are likely to be deleterious both to stand vigour and genetic diversity (Ahlberg 2014, Reid et al. 2015). Alsop (2014) promotes thinning in stands, particularly prior to infection, but warns against heavy thinning, particularly in infected stands. In young stands with a high proportion of healthy trees, Thomsen and Skovsgaard (2012) recommend marking at least 200 healthy trees ha^{-1} during the growing season and thinning among the unmarked trees. The joint advice from Natural England and the Forestry Commission (2015) under headings such as "What can we do about Chalara ash dieback (*Hymenoscyphus fraxineus*) on woodland SSSIs[1]?", states:

> Retaining as much ash as possible is important to ensure protection of any tolerant/resistant ash in the stand. However, thinning or harvesting mature ash as part of a normal programme of silvicultural management of the wood could continue. In uninfected sites where thinning operations are required we suggest ash trees with the biggest crowns and/or those which

[1] A Site of Special Scientific Interest (SSSI) is a formal conservation designation in the UK for an area which is of particular interest because of its fauna, flora or geological or physiological features.

are prime (biggest and healthiest) amongst their cohorts are retained. Once stands become infected, such trees in addition to all specimens showing the highest levels of disease tolerance, should be retained and promoted as these will have the best chance of survival and reproduction.

Skovsgaard et al. (2017) support the above recommendations regarding the retention of trees with the largest crowns. They state that ash dieback is less severe in trees with large crowns and therefore the disease takes longer to dominate these trees. Furthermore large-crowned trees will have a higher growth rate and increase their commercial value more quickly and will produce more seed, which may promote resistance if the parent is somewhat tolerant of the disease. On dying, large-crowned trees will also leave larger canopy gaps for stand regeneration.

In a recent study by the Wessex Silvicultural Group on *The Silviculture of Resilience,* Bladon et al. (2016) make a number of management recommendations in relation to combating the effects of ash dieback:

- maintain open stands to reduce spore loads and decrease humidity;
- develop an understorey which may help reduce re-infection;
- grow trees quickly – more vigorous trees appear less susceptible to infection;
- diversify – establish and maintain mixed stands;
- do not fell trees pre-emptively – pre- or early-stage infection; and
- avoid very heavy thinning/clearfelling.

In support of the above, sites with high air and/or soil humidity are reported to lead to increased spore production from the *H. fraxineus* fungus (Reid et al. 2015, Dvorak et al. 2016, Marçais et al. 2016). A well-developed understorey may also slow the rate of re-infection by acting as a physical barrier to spore movement from the litter toward the canopy (Skovsgaard 2013, Reid et al. 2015, Bladon et al. 2016). In the recruitment of natural regeneration, securing a greater range of tree and shrub species, and structural diversity, the control of deer and other mammal damage is critical (Reid et al. 2015).

The joint Natural England/FC publication (2015) and Reid et al. (2016) make some further recommendations on thinning:

- Keep as much of the current population of ash trees as possible to help to maintain a diverse genetic resource. Thin dense stands of ash to enable the more tolerant trees to seed and provide space for the seedlings to grow. Each time the tree produces seed they will be of a different genetic make-up to their parent trees. This "genetic turnover" provides an opportunity each year for more tolerant ash to develop.
- Thin tightly packed younger stands, because trees with larger crowns tend to survive best. Note that very heavy thinning and salvage operations to remove dying trees have been shown to accelerate the disease.

In synthesising the above two points and the aforementioned observations in relation to thinning, particularly for young stands with a good proportion of healthy trees, the general recommendation is to carry out a relatively conventional thinning in order to maintain the health and vigour of a selected cohort of trees, grow them is quickly as possible and promote resistance. This approach is highly suitable for pole-stage ash plantations in Ireland since in general they meet the age, stand density and health criteria outlined above, making thinning a viable mitigation treatment.

In relation to timber crops, the Forestry Commission (2018a) state:

> For uninfected stands, the best way to slow the impact of any future Chalara infection is to promote fast, healthy growth of selected trees. This will not prevent the onset of the disease if spores are present but will maximise the timber value at the time of felling.

Thinning guidelines are already available for managing the recently established Irish ash plantation resource (Short and Radford 2008). These are generally a combination of rack and selection thinning, designed to provide permanent access to the woodland and, fundamentally, to promote the rapid growth of selected trees. In first thinning, approximately 300 PCTs per ha^{-1} are marked and favoured via the removal of 2-3 main competitors. Guidelines on ash first thinning generally recommend c. 50% stocking reduction (Hawe and Short 2016). PCTs are best marked during, or just after, leaf flushing as early flushing trees have higher resistance to the disease (Skovsgaard 2013). These large, vigorous trees will form the basis of any future timber production, gene conservation and/or other ecological objectives (Skovsgaard 2013, Bladon et al. 2016).

As important as thinning are the potential risks of not thinning. Young, pure, unthinned stands represent a very high-risk category (Skovsgaard et al. 2010, Schumacher 2011, Bakys et al. 2013, Havrdová et al. 2017, Marçais et al. 2017, Alsop and Goldberg 2018, Forestry Commission 2018b), particularly in a high humidity environment and where they may already be under some stress due to sub-optimum site conditions. Indeed, continental European experience would suggest that total stand collapse due to *H. fraxineus* is only associated with dense, pole stage stands, a result of high spore loads and small crowns (Bladon et al. 2016). Furthermore, ash responds poorly to late thinning so timely interventions are critical to stand health and vigour (Hawe and Short 2016). The risks associated with a lack of management are clear for Ireland's most widely planted broadleaf tree. Studies have shown that Irish ash plantations in particular have the ability to respond very well to timely and appropriate thinnings, demonstrating higher than anticipated growth rates within selected PCTs (e.g. Hawe and Short 2016). Case Study 1 in the following section demonstrates how selection thinning may be employed/modified to achieve accelerated PCT increment and strong crown development and, if applied in a timely and appropriate manner, can therefore be a positive action to minimise the impacts of ash dieback.

