Species Mixtures in Irish Forests A Review

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COFORD
NATIONAL COUNCIL FOR FOREST RESEARCH & DEVELOPMENT

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Foreword

Forest Mixtures make up a considerable area of forest cover in Ireland. The National Forest Inventory data estimates that some 300,000 ha (47%) of the National Estate consists of mixtures. Many of these mixtures have been established over the last 25 years under the various afforestation schemes. Some mixtures have worked, some have not. While it is important to document the types of mixtures, it is more important now that we address the management issues they raise in order to learn from the past and maximise the potential of mixtures in our National Estate. Mixtures require skilled silvicultural intervention at the correct time to ensure the target species form the final crop. However, the knowledge and skill levels amongst forestry professionals of how to manage mixtures is low. Indeed, given the scale of mixtures, relatively little research has been carried out exacerbating an already unsatisfactory situation. There is an urgent need to provide forestry professionals with guidance.

A group was established under the COFORD council to address the management of mixed forests. The members of the group, which was chaired by Daragh Little, were Dr. Ian Short, John Redmond, Padraig O'Tuama, Gerard Dunne and Dermot Cunniffe. The terms of reference of the group were to:

1. Outline the extent and rationale of the main species mixtures used in commercial Irish and British forestry, taking into account relevant forestry literature and policy objectives

2. Review the main species mixture types over the past 20 years in relation to their subsequent performance and ease of management

3. Make recommendations on the potential use of mixtures, and on research work that may be needed to review existing trials and mixtures in more detail with a view to updating recommendations on future afforestation and management, and

4. Taking into account the findings from 1, 2 and 3, review the potential of specific mixtures types to address disease risk.

The report captures mixtures in their historical context bringing together knowledge from Ireland, the UK and farther afield to contextualise mixtures in forestry practice. It captures a wealth of data from various sources showing the size and complexity of the issue before us. Indeed, the results of the survey in the report illustrates starkly the demand from forestry practitioners for more guidance and knowledge vital if we are to address the challenges presented to us by mixtures. This report is the start of that journey.

I would like to thank the members of the group and the project team for their work in producing this report.

Michael Lynn,
Chairman, COFORD

Daragh Little,
Chairman, COFORD Mixtures Group

October 2018

Executive Summary

Introduction

Since the early 1990s in Ireland, mixed species plantations have been encouraged by the provision of specific Grant and Premium Categories (GPCs 3, 6 & 7) in the afforestation programme. Mixed plantations of conifers, broadleaves and conifer/broadleaves have been successfully established and today, foresters and owners are facing the prospect of managing these plantations as the crops reach post-thicket and pole stages. Having limited knowledge or experience of mixed plantations, there is an urgent need to provide sound guidance for best practice.

In recognising this requirement, a working group was established under the COFORD Council with the objective of determining the extent and type of mixed plantation forests and making preliminary recommendations regarding their management. This report is the result of a desk study commissioned to aid in these tasks. The report pools the issues concerning mixed plantations into a single document - including an historical perspective, rationale for their use, pros and cons of mixtures, attribute statistics, published performance of mixtures, practitioners' experiences, research and current guidance as well as identifying gaps in our current knowledge. It provides a basis for a discussion on policy matters concerning the future establishment and management of mixtures.

Methodology

The study was divided in to 5 tasks which follow the objectives set out by the COFORD Working Group viz:

Task 1. Examine, collate and critically review scientific evidence for the pros and cons of mixed forests related to growth and yield, wood quality, disease risk, biodiversity conservation and enhancement and climate change mitigation and adaption. The emphasis will be on plantation forests established as mixtures.

Task 2. Broadly catalogue species mixture types (including in tabular format) used in Irish and British forestry practice and their extent in Ireland and collate as far as practicable and available, the rationale for their establishment, taking into account 1 above.

Task 3. Review and critically examine evidence, including existing research, forestry practice, publications and other literature, the performance of mixtures in terms of compatibility of species, growth, form and management, including ease of establishment and wood quality, and the potential for mixtures to mitigate disease risk and for climate change mitigation and adaptation.

Task 4. Drawing on the above and with a view to informing future policy, measures and forestry practice, provide preliminary guidance on possible mixture types, and management of current intimate and non-intimate mixtures.

Task 5. Identify knowledge gaps and make recommendations on possible areas for inclusion in future National forest research calls.

Mixtures in the Forest Estate

Ireland

In discussing the total area of mixtures in the woodlands in Ireland, three main sources of data have been used:

1. National Forest Inventory (NFI) – contains data on all woodland in Ireland;
2. Grant and Premium Categories (GPCs) – contains data on woodland which has been planted under various grant schemes over the years; *and*
3. Coillte inventory – contains inventory data only from the Coillte estate.

Information from the NFI

Eleven parameters were selected to best describe the attributes of mixed crops at National level. These 11 attributes are summarised in Table 1 below. A more comprehensive breakdown of the data is given in the body of the Report and the Appendices.

TABLE 1: Parameters selected to describe the attributes of mixed crops at national level.

Attribute	General
Area	Similar areas of pure and mixed forests in the National forest estate - 337,000 ha (53%) pure and 300,000 ha (47%) mixed.
Ownership	There are 128,856 ha (38%) mixed crops in public ownership and 171,008 ha (58%) in private hands.
Age	Mixtures are 63% even aged and 37% uneven aged.
Tree distribution	Tree distribution of mixed crops tends to be either regular (56%) or random (42%) with very few groups (2%)
Mixture type	"Uniform" – The structure is uniform throughout the plot where one tree species is present (53%). "Individually mixed"- There is more than one species present, with the species occurring in a random manner (38%) "Group mixtures" – The structure is based on groups of trees of each species. Line mixtures are included in this category (9%).
Nativeness	Mixed crops comprise 48%. Non-native species and equal amounts of native species make up 26% and those of mixed nativeness 27%.
Development stage	48% of the mixed crops are in the thicket, small pole and pole stages (141,311 ha).
Establishment	Afforestation accounts for 54% of mixed crops, reforestation (26%) and semi-natural establishment (20%) make up the remainder.
Number of tree species	In the mixtures that contain broadleaves, there is a higher number of tree species present than in the conifer mixtures.
Number of non-tree plant species	The conifer/broadleaf mixtures lie midway between the pure conifer (75.7%) and pure broadleaf (91.7%) stands for 6 or more non-tree plant species.
Humus formation	Mixed crops are intermediate between conifer and broadleaf crops in terms of the different types of humus formation. 10% of conifer crops have mull formation, conifer/broadleaf crops (17%) while broadleaves have 29%.

Information from the Grant & Premium Categories

To gain further insight into mixed plantations in the private sector, the IFORIS (Integrated Forest Information System) was interrogated for data on mixtures under the different Grant and Premium Categories (GPCs). Under these categories, the largest area (99 K ha) contains two species per parcel followed by 66 K ha which contain one species per parcel. The areas under three and four species/parcel are 51 K ha and 18 K ha respectively.

Intimate mixtures are by far the most common mixture type employed (21 K ha), followed by Group mixtures (9 K ha) with Row mixtures being the least used (3.8 K ha).

Information from the Coillte estate

There is a wide range of mixtures in the Coillte estate, ranging from those planted in recent years to some established as far back as the early eighteenth century. Within the three land use types defined by Coillte (conifer high forest, broadleaf high forest and mixed high forest), there are a total of 67,321 ha of mixed forest in the Coillte estate (approximately 15% of the entire Coillte estate). This total is broken down in Table 2.

The ten mixtures with the greatest area in the Coillte estate are given below. Note that the primary species in the mixture is given first. The mixture types are quite different to those in the private estate in two ways – the Coillte estate contains relatively few areas of some mixtures commonly planted in private woodlands (e.g. conifers mixtures with oak) and the Coillte estate contains relatively large areas of mixtures which have resulted from natural invasion of planted conifer stands by broadleaves (e.g. spruce/birch mixtures in Table 3).

TABLE 2: Breakdown of mixture types in the Coillte estate.

Mixture type	Area (ha)
Broadleaf/broadleaf	8,241
Conifer/broadleaf or Broadleaf/conifer	15, 813
Conifer/conifer	43,267
Total	**67,321**

TABLE 3: The most common mixture types in the Coillte estate.

Mixture type	Area (ha)
SS/LP	16,630
SS/JL	10,905
LP/SS	4,937
SS/Bi	2,720
Bi/SS	1,064
JL/SS	1,037
NS/Bi	900
SS/NS	807
DF/SS	705
Bi/NS	687

Britain

The twentieth century afforestation programme involved the creation of extensive areas of single species plantation forests, often composed of non-native species. Sitka spruce is now the commonest tree species in Great Britain (Mason, 2007) and is the most important species for the timber processing sector, especially in Scotland. Throughout the last century, the deliberate creation of mixed stands was relatively limited and was largely confined to the use of conifers to nurse broadleaves in lowland Britain and to the planting of 'nutritional' mixtures on poorer soils in the uplands (Kerr *et al*., 1992).