Thinning in older stands

The Forestry Commission (2018b) recommend that an individual-tree approach is employed for older stands with infected trees. Felling should be considered for trees where >50% of the crown is infected and where survival of the tree depends on epicormic shoots. Where <50% of the crown is infected, regular monitoring should be conducted. Felling should also be considered if timber production is an objective when *Armillaria* (honey fungus) is present on a site as this is often the ultimate cause of death for trees infected by ash dieback. Thomsen and Skovsgaard (2012) also make recommendations regarding the thinning of older stands, cognisant of crown health and presence of *Armillaria*:

- inspect stands for ash dieback during the growing season and in winter;
- all trees with epicormic shoots on the stem should be felled as soon as possible, as infection of such shoots may cause stem wood discolouration;
- where most of the primary crown is dead and survival is based on epicormic shoots in the crown, trees should be harvested within the next year;
- where more than 50% of the primary crown is dead trees should be considered for harvest; and
- when more than 75% of the primary crown is intact trees may be considered healthy enough to keep for several years, unless there are signs of honey fungus attack at the base of the trees.

Thinning to promote species diversity

The best strategy to increase the resilience of a woodland to ash dieback is to increase its genetic and age diversity (Forestry Commission 2018a), including planting alternative species and provenances (Weir 2017). Where practicable, this may be done by adopting a continuous cover forestry approach, leading to a mixed-species stand with less vulnerability to disease. Silvicultural recommendations generally favour admixtures with several species (Skovsgaard et al. 2017, Enderle et al. 2017), particularly in stands with extensive attacks. Even in stands where one additional species is present, this can form the basis for securing ecological continuity by thinning to favour this species. Non-ash species should be afforded growing space via crown thinning, which may in turn increase the regeneration potential of the additional species (Reid et al. 2016). In ash-dominated stands with suitable understorey species present, these species should be favoured to give them the potential to assume canopy positions, maintain woodland conditions and ultimately regenerate (Alsop 2014, Pliūra 2017). Management interventions to increase species and structural diversity will vary depending on the amount of ash in the stand. Table 1 outlines potential management responses to varying percentages of ash in high forest SSSI woodlands in the UK. While such information is aimed at high nature conservation value woodlands, there

may be considerable symbiosis between prescriptions intended to develop ecological resilience and those which may promote economic resilience (current and future timber value).

In younger timber crops where there is a mixture of species, and there are enough trees of other species to form a closed stand within 10 years, it is likely that management objectives can still be achieved without replanting as the ash is phased out. If the stand is mixed, but there are not enough trees of other species to form a closed stand within 10 years, it is likely that the mixture will have to be supplemented via the planting of alternative species (Forestry Commission 2018b).

If the ultimate aim is to increase species diversity and stand resilience, through admixing (underplanting), then conventional thinning within a relatively healthy stand is unlikely to provide sufficient light in which to grow the admixed species. A timely, conventional 50% stocking reduction equates to a 0% canopy reduction in a relatively healthy stand, i.e. the woodland canopy will respond to the thinning and close again (most likely within five years) and so will not afford sufficient space for restructuring/underplanting. Even beech (*Fagus sylvatica* L.), the most shade tolerant naturalised broadleaf, would be unlikely to thrive following a conventional first thinning, much less any light demanding native broadleaf species such as oak (*Quercus* spp.). Underplanting is therefore likely to require an additional adapted thinning, which involves further removals in order to create planting space. This would be particularly true in healthy stands (when applied as a pre-emptive action) or in stands with a relatively high proportion of healthy trees. Case Studies 2 and 3 outline adapted

Table 1: *Potential management responses to varying proportions of ash in high forest SSSI woodlands in the UK. These allow for different responses to suit varying amounts of ash on a site. If only part of a site is suitable for ash, this applies to the part where ash is growing (or has potential to grow). For any specific site, more than one of these scenarios might apply.*

Proportion of ash			
<30% ash	**30-70% ash**	**>70% ash**	**>90% ash**
Leave the ash: survival important. Promote regeneration. Thin if needed to promote crown development and space for regeneration.	Diversify age structure and open up stands around minor species to promote their regeneration and that of "prime" as well as any tolerant ash.	Avoid drastic changes in forest conditions. Diversify age structure and promote minor component tree species. Retain at least 50% of ash. Encourage natural regeneration/underplanting of appropriate alternative species.	Avoid drastic changes in forest conditions. Re-structure stand if needed to promote crown development in "prime" ash; and encourage space for ash regeneration. Under-plant ash with appropriate species as the ash canopy thins.

Source: Reid et al. 2015, Reid et al. 2016.

thinning treatments intended to facilitate underplanting. As infections progress, increased mortality may lead to a loss of control over stand density (Skovsgaard et al. 2017). However, this may also afford the opportunity to take advantage of canopy gaps for the purpose of underplanting.

Underplanting coupe size, related canopy cover and light availability are central to the success of admixing. While some guidelines exist with regard to underplanting coupe size in broadleaf woodlands (Harmer et al. 2010), it is difficult to apply these across a very wide range of woodland, stand and block sizes, with different ages, structures, heights, etc. and for a potentially wide range of different underplanted species (mixtures). Specifically, even the smallest recommended coupe sizes (0.07 ha) may be inappropriate to small woods or stands, and smaller coupes (<0.07 ha) need to be assessed for their impact on the performance of underplanted species, both in the short term and in relation to the intensity of management required to ensure strong growth over the medium to long term. Underplanting coupe size is explored further in Case Study 3.

Thinning to promote species diversity should integrate the best practice of mitigatory thinning (minimising the impact of ash dieback as outlined above), together with utilising and/or creating opportunities to promote additional species within the stand, which will most likely require an adapted thinning treatment. This however, is an area that requires further research.

In Figure 1, Wilson (2014) encapsulates the range of management tools described in this section, which are fundamental to the development of resilient and structurally diverse stands of mixed species. This includes the need to adapt conventional thinning treatments in order to favour and integrate a wider range of species.

Admixing to promote species diversity

Since Hartig (1882) stated, the "best prophylactic measure against the occurrence and spread of epidemics is the cultivation of mixed forest crops", many studies have suggested that mixed stands afford a greater degree of resilience by mitigating pest and disease threats (Kelty 2006). Pautasso et al. (2005) demonstrated that there is a strong inverse relationship between tree species diversity and susceptibility to fungal pathogens and proposed that mixed-species ecosystems have a better ability to buffer disturbances in general.

Skovsgaard et al. (2017) state that for pure stands of ash, additional tree species should be introduced, and if the number and health of trees remaining allows for the maintenance of overhead shelter, then this may help ensure a gradual transition to the next generation of forest. For pure ash crops to all but the most mixed stands, some additional species and structural diversity can only benefit ecological and economic resilience. Not only has a lower re-infection rate of ash dieback been observed in

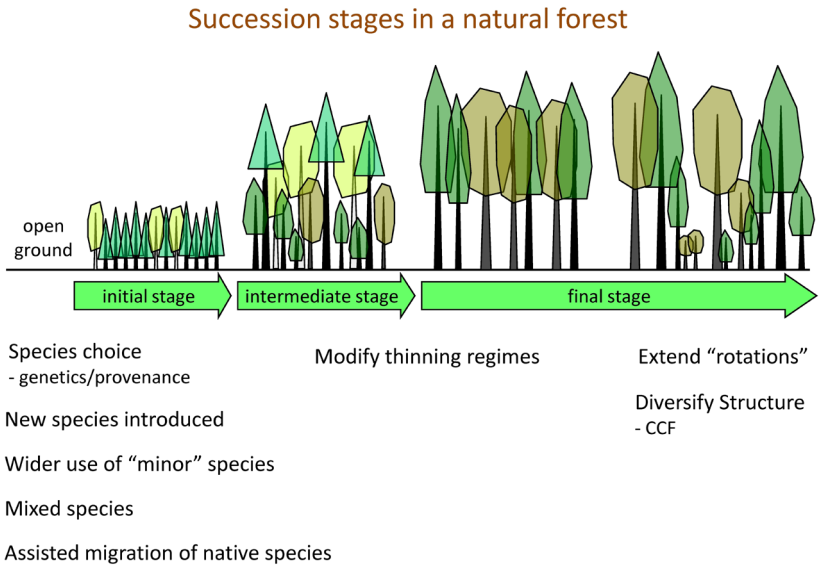

Figure 1: *Strategies for enhancing resilience (Wilson 2014). Diagram credit: Jens Haufe.*

mixed/multi-layered stands (Skovsgaard 2013), but more recent research suggests a higher likelihood of trees in mixed stands developing resistance (Pušpure et al. 2016).

Adapted thinning/coupe felling systems may be implemented to facilitate underplanting; thereafter a range of considerations must be given to the provenance and species selection of the admixture. Their choice should reflect a sound silvicultural understanding of the site's conditions and associated tree silvics (Harmer et al. 2010, Alsop 2014), and the availability of improved planting stock. Species options depend on site conditions, management objectives and site status/conservation designations (Forestry Commission 2018b). In timber stands admix species options may be quite extensive (depending on site constraints) – from similar native or naturalised broadleaf species such as oak (*Quercus robur* L. / *Q. petraea* (Matt.) Liebl.), beech or sycamore (*Acer pseudoplatanus* L.), to more adventurous choices such as walnut (*Juglans regia* L.) or hickory (*Carya* (Nutt.). spp.), to Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (Skovsgaard 2013). Beech may be a very useful admix species in that its shade tolerance will require the lowest level of restructuring. Underplanted species may also benefit from the shelter and nursing effect of the original stand, even if it is highly degraded from infection (Thomsen and Skovsgaard 2012) and even if the remaining ash trees are young (Skovsgaard et al. 2017). The potential silvicultural benefits (to stem quality) of growing broadleaved species in an uneven-aged woodland, as opposed to a greenfield environment, may represent one of the very few positive outcomes related to ash dieback.

In high conservation value woodlands, the admixture should utilise appropriate locally native species (Reid et al. 2016). In this case a range of factors should be considered:

- the species should be well suited to local growing (soil) conditions;
- they should reflect the species composition of the adjacent semi-natural woodland (Reid et al. 2016);
- ash supports a very wide range of associated bird, bryophyte, fungi, invertebrate, lichen, mammal and vascular plant species – 955 in total in UK woodlands (Mitchell et al. 2014). The underplanted species should have a high potential to support species associated with ash; and
- they should fulfil similar ecosystem functions as ash, such as nutrient cycling, carbon storage, decomposition, shading, productivity, water cycling, life-span and successional stage (Mitchell et al. 2016).

Mitchell et al. (2014, 2016) have carried out extensive work both in relation to alternative species which replicate the ecosystem functionality of ash and those which have the capacity to support the greatest number of ash-associated species in the UK. For instance, oak supports the greatest number of ash-associated species – 69% of all species (Mitchell et al. 2014). A mixture of oak and beech would support 74% of ash-associated species. A mixture of 11 tree species could support 84% of ash-associated species but adding further species did not increase this percentage (Mitchell et al. 2014). A "top three" would include oak, beech and sycamore (Mitchell et al. 2016). A "top four natives" in Ireland would include oak (*Quercus robur/petraea*), elm (*Ulmus procera* Salisb./*U. glabra* Huds.), hazel (*Corylus avellana* L.) and birch (*Betula pendula* Roth. /*B. pubescens*) (Broome et al. 2014).