Perhaps because of the relative lack of importance of mixtures in British forests, estimates of the extent of mixed forests in Britain vary considerably (Table 4).

TABLE 4: Estimates of the area of mixed stands in British forests.

Year	Area of mixtures (K ha)	Percentage forest area	Notes	Reference
1988	209.6	26	Forestry Commission forests only	Kerr *et al.* (1992)
1998	244.1	10	NIWT report	Anon. (2013)
2010	1,247.0	44	MCPFE indicator 4.1	MCPFE (2011)
2011	93.9	2	NFI	Anon. (2013)

Some of this variation is due to difference in the ways of defining a mixed species stand. In 1988, a stand was classed as mixed if more than one species occurred within a sub-compartment - even if the various species were planted in pure blocks (Kerr *et al*., 1992). The MCPFE 2011 report considers a stand to have more than one species if an admixed species represents > 5 per cent of the basal area of the stand. The 1998 and 2011 National Forest Inventory reports consider a stand to be mixed where no single species occupies more than 80 per cent of a stand (Anon., 2013). The considerable discrepancy between the 1998 and 2011 figures is almost certainly due to the latter only providing data on 'mainly conifer' and 'mainly broadleaved' mixtures. This seemingly ignores conifer-broadleaved mixtures which amounted to about 75,000 ha in upland Britain (Mason, 2006) with a similar estimate for the area of this type of mixture in lowland Britain.

The 2011 report (Anon., 2013) indicated that over 80 percent of the identified mixtures (81.6 K ha) occurred in private woodlands with only around 12 K ha found in Forestry Commission forests. Around 50 percent of the mixtures were reported from England with lower proportions present in both Scotland and Wales. The data suggest that the amount of 'mainly conifer' and 'mainly broadleaved' mixtures is quite similar at 48.8 K ha and 45.2 K ha respectively (Anon., 2013).

Performance of mixtures

Ireland

A literature review was undertaken to gather documented information on the performance of mixtures in Ireland. The dearth of both published and grey literature on mixtures reflects the policy and practice of establishing and managing single species plantations from the early days of afforestation until relatively recently. The performance of species mixtures recorded in Irish forestry literature is confined to a few publications and mostly concerns broadleaves as the target final crop species.

Survey

In addition to examining the performance of formal field trials on mixtures in Ireland, the project also looked at the performance of operational mixtures on the ground by carrying out a survey of people working with mixtures on a day to day basis. The survey used the 2017 DAFM Register of Foresters and Forestry Companies (177 names) and the membership of the Society of Irish Foresters (over 700 members) as potential participants in the survey. The full results are presented in the Report but some of the key findings from the survey include:

- There was a keen interest in the subject as there were over 100 replies.
- Mixed crops were most commonly chosen for their nursing effect, as a requirement under a grant scheme, or from a greater desire on behalf of the owner for improved visual amenity or recreation possibilities. The least common reason for mixtures being chosen was a desire for greater financial incentive from early thinning.
- 67% of respondents found mixtures difficult or very difficult to manage and what respondents wanted most from this study was better guidelines on how to manage existing mixtures on the ground.
- Over half of respondents knew of a mixed crop which had grown well and which had been thinned at least once. A quarter of respondents suggested a site visit by the Project Team to visit their mixed woodland.

Research on mixtures

A detailed assessment was carried out on the number and extent of field trials on mixtures in Ireland and Britain. In Ireland, most existing field trials on mixtures come under the current management of Coillte. These trials are in three areas:

1. Avondale
2. Experimental network
3. BOGFOR trials

Although many of the Avondale plots are over one hundred years old and some have experienced extensive windblow, they still provide a large amount of information on the performance of different tree species and their mixtures under Irish conditions.

The experimental network of field trials on the Coillte estate was established over a 50-60 years period and contains field experiments covering a wide range of silvicultural and management treatments. Information on the trials is contained in the NATFOREX (National Resource of Field Trials and a Database for Research and Demonstration) database, developed by UCD and funded by COFORD. A search of the database produced a list of 18 field trials that contain mixed species. The trials test a range of treatments aimed at achieving productive conifer and broadleaf crops. Details of the individual trials are given in the body of the report and further details can be accessed via hyperlinks embedded within the text. No work has been carried out on the trials since the end of the NATFOREX project (2013) and, because Coillte no longer employs specific research staff, there is now a real danger that these trials will fall into disrepair or be operationally harvested at the same time as surrounding stands.

In addition to the network of field trials described above, there are also small areas of mixture trials established on cutover bogs (five trials within the BOGFOR project) and by Teagasc (four trials). All are described in greater detail within the report.

Britain

In Britain, there has been relatively little formal experimentation to examine the effects of species mixtures on tree growth and productivity, compared with the extensive studies examining tree growth in pure stands. The most important long-term experiments formed part of a series of some 20 trials laid down between 1955 and 1962 which contained a range of two species mixtures together with pure plots of the constituent species, all planted in a replicated design. The mixtures were planted in a 50:50 mix using an alternate 'chequerboard' design so that the admixed species could be expected to survive until well beyond canopy closure. This series is almost unique in northern Europe in providing long-term statistically valid data on the growth performance of mixed stands. Unfortunately, many of the experiments in this series were lost to neglect or windthrow so that only eight (including the famous mixtures experiment at Gisburn in NW England) survived to canopy closure, after which measures of productivity could be made. Other experiments involving mixtures have been those examining nursing mixtures of pine or larch with Sitka spruce on nutrient poor soils, primarily in northern Scotland. There have also been a small number of experiments which have investigated mixtures between conifers and broadleaves.

Guidance on the management of mixtures

Existing guidance available
From the survey of practitioners and a search of the available literature, it is evident that guidance on the management of mixtures in this country is very limited. It is currently confined to five publications, most of which are inadequate to provide owners and managers with the required practical information to successfully manage mixed species plantations; also, the subject of mixtures does not seem to be adequately covered in the third level college courses in UCD or WIT.

Fundamental recommendations on the establishment and management of mixtures
The development of mixed species crops depends on many factors and as a result stands can vary greatly depending on genetics, site factors and silvicultural management. Currently, there is no understanding of how species mixtures perform over a range of site types. For example, SP/oak mixtures are performing perfectly on some sites but are a total failure on others. It is therefore difficult to provide specific guidelines at present for the management of mixtures other than some general principles which are given in the report.

The Team found that, while mixtures may initially appear a challenge to foresters who are used to managing pure conifer crops, those foresters we met on the ground were well able to provide the necessary advice and manage appropriate treatments for the crop. Providing opportunities for networking to share experiences, demonstration of best practice, etc. for mixtures, however, would greatly assist in helping to build confidence among the profession. Support systems in the form of woodland improvement grants are also very useful to ensure crops are managed correctly and at critical times.

Knowledge gaps

Based on the review of existing guidance, current research trials and stakeholders' comments, the Project Team identified a range of areas where major gaps exist in our current knowledge on mixtures. Where possible, potential solutions to rectify these gaps are given.

These gaps exist in fundamental policy areas (where a National Policy on mixtures is badly needed) to major gaps in the broad silvicultural area. Knowledge gaps in this latter area range from information on relative growth rates of different species to timing and extent of first thinning and from timber yields to appropriate harvesting equipment. Although excluded from this report, the area of Continuous Cover Forest (CCF) management also needs to be researched in terms of what it can offer in the management of mixed stands.

There is an urgent need to examine existing field trials to determine their condition and what new trials (if any) are needed. These new trials will take decades to provide information and, in the interim, improved models, appropriate for mixed stands, need to be developed to guide existing owners/managers on future choices. Major education programmes are required for educators, owners, managers and machine operators - based on the best current information.

Recommendations

1. **Immediate (within 12 months)**
    - Using the organisational framework of the Society of Irish Foresters, hold a series of regional workshops, bringing together researchers who are working on mixtures and operational foresters who are currently managing mixtures on the ground.
    - Put in place an assessment and maintenance programme for existing field trials and demonstration areas on mixtures.
    - Publish a COFORD summary document which updates the existing recommendations on mixtures in the Guide to Forest Tree Species Selection and Silviculture in Ireland (Horgan *et al*., 2004).
    - Initiate a planning and execution programme for a long-term research programme on mixtures in this country. This may initially involve growth models (if sufficient data exist) and establishment of additional demonstration areas and long-term experiments.
    - Work with policy makers to encourage the introduction of novel incentive schemes which encourage land owners and managers to manage mixtures from an early stage and over multiple interventions.

2. **Medium term (within 24 months)**
    - Based on knowledge gleaned from the workshops (above), compile a Decision Support System on management of mixtures and roll it out to practitioners via a technology transfer programme. The COFORD model on woodfuel should be used as a template for this.
    - Using the existing COFORD website, establish a users' "go to" portal which would bring together all existing information on management of mixtures.
    - Involve teachers of third level colleges in this technology transfer programme to begin to develop expertise in the management of mixtures at third level.

3. **Long term (beyond 24 months)**
    - Use the demonstration areas and experiments (both newly established and from previous research programmes) as a strong basis for an ongoing technology transfer programme on mixtures.
    - Begin to harvest and publish data from the long-term research programme, established under Phase 1 (above) and refine the growth models developed.
    - Strengthen links between researchers, educators and policy makers to ensure new results influence ongoing policy decisions in relation to mixtures.

Section 1 - Introduction

1.1 Background

Since the early years, Ireland's afforestation programme was mostly concerned with the establishment of conifer plantations, managed for commercial timber production, under the clearfell silvicultural system. Today, however, forests are required to perform a range of functions, combining economic, social and environmental objectives under the auspices of Sustainable Forest Management. This broader focus has required the adoption of measures to diversify the forest estate, including the diversification of tree species composition, particularly broadleaves.

Since the early 1990s, mixed species plantations have been encouraged by the provision of the Grant and Premium Categories (GPCs 3, 6 & 7) in the afforestation programme. Plantations of pure conifers, pure broadleaves and conifer broadleaf mixtures have been successfully established and today, forest managers and owners are facing the prospect of managing these plantations as they reach post-thicket and pole stages. Having little knowledge or experience of mixed plantations, there is an urgent need to provide sound guidance for best practice. In recognising this requirement, a working group was established under the COFORD Council with the objectives of determining the extent and type of mixed plantation forests and making preliminary recommendations regarding their management. This report is the result of a desk study commissioned to aid in these tasks.

1.2 Historical perspective

Plantations of mixed forests are not new to Irish forestry. Many of the old estate woodlands of the 18th and 19th centuries were mixed plantations, often with combinations of conifers and broadleaves. Clear (1944) states that "*while the practice of raising mixed crops is very long established in this country and while most of the timber felled here in recent times has come from mixed stands, there has been a tendency to depart from this old and well-tried system and to lay down extensive areas under pure spruce and pine. This practice is no doubt dictated by financial considerations and the exigencies of large scale afforestation*." His comments recognise the departure from mixed crops to the practice of establishing conifer monocultures, which subsequently lasted for many decades. The result of this practice was that the knowledge and skills necessary to manage mixed crops were lost to subsequent generations of Irish foresters.

The planting of mixed crops on scale resumed in the State forests in the 1980s when the nutrient nursing effect on Sitka spruce by larch and lodgepole pine became apparent. Extensive areas of these mixtures were established on the old red sandstone (ORS) podzols in the north Cork region. On these poor sites, the spruce was able to compete successfully with the nurse species, and in many cases overtop them, to form mostly pure crops which can be managed in the conventional way.

From 1993, the Afforestation Grant and Forest Premium Schemes, introduced under Council Regulation 2080/92 recognised that from an "*environmental, plant health and economic perspective, it is necessary to promote and ensure greater species diversity*" (Anon 1993). The grant and premium schemes gave significant encouragement to diverse and broadleaved planting and particularly with the latter, the use of mixtures to provide side shelter and encourage apical growth. In 1997, European larch/broadleaf mixtures were adopted for grant purposes in establishing oak and beech mixtures. On sites unsuited to European larch, Scots pine was used as a substitute (Huss *et. al.*, 2016).

1.3 Rationale for mixtures

The reasons why mixed plantations have been established in Ireland are many and varied. Silvicultural policy has changed over the years since the National afforestation programme began in response to new knowledge from research, experience, public demand and also external issues and pressures. Some of these are listed below - more or less in chronological order:

- **Convention** – British and continental silvicultural practices of planting mixed forests influenced Irish foresters in the 19th and early part of the 20th century. Hayes (1822) of Avondale in his "*Practical treatise on the planting and management of coppices*" extolled the advantages of mixed forests. Clear (1944) also wrote that "*the value of mixtures has long been recognised here as can be seen by the composition of the greater proportion of our mature plantations*." Anderson's ideas on species selection (Anderson, 1950) were also an influence. Besides advocating that species should be site adapted, he encouraged the planting of mixed crops to exploit any synergistic effects, as well as strengthen ecological stability.
- **Nursing** – The advantages of planting mixtures of SS/LP and SS/JL on nutrient poor sites were first determined from field trials in Ireland in the late 1970s (OCarroll 1978). This practice was then widely adopted and large areas of these mixtures were planted on the ORS region of the south of Ireland. Today, these mixtures feature prominently in the State and private forests, not only for the nursing effects, but in the case of SS/LP as self-thinning mixtures.
- **Self-thinning** – Stands of Japanese larch, lodgepole pine and Douglas fir in mixture with Sitka spruce can often inadvertently develop into self-thinning mixtures. However, mixtures of SS/LP(NC) were planted on unstable sites and on the western peatlands as self-thinning mixtures. The north coastal provenances of lodgepole pine are compatible with the growth rate of Sitka spruce in the early years. As the crop develops, the Sitka spruce overtops the lodgepole pine which is eventually suppressed leaving a canopy of pure spruce. The spruce crop can then continue to maturity without thinning.
- **Landscape enhancement**– During the 1960s and 70s, large tracts of pure Sitka spruce were planted in the uplands, thus creating what was perceived by stakeholders as a monotonous green conifer monoculture. The practice of planting Japanese larch in intimate mixture with SS was introduced in the 1980s to break up large tracts of uniform conifers. Japanese larch was considered very suitable for this task as the species follows the colours of the seasons.
- **Species Diversity** – The necessity to spread biological ris K has been/is one of the main reasons for planting mixtures. Having a second or third species in the plantation will ensure that, should any one fail as a result of disease, windthrow, drought, etc., the remaining species will continue to form a final crop. During the early 1980s there was an awareness that the planting programme was relying too heavily on one species with annual planting of Sitka spruce comprising approximately 80%. There was therefore a need to create greater species diversity in the National forest estate, not only to mitigate against plantation failure in the event of biotic or abiotic disasters, but also to provide a diversity of timber products including finishing timbers produced by species such as Douglas fir and broadleaves.
- **Hardwood timber** - In the mid-1980s the deforestation of the tropical regions became an international issue. The unsustainable exploitation of the hardwood resource occurred in many countries – Brazil, Indonesia, West Africa, etc. As Ireland imported much of its hardwood timber from tropical countries, there was a policy of increasing the planting of broadleaves to provide import substitution. This increase, while modest at first, gained impetus with the public demand for more broadleaves, the introduction of SFM and the EU requirement to significantly increase the percentage of broadleaves planted in the afforestation programme – mostly for the enhancement of biodiversity.
- **Silvicultural requirements for broadleaves** – traditionally, broadleaves have been planted in mixture with a nurse species for several reasons - provision of side shelter, reduction in the cost of establishment and early returns provided by the conifer nurse. Examples of excellent broadleaf stands that had been planted in mixture with conifers were reported by Joyce *et al*. (1998) and in addition to advice from abroad, were influential in deciding on a policy of mixtures for the establishment of broadleaves. Unfortunately, one of the mixtures suggested at that time was for alternate single lines of European larch or Scots pine with oak. This specific mixture has subsequently led to many poor crops of oak.
- **Stakeholder demand** - In the 1990's, increasing pressure came to bear on National forest authorities and companies to increase their level of broadleaf planting. FSC certification (and later PEFC) resulted in Coillte increasing their level of broadleaf planting. Major research projects at that time in areas such as biodiversity and public attitudes to forestry also concluded that increasing levels of broadleaves (especially native broadleaves) was desirable for the environment and society. This increase in pressure to plant more broadleaves resulted in more conifer/broadleaf mixtures being planted, for reasons already presented above.

1.4 Current situation

The National Forest Inventory (NFI) in Ireland currently defines pure crops and mixtures as follows:

- **Conifer pure**: More than 80% of coniferous tree species
- **Conifer/conifer mix**: More than 80% of mixed coniferous tree species
- **Broadleaf pure**: More than 80% of broadleaf tree species
- **Broadleaf/broadleaf mix**: More than 80% of mixed broadleaf tree species
- **Conifer/broadleaf mix**: A forest composed of broadleaved and conifer species, the minor category making up at least 20% of the canopy.