Unfortunately, there is not necessarily a strong overlap between ecosystem functionality and species association. For example, ash litter is more easily degradable than that of oak or beech, which are ranked as very different to ash in terms of ecosystem function due to their recalcitrant and low-nutrient litter (Mitchell et al. 2016). Alternatively, sycamore, common alder (*Alnus glutinosa* (L.) Gaertn.) and field maple (*Acer campestre* L.) are ranked as good alternatives to ash with regard to ecosystem function.

Ultimately, the points above need to be considered together when prescribing an admixture specification within conservation sites. Added to this may be the very specific host needs of ash-obligate species (Broome et al. 2016). In view of the findings of Mitchell et al. (2014, 2016), consideration must be given to the extended use of "future natives" such as beech and sycamore (Kirby et al. 2016). However, the inappropriate use of untested non-natives may lead to an increase, rather than a decrease, in pest and disease problems, and may negatively impact our native woodlands and their associated biodiversity (Ennos et al. 2019).

In summarising the findings of Mitchell et al. (2014, 2016), Reid et al. (2016) make some further useful practical recommendations regarding replacement species in high conservation value sites:

- Identify useful species using the database produced by Mitchell et al. (2014) which lists wildlife species associated with ash, together with potential surrogate tree and shrub species.
- Promote other native trees associated with a site using the appropriate national vegetation classification community as a guide[2].
- Where appropriate, include other main canopy species like oak and beech, and make use of any less frequent species such as birch, rowan (*Sorbus aucuparia* L.), whitebeam (*Sorbus aria* Crantz.), aspen (*Populus tremula* L.), willow (*Salix* spp.), alder, lime (*Tilia* spp.), yew (*Taxus baccata* L.), holly (*Ilex aquifolium* L.), field maple, hazel, wych elm (*Ulmus glabra* Huds.), and cherry (*Prunus avium* L.).

Reid et al. (2016) also consider the use of sycamore in SSSIs, as a naturalised species, due to the similarity of ecosystem functionality and species associations to ash. Based on a series of 15 woodland management site studies, Broome et al. (2016) suggest that a radical change in practice will not be required to conserve ash-associated species in UK broadleaved woodlands containing ash. Generally, the recommendations emphasise good silvicultural practice, continuation of woodland cover, and adjustment of species structure. To achieve the necessary changes in species abundance and mixture, modification of current management regimes at most sites will be required and involve such practices as thinning, prevention of browsing damage and establishing trees by planting in conjunction with robust vegetation control. This could be to the case for sustainable, multi-functional management of all ash-dominated woodlands in the UK and Ireland.

Retention of tolerant trees

The retention of potentially tolerant trees is a common recommendation throughout affected Europe. Kirisits and Freinschlag (2014) provide some guidance for Austrian forest owners. Reafforestation with ash is discouraged and a change to other tree species or a mixed forest with relatively low ash stocking is aimed for in the management of natural regeneration. In young stands, affected ash is preferentially removed or preserved as dead wood whilst healthy and weakly diseased vigorous ash grown together with mixed species, are encouraged and development of a stand is to favour the mixed tree species. Severely damaged mature trees (70 to 80% of the crown dead) and freshly dead ash should be harvested quickly, and the wood

[2] In the case of Ireland, *The Classification of Native Woodlands in Ireland and its Application to Native Woodland Management* (Cross et al. 2010) should be used.

marketed. It is estimated that approximately 1-5% of ash has a high level of resistance. For this reason, it is important to maintain and promote healthy and lightly diseased trees in heavily affected populations in all phases of crop management to encourage regeneration with resistant individuals. Ash should be selected during the growing season, by the end of July – mid August, as the extent of dieback is less reliably assessed after premature leaf fall, and permanently marked to prevent them being felled. Hauptman et al. (2016) also focus on the selection and retention of resistant trees, in their case *F. angustifolia* Vahl., and silvicultural measures employed to promote these trees. Sanitary fellings of severely damaged ash trees must necessarily be timely to prevent deterioration of wood quality. Resistant trees should serve as a source of breeding material to facilitate seed production in seed orchards to produce potentially resistant saplings. Budde et al. (2016) also highlight the need to maintain trees so that resistant individuals can be identified. A common forest management tool to avoid the spread of new pests and diseases is pre-emptive and salvage logging in the neighbourhood of an infested forest patch. Whilst this strategy is very relevant when a newly introduced pest or pathogen is detected for the first time, it should only be employed in initial and locally restricted cases of first disease incidence (Budde et al. 2016). It can become counterproductive when several disease centres emerge, due to the removal of high numbers of healthy, and some potentially resistant, trees.

Safety

As ash dieback severity increases so the frequency of dead trees will increase, potentially leading to concerns of safety for the public, land owners and forest workers. These concerns are incorporated in some of the guidance available for the management of ash. Rigling et al. (2016) provide some guidance for Switzerland in the form of a decision support tree. Primarily, if there is a safety risk due to dead/dying trees then infected trees should be felled and the remaining trees monitored. Secondly, if a tree belongs to a biotope (niche habitat for threatened or protected species) then there should be no intervention. Thirdly, if there is a risk of marketable and profitable wood assortments being devalued, then infected trees with >70% loss of foliage or with collar necrosis, and epicormics on the stem should be felled. Healthy or least affected individuals should be preserved and favoured. Finally, if the stand is pure ash then there should be no intervention as natural selection of resistant individuals will occur. If the stand is mixed then intervention is unnecessary because the other species will be promoted by the disappearance of the ash. The Forestry Commission (2018b) also identify public safety as one of the biggest management issues and recommend the felling or pruning of dead or dying trees. However, there is also additional risk to chainsaw operators associated with felling dead ash trees and additional considerations should also be made. Felling such trees by manual

chainsaw is particularly risky due to the increased risk of dead branches dropping or the unpredictability of the felling hinge due to potential reductions in timber strength. The UK Forest Industry Safety Accord has published guidance for the industry (see FISA 2018), the main recommendation being to fell mechanically, rather than by manual chainsaw, whenever possible.