This definition does not always mean that the two (or more) species in a mixture are, in fact, interacting. For example, in a mixture as defined above, the minor species may occupy e.g. 25% of a woodland but this may be a stand-alone block and not interacting intimately with the remaining 75% of the woodland.

Today, mixed species crops are an important part of the forest types in this country with the NFI recording 300,000 ha of mixed forests or 47% of the National estate. Having a significant broadleaf element (172,000 ha), these crops require skilled silvicultural intervention at the correct time to ensure that the target species form the final crop.

Most mixed forests that have been planted since 1990 need urgent management within the next few years. If not thinned properly and in time, there is a high probability that many mixed stands will ultimately not meet the objectives for which they were established (Huss *et al*., 2016) as many conifer crops are already suppressing slower growing broadleaves.

While Irish foresters are very familiar with plantation establishment, and many mixed plantations have been successfully created, they have limited knowledge or experience in managing these crops in the succeeding life phase of the stands. Technical support and guidance to equip the forest managers/owners with the necessary skills to treat these crops is lacking at present. Also, research field trials and demonstration plots are limited, especially on farmland sites.

1.5 Methodology

The study was divided in to 5 tasks which follow the objectives set out by the COFORD Working Group viz:

Task 1. Examine, collate and critically review scientific evidence for the pros and cons of mixed forests related to growth and yield, wood quality, disease risk, biodiversity conservation and enhancement and climate change mitigation and adaption. The emphasis will be on plantation forests established as mixtures.

Task 2. Broadly catalogue species mixture types (including in tabular forma) used in Irish and British forestry practice and their extent in Ireland and collate as far as practicable and available, the rationale for their establishment taking into account 1 above.

Task 3. Review and critically examine evidence, including existing research, forestry practice, publications and other literature, on the performance of mixtures in terms of compatibility of species, growth, form and management, including ease of establishment and management, wood quality and the potential for mixtures to mitigate disease risk and for climate change mitigation and adaptation.

Task 4. Drawing on the above and with a view to informing future policy, measures and forestry practice, provide preliminary guidance on possible mixture types, and management of current intimate and non-intimate mixtures.

Task 5. Identify knowledge gaps and make recommendations on possible areas for inclusion in future National forest research calls.

Section 2 Pros and Cons of Mixed Forests

2.1 Introduction

Debate about the role and contribution of mixed forest stands to sustainable forest management goes back to the early years of forest science in the eighteenth and nineteenth centuries. Thus, in Germany, Hartig stated in 1791 that the "*mixing of deciduous and coniferous species is not advantageous*" and further asserted in 1804 that "*all mixed stands […] should be converted into pure stands of the constituent species* […]" (Pretzsch, 2005). By contrast, in 1828 von Cotta felt that *"[tree] growth is more lively in mixed stands […]* while, in 1886, Gayer's view was that "*The mixed forest does not only produce more, but also more valuable timber than that grown in pure stands*" (Pretzsch, 2005). Controversy about the relative merits of pure and mixed stands has continued until the present day, often hampered by the lack of empirical evidence to assess the validity of claim and counter-claim. These issues have often proved most problematic in countries and regions with extensive afforestation programmes that are generally based upon the planting of fast growing robust tree species in single species stands, as has been the case in both Ireland and Great Britain. For example, Steven (1927) noted that there had been an increasing use of pure rather than mixed plantations in Britain and also noted a tendency for planted mixtures to result in pure stands of one of the constituent species. The favouring of pure stands continued in Britain through much of the twentieth century, especially once the development of yield tables for single species stands, combined with the application of financial evaluation tools, appeared to indicate a better financial outturn from single species stands. Thus, in a seminal 1960s text on Forest Planning, one finds the following:

> *"In a crop composed of two or more species in mixture, one species will usually achieve a better combination of volume production and value per unit volume than the others. If this is so, revenue is lost by diluting the more profitable with less profitable species. The mixture can only be justified from the point of view of profitability if it can be demonstrated that the less profitable species produce a benefit equal to revenues foregone." (Johnston et al., 1965)*

The logical conclusion from such statements was that use of mixtures should be largely confined (in Britain) to marginal situations or non-commercial woodlands which, towards the end of the last century, resulted in use of mixtures being restricted to native broadleaved woodlands primarily managed for non-market purposes, to the use of conifer nurses in broadleaved plantings, and to nutritional conifer mixtures planted on sites of the poorest soil quality.

However, from the late 1990s, there started to be increasing awareness of the desirability of fostering mixed forests as a means of enhancing resilience to the impacts of climate change and the increasing occurrence of damaging pests and diseases. Thus, in the Read report (Read *et al.,* 2009), one finds the following:

> *"Uncertainties over future growth and potential threats to particular species […] have led to favouring the use of mixtures of species […] at a variety of scales as an 'insurance mechanism'." (pp 174-175).*

Reflecting this change in awareness, the forest policies of all countries in Britain have statements which support an increase in the area of mixed woodland (Mason, 2016). Thus, forest policy in Wales aspires that Welsh woodlands should comprise '*a diverse mixture of species'* and an increase in the proportion of mixed woodland is seen as one of the target indicators. In England, a recent corporate plan seeks to ensure that state woodlands (the Public Forest Estate) are diversified away from '*even-aged, single species plantations towards productive woodlands with a higher proportion of mixed species'* (Forestry Commission England, 2014). Meanwhile in Scotland, a recent review of the Scottish forestry strategy promoted the planting and management of mixed woodlands as part of climate change adaptation (Forestry Commission Scotland, 2014).

However, despite the greater interest in mixed forests in many parts of the world, including Britain and Ireland, there is arguably a 'policy-practice' gap in that forest managers find implementation of a policy favouring mixtures difficult to achieve and they are often uncertain of the implications for delivery of a range of ecosystem services. Some of these points were highlighted in a recent paper on knowledge gaps about mixed forests based on a survey of forest managers across the EU (Coll *et al*., 2018). The survey included managers from both Ireland and Britain, with no evidence of any difference in response from them compared to other managers elsewhere in the EU (Coll et al., unpublished data). The 10 questions that were highest ranked in this survey (i.e. where knowledge was most needed by managers) are shown in Table 5, together an evaluation of the current research knowledge on these topics. Some of the highest ranked questions relate to issues concerning the actual management and outputs from mixed forests (numbers 3, 5, 7 and 8) and for several of these, there is quite limited research information available. In the following section, we focus on evidence about the impact of mixtures on wood production, first considering volume of timber production and then implications for timber quality. Experimental evidence from Britain is noted where this is available.

TABLE 5: The 10 high-ranked questions relating to mixed forests resulting from a survey of 168 forest managers in 22 different European countries. For each question the current level of scientific knowledge was evaluated as follows: + (hardly any research results available), ++ (individual case-studies available), +++ (integrative studies, reviews or meta-analyses available). (Adapted from Coll et al., 2018).

Rank-position	Question	Current knowledge
#1	Which mixtures of species provide the best resistance and best resilience to climate change and natural disturbances?	+
#2	Are mixed forests more resistant and resilient to climate change and natural disturbances?	+++
#3	What silvicultural treatments should be applied to maintain the desired species throughout the entire stand rotation?	+
#4	Which mixture of species (or functional groups) should be used to optimise specific or combined management targets (e.g. productivity, biodiversity, stability…)?	++
#5	How do mixed forests affect the quantity and quality of wood production?	+++*
#6	Which positive and negative effects on different ecosystem functions (e.g. productivity, litter decomposition, stem quality) can occur when mixing particular species?	++
#7	How does the expected balance of benefits and costs compare between pure and mixed stands?	++
#8	Do mixtures allow more flexibility and provide more options to adapt to changing management objectives than monocultures?	+
#9	Do mixed-forests provide more ecosystem services than monocultures?	++
#10	Are mixed-forests more efficient in using resources (light, water, nutrients) than pure ones?	+++

* Refers to the level of knowledge on the relation between mixtures and the quantity of wood production. The existing knowledge in relation to the effects of mixtures on wood quality is much lower (+)

2.2 Growth and Yield

The traditional approach used for estimating wood production from mixed stands was to assume that it was equivalent to what would have been found in pure stands of the constituent species of the mixture expressed as a proportion of their occurrence in the mixture. Thus Johnston *et al*. (1965) considered:

> *"For practical purposes the volume produced by a mixture can be regarded as a mean of the production of each constituent. Therefore, with a species of Yield Class 20 on a particular site there would be no possibility of increasing the total production significantly by planting a second species in mixture unless it has a yield class of more than 20."*

However, by the late 1990s, evidence from long-term experimental trials in Germany and other European countries had begun to show that this approach could be over simplistic and that there were numerous instances where the yield from a mixed stand was greater than anticipated from the performance of the constituent species in pure stands. A number of reviews have been carried out to try to summarise the international experimental evidence on this topic (Table 6) covering a range of forest biomes from the tropics to the boreal region. These broadly indicate superior growth in mixtures compared to the predictions derived from pure stands.

The terminology now used in the literature to consider 'mixture effects' upon stand biomass production refers to **'overyielding'** where the productivity of a mixed stand is more than would be predicted based on the weighted average of the productivities found in pure stands of the component species. **'Neutral'** is where there is no interaction in the mixture and the productivity is simply an additive function of the species composition, while '**underyielding**' is where the productivity of the mixture is less than would be predicted from the pure stands. A special case is '**transgressive overyielding'** where the productivity of the mixture is greater than that of the most productive pure stand of the constituent species (Pretzsch, 2009).

Factors that can result in better performance in mixture include the ecological characteristics of the species being mixed (e.g. shade-tolerant species combined with light-demanders, or the use of a nitrogen fixing species as part of a mixture) or, if the species used in the mixture occupy different ecological niches, so that they can complement one another. While the gains reported may seem relatively modest, the trend of improved productivity in mixture is sufficiently general to suggest that the traditional assumption, that mixing of species had only a purely 'additive' effect upon stand productivity (*cf* the above quote from Johnston *et al*. (1965)), is incorrect and that 'multiplicative' effects can be found, given appropriate species combinations. Furthermore, other studies have indicated that a productivity increase of only 10 per cent (i.e. less than reported in Table 6) is sufficient to offset any additional costs associated with planting and managing mixed species stands, depending upon on product and rotation length (Nichols *et al*., 2006).

TABLE 6: A list of recent reviews of productivity in mixed forest stands compared with predictions derived from component species growth in pure stands.

Authors and year	Scope of study	Results
Piotto, 2008	14 tropical and sub-tropical studies	Positive effects of mixture upon plantation growth
Paquette and Messier, 2011	Temperate and boreal forests in Eastern Canada	Positive effects of increased species diversity upon stand productivity, especially in boreal forests
Zhang *et al*., 2012	54 studies in different parts of the globe	Taken overall, there was a 24 per cent overyielding in mixed stands compared with predictions from pure stands.
Gamfeldt *et al*., 2013	Boreal and temperate forests in Sweden	Biomass was >50 per cent greater, age for age, in stands with 5 species compared to those with one.
Pretzsch and Forrester, 2017 (Table 4.2)	Seven different two-species mixtures in long-term experiments in central Europe	Overyielding in the mixtures varied from 11-30 per cent depending upon species combinations.
Jactel *et al*., 2018	126 experimental case studies across the globe	Average overyielding in mixture of 15 per cent depending upon climatic factors.

The main dynamic processes which influence the occurrence of overyielding in mixed stands are competition, competitive reduction and facilitation (Bauhus *et al*., 2017a). Competition is the driving force when the component species compete strongly for the available site resources (e.g. light, moisture, nutrients) and there is no positive interaction between them. Competitive reduction occurs where the competition between the component species is less intense than that within a single species, which can result from different patterns of growth or niche occupancy between the species, such as might happen where a two-storey mixture develops with a light demanding species occurring in the overstorey and a shade tolerant one occupying the lower layers of the canopy. Facilitation arises where there is interaction between the species which results in an increase in a resource (e.g. moisture, nutrients) which might otherwise limit growth of the stand. This interaction can benefit all species in a mixture or may only benefit one constituent. The use of nitrogen fixing tree species as components of stands growing on nutrient limited sites is one example of this process (Piotto, 2008).

The extent to which these processes occur in a given mixture is thought to be influenced by the ecological characteristics of the component species, often termed their 'functional traits' (Bauhus *et al*., 2017a). These are factors that affect species performance such as their ability to survive, grow and regenerate. It is generally considered that complementary interactions between species are more likely if there is a difference in key functional traits (e.g. combining light demanding with shade tolerant species). The extent to which such interactions may occur is also thought to be affected by site conditions, in that facilitation is more important on sites with increasing biotic and abiotic stress (the so-called 'stress gradient hypothesis') while competitive reduction is more prevalent on less demanding sites.

2.3 Wood quality

As noted by Coll *et al*. (2018), knowledge about the effects of mixtures upon wood quality is substantially less than that for wood quantity (see Table 6 above) with very little information about the development of wood quality in mixed stands. Pretzsch and Rais (2016) reviewed some 100 publications which had compared wood properties in pure and in mixed stands (both even-aged and uneven-aged mixtures), which suggested that the greater structural heterogeneity found in mixed stands tended to result in trees with larger branch sizes and deeper crowns compared with pure stands leading to greater knottiness in the timber. Aspects such as wood density were unaffected, but incidence of reaction wood and the variation in ring width was higher in mixed stands (Pretzsch and Rais, op. cit., their Table 5). Benneter et al. (2018) carried out an assessment of stem quality in pure and mixed stands in six different regions of Europe which suggested a slight (but non-significant) trend towards lower stem quality in stands with more species, although high quality stems could be found in all stand types and all target species. The influence of silvicultural regime upon stand structure was thought to be critical for determining stem quality, with the use of group mixtures being seen as one way of providing patches of competitive uniformity to maintain stem quality within mixed forests.

Just as in Europe, there appear to have been few studies in Britain that have considered effects of mixtures upon wood quality. Cameron and Watson (1999) looked at branch formation and knottiness in Sitka spruce at 25-30 years of age when grown in nutritional mixtures with hybrid larch or lodgepole pine in north Scotland. They found that, in particular, the deciduous habit of the larch promoted greater ring width and detrimental knottiness in the spruce compared with the evergreen pine, with potentially negative consequences for sawlog outturn. Supporting studies also suggested greater incidence of compression wood in Sitka spruce growing in these mixtures compared with pure stands (Watson and Cameron, 1995). However, a subsequent study in a 41 years old experiment in the same region found no difference in either total volume production or sawlog recovery between pure Sitka spruce stands and two different nursing mixtures with larch species (Mason, 2014). In another experiment in northern England, after 47 years, stem form of several broadleaves (sessile oak, beech, and sweet chestnut) was appreciably straighter after being grown in mixture with larch and Scots pine when compared to the poor stem form in pure stands. However, no such improvement was found with silver birch (Gabriel et al., 2005). This result was thought to reflect the nutritional quality of the site being marginal for the first three broadleaves, which benefited from the nursing provided by the conifers, in an analogous way to that proposed for nutritional mixtures of conifers (Morgan *et al*., 1992).

In summary, there is a lack of definitive information upon the potential impacts of mixtures upon wood properties. Based on first principles, it seems reasonable to assume that the greater heterogeneity within mixed stands could result in greater variation in some wood properties (e.g. more variable ring width, larger branch size), and that such factors could be detrimental to aspects of wood quality. However, the actual implication of this variation will be dependent upon the silvicultural practices that are deployed, since careful thinning or group planting could do much to mitigate these potentially negative factors. Similarly, the effect of variation in growing environment may change over time, with differences that seem serious at a younger age lessening as the stand develops. The possibility that nutritional mixtures could be used to improve the stem quality of high value broadleaves also needs further investigation. The safest conclusion is that the practical consequences of the greater variation in environment within mixed stands upon wood quality depends upon the species being grown in mixture, the pattern of mixture that is used, the silviculture that is deployed and the qualities of the site where they are being grown.

2.4 Economics

As suggested by the quote from Johnston *et al*. (1965) in section 2.2, analysis of the financial performance of mixed stands traditionally assumed that the components of the mixture each performed like pure stands and that there was no interaction (beneficial or otherwise) between the components of the mixture. Perhaps for this reason, the economic outturn from mixed stands has rarely been examined or reported in the scientific literature (Knoke, 2017). However, in recent years a number of studies have been carried out in Germany, examining the financial returns and risks associated with growing pure stands of Norway spruce compared with mixtures of Norway spruce with beech on rotations of around 120 years (Greiss and Knoke, 2013). Using sample data from the Rhineland-Palatinate, they suggested that incorporating a small percentage of beech in mixture with the Norway spruce both increased economic return (estimated as Net Present Value (NPV)) over pure spruce and reduced the variation in the returns (see Table 7 below).

The main reason behind this was the lower incidence of wind and other damage to the spruce growing in mixture. Although increasing the proportion of beech to about 50% of the stand reduced the NPV of the mixture compared to pure spruce, the variation in the returns was again appreciably lower than that of the pure spruce. These results, and other similar studies, suggest that mixtures can offer an attractive financial proposition for a risk-averse forest owner (Knoke, 2017) (Table 7). The same author has argued that the financial benefits from a mixture are likely to be greater if the component species have different end-uses for their timber, thus allowing managers to access a wider range of markets.