Additional considerations

In addition to the above practical silvicultural considerations, some other management actions are key to minimising the impact of ash dieback:

- Regular monitoring – ideally all ash stands should be inspected at least once per year during the growing season (Thomsen and Skovsgaard 2012, Rosenvald et al. 2015, Rigling et al. 2016). This is fundamental to the implementation of timely mitigation treatments, which are appropriate to the scale of the infection;
- "Don't panic" – management actions should be considered and not be reactive (Skovsgaard 2013);
- Adapting woodlands to become more resilient will require anticipatory action – changes need to be made before the impact of biotic and abiotic threats becomes observable (Bladon et al. 2016).

In Ireland, on the north-western frontier of the disease, there may still be a window of opportunity in which to take pre-emptive practical management actions to adapt the ash-dominated woodlands, which can be more effective than any subsequent reactive actions.

Case studies on potential remedial silviculture options in Ireland

Three case studies were investigated to discuss the potential range of practical silvicultural options for Irish forest sites.

1. Free-growth/halo thinning.
2. Line thinning and underplanting.
3. Conventional thinning with group selection and underplanting.

The first two case studies were initiated in 2010, prior to ash dieback being identified in Ireland, with the objective of improving potential productivity of poorly performing broadleaf stands. Both are situated on a privately-owned 6.5 ha broadleaf site near Charlestown, Co. Mayo, planted in 1992 primarily with ash. There had been no thinning carried out prior to the activity associated with the B-SilvRD project. The third case study was initiated in 2018 in a stand near Maghera in Co. Derry.

1. Free growth/halo thinning, Charlestown, Co. Mayo

A free-growth/halo thinning approach was suggested by Short (2013) as being suitable for management of pole-stage plantation in Charlestown in light of ash dieback. The treatment was planned for this pure stand, which had a stocking of 2,850 stems ha^{-1}, top

height of 12.6 m and a yield class of 10 $m^3ha^{-1}yr^{-1}$ in 2010, but which had insufficient numbers of potential crop trees (PCTs) to carry out a conventional thinning (as per guidelines, see Short and Radford 2008). A halo thinning was initiated in winter of 2010/11 in a 20 × 20 m plot when the stand was 18 years old. Two-hundred PCTs ha^{-1} were selected, permanently marked and the four strongest crown competitors per PCT removed. Adjacent suppressed stems were retained to facilitate stand stability. Racks were also introduced at this time to facilitate future access (Figure 2). In total, 44% of stems were removed in the thinning operation. The objective of the halo thinning system was to give the selected PCTs the best chance to increase stem diameter and volume as quickly as possible to reduce the rotation length and therefore, provide an earlier income from the final crop. It would also reduce their susceptibility to ash dieback. Further high pruning of the PCTs may be carried out in the future if required and only a proportion of them (80–120) were intended to become final crop trees.

The growth in DBH of the stand has been restricted by site conditions and the delayed thinning operation. However, the PCTs have had a mean annual increment of 0.8 cm yr^{-1} since the intervention, compared with 0.4 cm yr^{-1} for the remaining matrix of trees (Figure 3). During the intervening period there has also been some coppice regrowth from the stumps. If the halo/free growth system is to be used, it would seem prudent to control coppice regrowth to minimise future potential spore production.

2. Line thinning and underplanting, Charlestown, Co. Mayo

Two line-thinning and underplanting treatments were introduced in two stands at the same time (18 years old)[3]. Stand productivity ranged from yield class 4 to 6 $m^3ha^{-1}yr^{-1}$

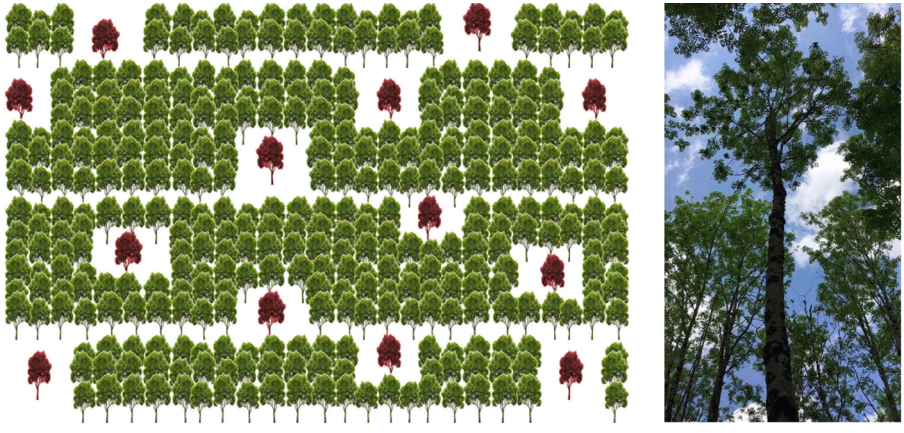

Figure 2: *Schematic diagram (left) illustrating free growth/halo thinning. The crown of a selected tree seven growing seasons after intervention (right).*

[3] A similar intervention was carried out in a sycamore stand but without underplanting (see Short et al. 2015).

and were poor quality. Top height and DBH data were collected in 2010 and 2018 (Table 2). A change of species was required for these two areas and therefore two treatments were initiated in winter of 2010/11:

(a) felling of three out of four rows of ash and replanting with alder (*A. glutinosa*); and,

(b) felling of two middle rows out of four and replanting with alder (see Figure 4).