TABLE 7: Economic returns from pure stands of Norway spruce and beech, compared with that from different group mixtures between these species (adapted from Knoke, 2017, TABLE 11.4)

Treatments	Average NPV (€/ha)	Standard deviation (€/ha)
Pure beech (BE)	2,506	1,380
Pure Norway spruce (NS)	4,850	1,820
NS 93%: BE 7%	5,255	1,494
NS 49%: BE 51 %	3,743	836

A Swedish study recently attempted to summarise the implications of converting Norway spruce monocultures to mixtures with either birch or Scots pine, such as the effects upon a range of ecosystem services including consideration of operational costs (Felton *et al*., 2016). They noted that promoting natural regeneration of either of the admixed species would likely reduce establishment costs, since the spruce could be planted at a lower density per hectare. However, there were likely to be increased costs due to complexity in managing mixtures while the larger number of timber assortments that might be anticipated from mixtures might be expected to raise logging costs by up to 6 per cent relative to pure spruce stands (Felton *et al*., *op. cit*.). However, as argued by Knoke (2017), they considered that mixtures could offer increased flexibility, allowing managers to respond to differing market conditions for the components of the mixture. Older Scandinavian studies had found that two storied mixtures, where birch formed the overstorey and Norway spruce the understorey were as profitable as pure Norway spruce (Mielikainen, 1996). Subsequent Finnish studies involving modelled outturns found that such mixtures were substantially more profitable than pure spruce, irrespective of whether the overstorey was comprised of silver or downy birch (Valkonen and Valsta, 2001).

There appear to have been few attempts to consider the economic implications of growing mixtures in Britain or Ireland. The main exception is in the case of the nutritional mixtures of pine or larch combined with Sitka spruce on nutrient poor soils. On these sites, stands of pure spruce might require several applications of nitrogen to reach canopy closure, not to mention possible herbicide applications to control heather competition. By contrast, the use of a mixture would reduce the need for heather control and eliminate the requirement for nitrogen inputs. This could result in a saving of over £500/ha in establishment costs for a mixture, compared with a pure Sitka spruce stand (Mason and Connolly, 2018). This would offset any potential loss in production at rotation age, resulting from the presence of the admixed species.

In summary, there has been relatively little examination of the economics of growing species in mixture, largely because historically there was a lack of definitive evidence showing positive interactions between species. However, with increasing awareness that mixed stands may offer greater resistance to abiotic and biotic risks, it is becoming clearer that mixed stands can offer economic improvements over pure stands in certain circumstances. These include:

1. where natural regeneration of useful woody species can provide a matrix within which trees of a planted crop species can flourish, so saving on establishment costs;

2. where the structure of the mixed stand improves the stability of individual trees of a vulnerable species and hence its resistance to windthrow;
3. where an admixed species can facilitate the growth of a desirable species on a site where it would otherwise be marginal.

2.5 Vulnerability of mixtures to insect pests, pathogens and browsing pressure

There is increasing evidence from studies across Europe to indicate that, on average, a given tree species is less likely to be damaged by insects when it is growing in mixture than is the case in pure stands (Jactel *et al.*, 2017). This phenomenon appears to be caused by differences in feeding strategy between specialist and generalist insect herbivores whereby the mixtures provide resistance to insects that attack particular species. There are three mechanisms proposed for this difference, first that specialists achieve higher density in pure stands and so cause greater damage, second that host trees are less 'visible' when growing in mixture and therefore are harder for the specialists to find, and third that mixed stands are likely to contain a higher abundance of insect predators which helps to control specialist pest populations. A specific point emerging from these studies is that the amount of tree species richness in mixture (i.e. the number of species in the stand) is less important than that the mixture contains contrasting species with different functional characteristics (e.g. a mixture of conifers and broadleaves is likely to be more resistant than a mixture of pine species) (Bauhus *et al.*, 2017b).

Although these conclusions are based on an extensive meta-analysis of studies dating from 1960 to 2012 (Castagneyrol *et al.*, 2014), there are exceptions where mixtures appear to confer no improvement in resistance to insect pests, which occurs when the pest is a generalist which can feed on a wide range of tree species. Mixture effects can also change over time, as shown by a study of damage by one specialist insect pest, the pine processionary moth, to maritime pine (*Pinus pinaster*) trees in south-western France. Both the density of this moth and the rate of attacks on the pines were reduced in mixtures of maritime pine and silver birch compared with pure pine stands (Damien *et al.*, 2016). However, the benefit appeared to decline across the three-year period of this study, as the height of the pine began to exceed that of the birch, presumably making the former more apparent to the moth. Thus, realising the potential for increased resistance provided by mixtures against insect pests will depend upon the characteristics of the insect, the types of tree species used in the mixture, and the relative growth of the components of the mixture over time - including how this is affected by management interventions such as thinning.

There appear to be fewer studies that have investigated the impact of mixtures upon fungal pathogens, although Jactel *et al.* (2017) cite reports from North America where the incidence of root rots (caused by *Armillaria ostoyae*) was lower in mixed stands of conifers and broadleaves than in pure conifer stands. Other evidence suggests that mixed stands can reduce the impact of *Heterobasidion annosum* in susceptible conifers in Europe, although the magnitude of any effects was quite small and seemingly up to 20-30% of resistant species are required for the mixture to have any substantial impact. In general, the benefits of mixtures appear to be greater when a specialist pathogen is involved (as for insect pests), but interestingly, a report from California indicated that the risk of damage by *Phytophthora ramorum* was lower in areas with high tree species diversity (Haas *et al.*, 2011 in Jactel *et al.*, 2017). The reports of impacts of mixtures upon leaf pathogens are limited, mostly inconclusive, and are mostly confined to studies in experiments with young stands established in recent years (Bauhus *et al.*, 2017b). However, studies in short rotation coppice stands of willow have shown that incidence of foliage rust is much lower in clonal mixtures than in pure stands (McCracken and Dawson, 1998).

Reports of differences in ungulate browsing pressure between mixed and pure stands appear to be mostly based on observation rather than on experimental evidence (Jactel *et al.*, 2017). These authors cite some Finnish studies which suggest that the percentage of trees browsed by moose and the intensity of browsing was greater in the plots with more tree species present. However, the use of less palatable nurse species can be one way of using mixtures to reduce the browsing pressure on more palatable species.

2.6 Biodiversity

One of the fundamental reasons which many people use to argue for an increased use of mixtures is that they improve forest biodiversity. Some European studies have attempted to see how far this assumption is valid. For example, Gamfeldt *et al*. (2013) used Swedish national inventory data and various indicators of biodiversity to see how tree species richness affected the provision of a range of ecosystem services. They found a positive relationship between number of tree species and factors such as the game production potential, understorey plant species richness, and the incidence of deadwood habitat. More recently, Felton *et al*. (2016) attempted to synthesize knowledge on the potential impact of converting pure Norway spruce stands in Southern Sweden to mixtures with either birch or Scots pine. They found particular benefit from mixtures with birch, with likely increase in both species richness and abundance for forest birds, understorey vegetation, certain beetles dependent upon decaying wood, and lichens. These increases could be further augmented through modifications to stand management, such as the provision of deadwood or the lengthening of rotations. By contrast, the biodiversity benefits anticipated from pine-spruce mixtures were less, although the different bark characteristics of two species would increase the range of micro-habitats while the two species were known to support different lichen and fungal flora. However, a study examining differences in spiders and carabid beetles in mixtures of Scots pine and oak as well as pure stands of each species in three regions of Britain and Ireland was unable to find any differences between the stand types (Barsoum *et al*., 2014).

The key piece of research which has been carried out in Ireland on the subject was through the COFORD funded FORESTBIO project, published in 2011 (O'Halloran *et al*., 2011). Although the earlier BIOFOREST project looked at the biodiversity of Irish afforestation plantations, the FORESTBIO project looked specifically at intimately mixed-species plantations.

Within the project, Norway spruce (NS) was chosen as the primary plantation tree to examine. Sitka spruce would have been preferable because of its importance in Ireland but suitable mixed plantations were not available. Oak and Scots pine were chosen as the secondary mix species. Five NS/oak mixes and five NS/Scots pine mixes and ten nearby stands of pure NS were selected, resulting in 20 forests in total to be studied. In all the study sites, the secondary mix species (oak or Scots pine) accounted for between 5 and 40% of the planted crop and this was intimately mixed with the primary tree species (i.e. distributed more or less evenly throughout the stand). To minimise environmental and other variation, mixed and pure forests were located in geographic pairs, as close to each other as possible.