The remaining lines of ash remained to provide a nurse to the alder and maintenance of ecosystem functions.

The alder has grown very well since establishment and has the potential to produce a good quality crop in later years. By May 2018, the alder had increased in height by over 7 m since planting (average growth of 1 m yr^{-1}). Some of the alder is of similar height to that of the remaining original ash trees (Table 2) (Figure 5). Thinning will be required to reduce competition and ensure continued vigour of the future crop. There has also been significant resprouting from the ash stumps and will need to be prevented or controlled.

3. Adapted conventional thinning to include group selection and underplanting, Maghera, Co. Derry

The 31.9 ha Drumnaph Wood near Maghera is owned by the Woodland Trust. The wider Community Nature Reserve comprises a range of important habitats, but fundamentally contains 14.7 ha of ancient woodland. The overall woodland area was extended within the Trust's "Woods On Your Doorstep" millennium celebration through the planting of an additional 11.8 ha of new native woodland in 2000. About 4 ha of this plantation

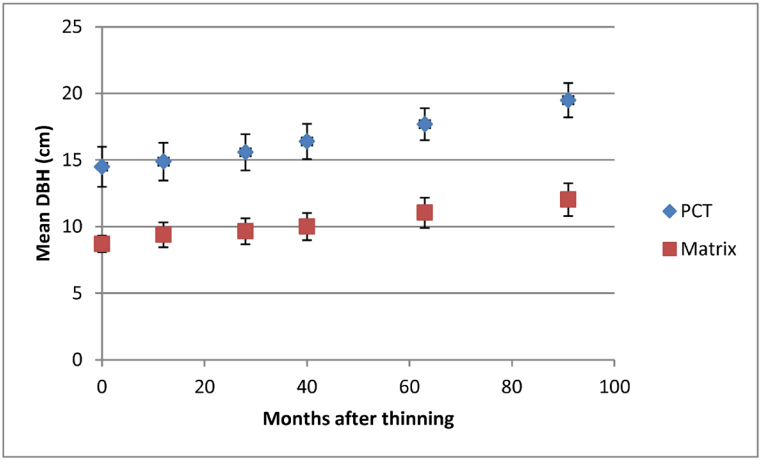

Figure 3: *Change in diameter of potential crop trees (PCT) and the remaining matrix of unselected (non-PCT) trees following halo thinning in an 18-year-old ash stand, Charlestown, Co. Mayo. Error bars represent 95% confidence intervals around the means.*

is comprised predominantly of ash. Left untreated, these young, single species blocks of ash are clearly at risk of very rapid decline from ash dieback. The Woodland Trust recognises this risk and has been taking steps to minimise the ecological impact of such an anticipated infection. The recent work programme in the wood, completed as part of a project funded jointly by Teagasc and Woodland Trust, incorporated group selection into a conventional thinning (Figure 6) and has two primary objectives:

(a) promoting the vigour of selected ash trees through thinning; and,

(b) diversifying the species composition of the predominantly ash stands through underplanting.

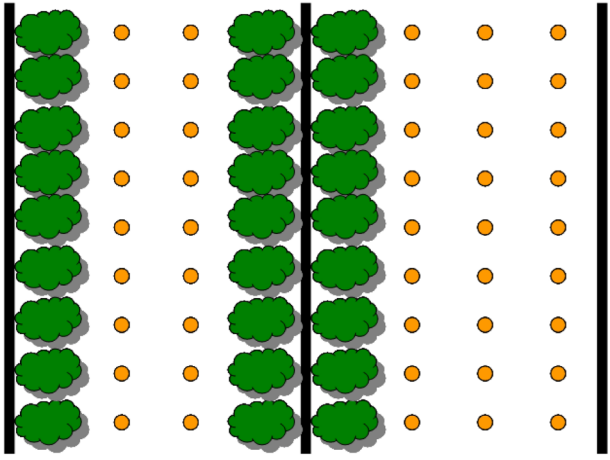

Figure 4: *Representations of the line-thinning treatments used. Lines removed are shown by orange circles and drains in black.*

Table 2: *Height and DBH of ash and alder of two stands subsequent to line thinning treatment with admixing with alder in winter 2010/11. Data from case study 2. Plots 2A and 2B: two ash lines removed; Plots 3A and 3B: three ash lines removed. Figures in parentheses are standard errors.*

			Ash			Alder	Ash		Alder
Plot	**Stand**	**Ash lines removed**	**Top height 2010** (m)	**Top height 2018** (m)	**Mean height 2018** (m)	**Mean height 2018** (m)	**DBH 2010** (cm)	**DBH 2018** (cm)	**DBH 2018** (cm)
2A	A	2	9.4 (0.17)	10.5 (0.13)	9.1 (0.34)	7.7 (0.17)	8.8 (0.68)	10.6 (0.82)	6.8 (0.22)
2B	B	2	10.0 (0.41)	11.7 (0.48)	9.5 (0.57)	7.8 (0.24)	8.2 (0.75)	10.5 (0.95)	5.8 (0.29)
3A	A	3	8.3 (0.20)	9.8 (0.57)	7.7 (0.64)	7.4 (0.14)	6.7 (0.87)	9.8 (1.12)	6.6 (0.20)
3B	B	3	7.1 (0.36)	8.5 (0.35)	7.3 (0.40)	7.3 (0.12)	6.5 (0.73)	8.6 (0.91)	6.6 (0.20)

Figure 5: *Schematic diagram representing line thinning and underplanting (left), and a "real-world" example at Charlestown in Co. Mayo (right).*