Within the study, surveys were carried out of epiphytes, ground vegetation, invertebrates (ground- and canopy-dwelling spiders and beetles, and lepidoptera) and birds across all 20 sites. A summary is given below for each group studied.

Epiphytes

The NS/Scots pine mixtures were significantly richer in lower trunk and canopy epiphytes than the pure NS plots. When mixed with Scots pine, the NS held more canopy epiphyte species than when planted with the oak. However, species richness of any of the investigated taxa did not significantly differ between pure NS and NS/oak mixtures. The canopies of both pure NS and the NS/oak mix plantations were significantly less open than those of NS/SP mixtures and the oak was generally suppressed by the NS.

Ground vegetation

The research found no significant enhancement of ground vegetation species richness in mixed stands. In addition, the pure NS and the NS/SP mixtures had similar values for all species combinations and both had higher values of total, vascular plant and typical woodland species richness than the NS/oak mixtures. The project found evidence of increasing light availability on the forest floor in SP mixtures compared to pure stands.

As mentioned earlier, the oak, particularly, had been supressed by the NS and this had led to the oak making up a small proportion of the canopy when the study was carried out. At that point in the rotation, the oak may have very little impact on overall diversity as the main structure of the stand was composed of the spruce.

Ground-dwelling invertebrates and lepidoptera

The project found that, in the stands assessed, the mixed and pure crops did not show any strong differences in assemblage composition and species richness. In addition, stand structure, litter and vegetation cover were similar between mixed and pure stands. In the NS/oak mixtures, this may be due to the smaller size oak trees in comparison with the spruce - with the former sub-dominant in the canopy. Previous work suggests that the deciduous proportions need to be higher than 50% to support invertebrate species associated with a deciduous forest.

In previous studies, SP, because of its more open canopy, generally supports greater plant and invertebrate diversity compared to pure spruce. In this study, however, the NS/SP mixture did not support a different invertebrate fauna compared to the matching pure NS stands.

Previous research has shown that moth richness is positively related to tree species diversity. In this study, however, there was no strong indication of a difference in species composition between the mixed and pure stands. As discussed previously, the secondary mix trees (oak and SP) may not have been present in high enough proportions to facilitate the development of a ground vegetation community typical of oak or SP pure plantations, and hence provide the larval food plants with which specialist moth assemblages are associated.

Canopy-dwelling invertebrate

NS/oak mixtures supported an intermediate number of phytophagous species, perhaps because colonisation of oak trees in the mixtures may have been more difficult for phytophagous species than in pure oak woodlands due to the intimate mixing of NS and oak (with relatively low mixing ratios of just 20-40% oak). In addition, as mentioned previously, the oak was suppressed by the NS and was being shaded out. The smaller oak trees in the NS/oak mixtures provided a smaller available canopy habitat for phytophagous beetles, relative to the sampled trees in native oak woodlands or pure, planted oak forests.

The NS/oak woodland supported an assemblage of spiders more similar to that found in native oak woodlands, and the presence of a native broadleaved tree species in the oak mix plantation doubled the diversity of spider guilds present compared to the pure plantations. The presence of oak trees in the oak mixes had a significant influence on phytophagous beetle species, which were present in significantly higher proportions in oak mix than in pure plantations. This may be due to one or more of several factors, including the small size of the oaks in the oak mixes, their isolation in the coniferous plantation, and the low numbers of oak specialist phytophagous species found overall.

Birds

No consistent differences in bird populations between mixed and pure plantations were found in the study, although the trend was for both NS/SP and NS/oak mixtures to have higher species richness and total bird density than pure NS plantations. The relationship between shrub cover and species richness and bird density suggests that the ecological state of the forest rather than the tree species per se probably has the greatest influence on the bird communities in woodland. Crop management can play an important role here and thinning increases light transmittance to lower canopy levels. Mixtures often carry bird populations somewhere between those of pure coniferous and pure broadleaved stands, but this pattern was not evident in this study where differences between the pure NS and the mixed plantations were small.

Most species achieved their highest population densities in mixed plantations, with some (e.g. blackcap, blue tit and treecreeper) two to three times more plentiful in mixed plantations compared to pure Norway spruce. Some of the differences between the NS/oak and NS/SP mixtures may be due to the different growth rates of the secondary tree species (as already mentioned above).

Conclusions and Recommendations

- In this study, the presence of oak or SP in an intimate mixture with NS appeared to have little effect on diversity and community composition of the taxa studied, with the important exception of those groups specifically adapted to living or feeding on native broadleaved trees.
- Results suggest that the inclusion of a light canopied conifer (e.g. SP) or a broadleaved species (oak) does not always increase light penetration to a point where the biodiversity of NS plantations is enhanced.
- The reason for the limited effect of the mix species on biodiversity may, in this study, be because the proportion of SP and oak in the mixtures were low and that the subsequent supressed crowns were insufficient to affect light penetration. Using faster growing broadleaf trees e.g. birch may have an advantage over oak in this situation.

- The influence of a native tree species on the invertebrate fauna of mixtures may be affected by factors such as the proportion of the canopy occupied by that species, its ability to compete successfully with conifers, and the ratio of edge: patch size of that tree species. Mixed plantations may therefore benefit environmentally from planting more competitive native broadleaved trees or favouring more of them when thinning to increase their competitiveness and enhance habitat availability for broadleaved-associated species.
- Another possible solution, which may be preferable from a commercial point of view, is to mix conifers and broadleaves at a larger scale by planting pure stands adjacent to each other rather than mixing species intimately. Although not mentioned in the Report, the planting of group mixtures might also have been an alternative.

2.7 Climate change

The use of mixtures is frequently cited in the literature as one of the recommended ways of adapting forests that are composed of species that may be vulnerable to the potential impacts of climate change (e.g. increased risk of drought). Thus, Bolte *et al.* (2009) considered that an adaptation strategy could involve:

> *'[…] adaptation includes the active transformation of forest[s] to […] admix species sensitive to climate change with tolerant species […] that are potentially better adapted to future climate conditions.' (p. 476)*

A number of European studies have sought to explore the basis for this approach, focussing particularly upon mixtures involving species such as Norway spruce and beech which could be vulnerable to drought under a warming climate. For example, Neuner *et al.* (2015) carried out a modelling study using data from southern Germany. This indicated a substantially higher mortality for pure spruce stands grown on a 120-year rotation than when the spruce was admixed with beech. More detailed studies in the same region investigated the growth response to drought stress of beech, sessile oak, and Norway spruce when grown in pure and mixed stands (Pretzsch *et al.*, 2013). They found that beech recovered quicker from stress when grown in mixture with sessile oak, believed to be due to the hydraulic lift of water from lower soil horizons by the deeper rooting oak. In contrast, the response to drought stress of the beech and spruce (both comparatively shallow rooted species) showed little difference between pure and mixed stands. Therefore, it appears that the functional characteristics of the species can be an important feature in designing mixtures that are likely to be resistant to stress (see also Metz *et al.*, 2016).

In contrast to drought, there appear to have been fewer studies which have sought to investigate the potential impact of mixtures on an increased risk of wind disturbance due to climate. Most reports of lower levels of wind damage in mixed stands are based upon surveys following major storms where the results can be compromised by differences in soil type or past management (Bauhus *et al.*, 2017b). For example, Schutz *et al.* (2006) investigated the incidence of damage to Swiss forests following storm Lothar in December 1999. Their results suggested that the stability of spruce stands had been improved by the presence of 10-20% of beech in these stands, possibly because the spruce had developed deeper crowns and a more stable form when growing in mixture. Their results also indicated a similar benefit when a small percentage of Douglas fir (a deeper rooting conifer than spruce) was present in the mixture. One problem is that it is not clear whether incorporating a more stable (deeper rooting) species into a mixed stand with a more vulnerable species will make the whole stand more resistant to windthrow, or simply reduce the overall level of damage in line with the proportion of the more stable species. In an examination of strategies for increasing the resilience of Scottish Sitka spruce forests to climate change, Cameron (2015) has recommended wider use of conifer-conifer mixtures as a means of easing uncertainties over future health and growth of pure Sitka stands in a changing climate. He followed Wilson and Cameron (2015) in recommending western hemlock, Douglas fir, and grand fir as being the most likely species to be suitable for planting in mixture.