The species composition has been diversified by replanting predominantly with either oak or birch, with some additional hazel also incorporated (see Figure 7). Ten coupes were superimposed on the standard rack and selection thinning. The mean height of the ash trees surrounding the coupes ranged between 8 and 11 m. Site size constraints limited the coupe sizes which ranged in size from 0.025–0.045 ha, though the authors believe these are practical for small-scale private ash woodland sites. As a comparison, the size of the coups developed at this case study site were compared with recommendations from Harmer et al. (2010), who suggest minimum group areas for planting of birch and oak which relate to surrounding tree height (ranging from 15 to 30 m). For example, the minimum area for a coupe with a surrounding tree height of 15 m is 0.16 and 0.07 ha for birch and oak, respectively. Creating regressions lines from Table 6.7 of Harmer et al. (2010) and extrapolating allows for comparison between the coupes established in Drumnaph Woods and the sizes recommended (see Table 3). The coupe sizes in Drumnaph tend to be smaller than those recommended from the extrapolation, particularly for the birch coupes. Birch is more light-demanding than oak and recommended coupe size is increased relative to that for oak to reflect this. The trial intervention in Drumnaph was carried out specifically in response to the

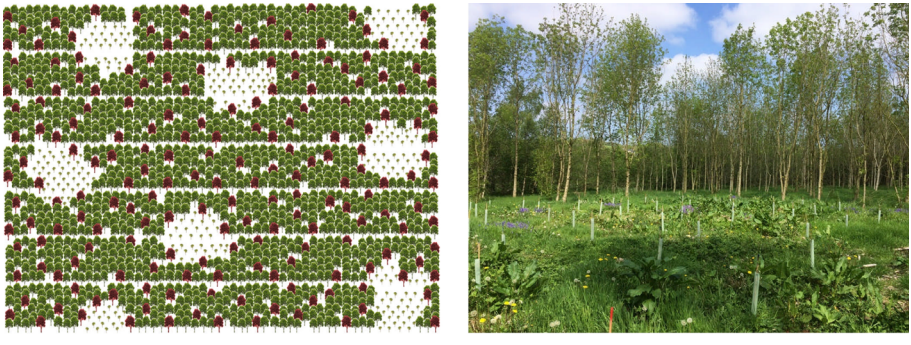

Figure 6: *Schematic diagram representing an adapted conventional thinning with group selection and underplanting (left), with an example from Maghera in Co. Derry (right).*

presence of ash dieback in Ireland and, therefore, coppice regrowth from the stumps has been prevented from occurring by using a mulcher to damage the tops of the stumps. Future management will entail continued selection thinning within the ash and concurrent removal of trees on coupe boundaries as their canopies encroach into the open space. The trial will monitor how changes in the canopy gap and light regime over time affect the growth of the interplanted trees.

Discussion

Much of the ash-dominated woodland resource in Ireland is young, even-aged and monocultural and, as such, is in a high-risk category regarding the impact of ash dieback (Skovsgaard et al. 2010, Alsop and Goldberg 2018). Comparative studies of the continental European experience, such as Alsop (2014), and resulting management guidelines (Reid et al. 2015, Forestry Commission 2018b), emphasise that restructuring this resource to integrate some degree of species and structural diversity, sooner rather than later, will be fundamental to lessening the silvicultural, economic, ecological and social impact of the disease. Studies such as by Skovsgaard et al. (2009), Bakys et al. (2013) and Ahlberg (2014) have shown that particularly for young, and mostly relatively healthy stands, conventional thinning is the first step toward resilience by promoting the general health and vigour of the stand. Free-growth, the aim of the first case study, and rack and selection thinning, aims to promote the vigour and health of selected trees. Management interventions should be targeted to alleviate the immediate consequences

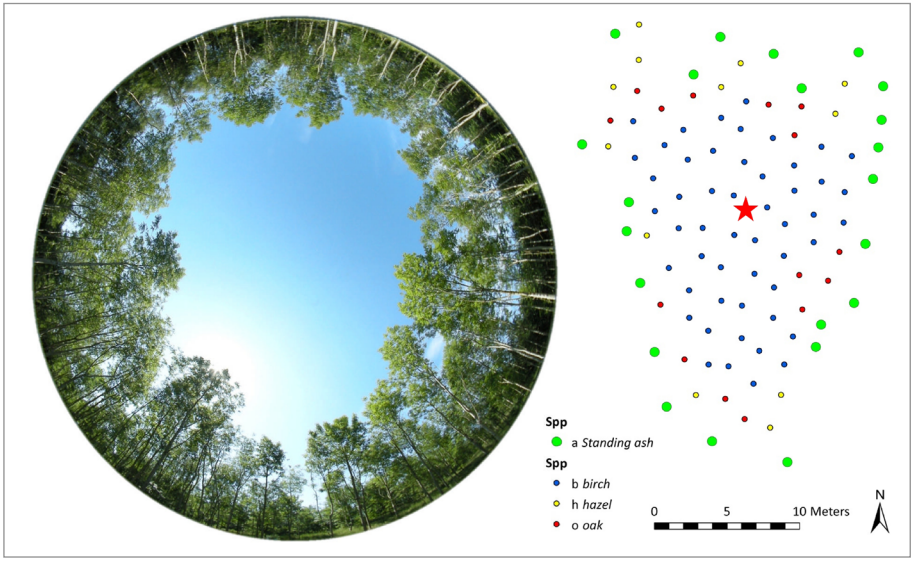

Figure 7: *Hemispherical photograph from coupe 3 in Drumnaph Woods, Maghera, Co. Derry (left) and locations of planted and remaining trees in diagram (right). The red star denotes the location from which the hemispherical photograph was taken.*

Table 3: *Comparison between the coupe sizes developed by the authors at Drumnaph Woods, Maghera, and those recommended by Harmer et al. (2010).*

Coupe	Species	Stand height (m)	Coupe size in Maghera (ha)	Recommended minimum size[a] (ha)	Difference in area (%)
1	Oak	10.8	0.034	0.04	-3%
2	Oak	10.8	0.027	0.04	-23%
3	Birch	11.0	0.043	0.08	-49%
4	Oak	8.0	0.027	0.02	40%
5	Oak	11.1	0.028	0.04	-24%
6	Oak	11.5	0.041	0.04	3%
7	Oak	10.5	0.039	0.03	18%
8	Birch	10.0	0.038	0.07	-46%
9	Birch	8.5	0.031	0.05	-39%
10	Oak	9.0	0.040	0.02	64%

[a] The recommended minimum coup sizes were extrapolated from the categories based on stand height provided by Harmer et al (2010) whose Table 6.7 lists height from 15 to 30 m, at 5 m intervals. Regression equations were developed to suit the stand heights (m) for oak and birch encountered at Drumnaph Woods.

Oak: minimum coup area = $0.0003 \times \text{height}^{2.0006}$; $R^2 = 0.99$.

Birch: minimum coup area = $0.0007 \times \text{height}^{1.9998}$; $R^2 = 0.99$.

of ash dieback. However, silvicultural strategies should generally be conservative and should aim to retain as high a proportion of healthy or slightly damaged trees as possible, through all stages of stand development, as this is critical to the development of natural resistance. Felling all ash trees regardless of their health condition risks losing potentially tolerant genotypes (Skovsgaard et al. 2017). Forestry practice therefore plays a key role within the overall ash conservation strategy.

Choice of remedial management options, such as those illustrated, should be based on stand age, the relative proportion of ash and the severity of the infection (Thomsen and Skovsgaard 2012). Variable site, stand and wider environmental factors affect the severity of the disease and therefore site-specific remedial management prescriptions are required (Skovsgaard et al. 2017). For carrying out individual stand assessments, a requirement under "Step 1" of the DAFM-prescribed actions, Skovsgaard et al. (2017) provide a useful and transferable inventory procedure for ash dieback. Initial stand assessment should be backed up by regular monitoring, at least once during the growing season (Skovsgaard 2013, Thomsen and Skovsgaard 2012). Such monitoring will be fundamental to the implementation of timely mitigation treatments, which are appropriate to the scale of the infection. Any future management guidelines should therefore reflect the age, overall species composition, structure (past treatment) and relative health of the stand, as well as the potentially broad range of management objectives attached to the ash-dominated woodland resource in Ireland.

Furthermore, any such guidelines and associated management incentives may also consider the promotion of mixed species stands as the basis of resilience (Weir 2017)

and in doing so endorse the appropriate restructuring treatments (e.g. adapted thinning/ coupe felling and underplanting) necessary to achieve such a result, such as illustrated by the last two case studies.

The three case studies presented here are limited in their scope since they cover only two sites, but nevertheless should prove useful for demonstration and discussion purposes. Table 1 makes general recommendations on how conventional thinning should be adapted in stands with a high proportion of ash in order to facilitate the development of mixed species woodlands through admixing. Such adapted thinning treatments are yet to be fully demonstrated or tested in Ireland, but must be seen as necessary, timely and hopefully worthy of trial by owners and managers of young ash forests.

Conclusions

This paper presents some silvicultural strategies for the mitigation of the impact of ash dieback in Ireland. Its intention is to better equip forest owners and managers when it comes to making management decisions regarding their ash-dominated woodlands. In summary, mitigatory management may have two broad objectives:

- Promotion of the health and vigour of selected ash trees to maximise the longevity of the existing stand and support its economic, ecological and aesthetic functions (as it transitions to a more mixed species woodland).
- Support the transition to a more mixed species woodland through appropriate restructuring and admixing treatments, in order to build a greater degree of economic, ecological and aesthetic resilience in the future.

While proactive management guidelines in relation to ash-dominated woodlands have begun to be developed, there is only limited experience of implementing many of these in the presence of this disease. "Therefore it will be necessary to trial different management strategies, monitor their effectiveness, and continue to share practical experience" (Reid et al. 2015). This is particularly true in relation to the restructuring of monocultural ash woodlands. In Ireland, fully replicated research trials investigating a range of adapted thinning and underplanting treatments are required sooner rather than later in order to confidently inform and reassure ash woodland owners that management options with potentially positive silvicultural, economic and ecological outcomes are possible, and in doing so hopefully minimise panic and inappropriate reactive actions (Skovsgaard 2013).

The silvicultural challenges of growing quality hardwood in first rotation open-field situations has been well documented (see Hawe and Short 2012). The objective to smooth the ecological transition from ash-dominated stands to more mixed woodland has also been presented as a fundamental element of remedial management. Maintaining the existing ash stand for as long as possible presents the opportunity to grow different broadleaf species in an intimate woodland as opposed to an open

greenfield situation, with a higher degree of inter- and intra-species competition, and competition for light. For species such as oak and beech, which are particularly prone to loose apical dominance in greenfield plantation conditions, the small scale, uneven-aged systems necessitated by a requirement to restructure ash-dominated stands may actually present conditions which are substantially more favourable to the growth of quality hardwood timber. This may only be achieved however, if forest policy and related financial supports encourage sympathetic management of the current ash plantation resource, and if owners and managers are willing to support and practice a more sophisticated silviculture. In the future, the establishment of mixed species plantations (as opposed to monocultures) may represent a sensible precaution to ensure the future resilience of Irish forests against increasing threat from pests and diseases (Hartig 1882, Pautasso et al. 2005, Kelty 2006, Huss et al. 2016).

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