Conceptually, greater use of species mixtures can be a means of providing an insurance against the uncertain hazards that can arise from climate change (e.g. extreme droughts or increased frequency of winter storms). Thus, if one species succumbs, the presence of other species in the stand offers some continuity of a forest structure and the continued delivery of the desired ecosystem services. However, delivering this theoretical benefit from mixtures depends upon a good diagnosis of the particular site(s) and the likely vulnerability (or otherwise) of the species present to the hazard of interest. The advent of decision support systems such as the Ecological Site Classification (ESC) (Pyatt *et al*., 2001) which can be coupled with climate change projections makes it possible to indicate the likely effects upon individual species in the future and so to identify combinations which might make for more resistant mixtures. Such 'stable' combinations can be used to develop a framework of Forest Development Types, incorporating both conifers and broadleaves as exemplified in Denmark (Larsen and Nielsen, 2007).

2.8 Public attitudes/Landscape

Although timber production was the key objective of early afforestation in this country, attitudes have changed and today it is generally accepted that our forests provide more than simply economic benefits to society. In addition to wood products, forests provide services such as biodiversity, carbon sequestration, employment, water protection and recreation opportunities. It can be difficult, however, to place a specific value on these latter benefits. Only in recent years have techniques become available to aid researchers and policy makers in this regard and it is in the last twenty years that researchers in this country have started looking at benefits of forestry other than those linked specifically to the value of timber produced. The publication of COFORD's Report "*Economics of Irish Forestry*" (Clinch, 1999) included, for the first time in this country, the potential costs and benefits of forestry to wider society and not just the forest owner.

Public attitudes to mixtures

Since the Clinch (1999) study mentioned above, most of the work carried out in this area here has concentrated on the attitudes of various groups and communities to forests. Most of these attitudes have been assessed through the use of household surveys (O'Leary *et al*., 2000) or directly through interviews (Ní Dhubháin *et al*., 2009). In both the surveys and the interviews, respondents have generally been asked a wide range of questions about their attitudes to forests in this country. These questions range from preferences around forestry vs. agriculture, species used in afforestation, harvesting systems used and access to recreation facilities provided in the forests.

In terms of specific questions on species, respondents have generally been asked for preferences around conifers vs. broadleaves and only sometimes have mixtures been included as an option in these surveys. When included, the use of mixtures has generally implied the use of conifer/broadleaf mixtures and not conifer/conifer or broadleaf/broadleaf mixtures.

In 2011, Coillte and the Heritage Council commissioned a study (Goodbody, 2011) to determine the value that the Irish public place on three public goods provided by the Coillte estate:

- The forest landscape provided by Coillte's management of its forests (Figure 1);
- The habitats and species (as a proxy for biodiversity) supported by the Coillte estate;
- The protection and management of a range of cultural features on the Coillte estate.

Within this study, the term mixture was not used but images of mixed stands were used in both the sections on landscapes and habitats/species (Figure 1). Respondents were given choices on creation of attractive landscapes and maintaining a wide range of habitat and species. The results from the survey suggested that people valued the public good provided by the habitats/species within a forest over three times more than the landscape provided by that forest (€92/person/year vs €27/person/year respectively) (Goodbody, 2011). Although the various questions and choices provided to those surveyed alluded to mixtures, the results from this study do not allow the effect of mixtures per se to be assessed in a standalone way.

Questionnaire on some public benefits provided by Coillte

Goodbody ECONOMIC CONSULTANTS

Coillte is a state-owned company that is charged with managing the State's forests on a commercial basis. It does this in a way that benefits the Irish public[1]. As part of its management of its forests, Coillte:

- Impacts on the landscape;
- Maintains a range of different habitats for plants and animals on its land; and,
- Conserves archaeological and historic features[2] on its land.

Landscape

If Coillte wanted to earn as much money as possible it would plant large, uniform, blocks of trees. These blocks would all be cut at the same time creating large clear areas.

In fact, Coillte aims to manage its forests in a way that harmonises with the landscape. Trees are planted in smaller plots; a range of different tree types are planted; and the trees are harvested at different times so that some forest cover is always in place.

If Coillte only wanted to create an attractive landscape it could plant "natural looking" forests of native trees; tree harvesting would be very limited and these forests would be of very limited commercial value.

FIGURE 1: Image shown to respondents in Coillte/Heritage Council study showing a transition from one species to a mixed forest within a forested landscape.

In a COFORD study in 2006 (Ní Dhubháin *et al*, 2006), the authors used a technique called input-output analysis to assess the linkage between the forestry growing side, the wood products sector and other sectors of the economy. The impacts were determined using a combination of qualitative and quantitative techniques in three case study areas. These areas were Shillelagh, Co Wicklow, Arigna, Co Roscommon and Newmarket, Co Cork.

Although the study did not set out to assess the attitudes to mixtures specifically, the topic was raised at various points in the report (text in *italics* below are direct quotes from interviewees):

Shillelagh area

There was also a concern that not only should forestry development be kept under control in Shillelagh but that a balance in species **mixture** should be achieved in order to respect the traditional character of the forest landscape.

"Hardwoods are mainly the legacy of the former demesnes, the old estates… When the forestry programmes started in the late 40s, early 50s, 90 to 95% of what was planted was conifers. That's mainly what's there if you look around Wicklow. But now and again broadleaves are encouraged… We wouldn't want to see just a continuous line of conifers all over the place."

Newmarket and Arigna areas

"In both Arigna and Newmarket few of those surveyed referred to the amenity value of forests. Those who did were negative.

The Sitka spruce forests are of no interest as amenity woodland for people…… would be more acceptable for people if they had amenity woodlands with broadleaved species or with a ***mixture****.*

The low amenity value of forests in general in the Newmarket area was confirmed by the foresters interviewed.

Forests in the area have a very low use for amenity; the main objective so far has been timber production. But the situation now is changing and we try to develop opportunities such as picnic areas and marked roads. We are also developing horse riding and long-distance trails and we encourage a mixture with broadleaves in new afforestation sites."

In general, those interviewed over the course of this study had definite ideas of what type of forests would be acceptable to them into the future. In general, respondents (some of whom were foresters) felt that more space should be given to broadleaved and mixed forests.

In a more recent study in this country (Upton *et al*., 2012), public preferences were investigated in relation to management approaches to our afforestation programme. It became evident from early focus groups, however, that public understanding of the identity of tree type was limited. The study, therefore, simply divided the forest types into conifer, broadleaf and mixed (as in mixed conifer/broadleaf) as had been used in other studies elsewhere (e.g. Nielsen *et al*., 2007). Although the word "biodiversity" was not familiar to the focus group participants, it was suggested to the participants (based on previous studies) that mixed forests supported the greatest diversity of species, followed by broadleaves.

The results from the Upton et al. (2012) study suggested that participants preferred mixed forests over broadleaf, followed by conifer. It is not known, however, how much of this preference is influenced by the implied biodiversity ranking mentioned earlier. In other studies, however, mixed forests were also preferred over broadleaf and conifer forests (Mill *et al*., 2007; Nielsen *et al*., 2007). It can be difficult in studies like this, however, to tease out why certain individuals or groups prefer one forest type over another. In the Nielsen study already mentioned (Nielsen *et al*., 2007), the authors found that respondents with a greater "environmental knowledge" (not defined) generally had a more positive preference for mixed forests.

Section 3. Mixtures in the forest estate

3.1 Mixtures in Irish Forests

3.1.1 Inventory Databases

To provide guidance on policy and best practice in dealing with existing mixed species plantations, statistics (such as type, extent, species composition, location, etc.) are required on their attributes. This information is contained in three main databases:

- National Forest Inventory (NFI)
- Grant and Premium Categories (GPCs) and
- Coillte inventory.

The NFI is a statistical and multi-resource survey first carried out in 2006 in the National forest estate on a series of permanent sample plots on a randomised systematic grid sample design. The survey is repeated periodically and a second assessment was carried out in 2012. It is these published data that will be used in this part of the report. The NFI gives an overview of the attributes of mixtures of all ages, both planted and naturally occurring, that are contained in the National forest estate (both private and Coillte).

The GPCs are categories under which Grant and Premia are administered for the different forestry schemes. Detailed information on all afforestation carried out under these schemes is available, including data on mixtures from 2006 to 2017, with less detailed information from 1989 to 2005. This database provides the most accurate information on mixed plantations that have been established in the last 20 years and, for which, urgent guidance is required.

The Coillte inventory provides further information on the nature of the species mixtures that are to be found in the public forest estate.

Between the three databases, it is possible to provide a comprehensive view of mixed plantations which will help to focus on the most common mixtures for which guidance is required.

3.1.2 National Forest Estate

The second National Forest Inventory (NFI) was carried out between 2009 and 2012 by the Forest Service. The objectives were to assess the current extent, state, composition and change to Ireland's forest resource, both public and private in a timely, accurate and reproducible manner. Data from this inventory provide multi-resource information on parameters such as area, species, growing stock, biodiversity, health and vitality, carbon content and soil type for the entire forest estate.

In categorising mixed species crops, the NFI database was interrogated to provide information at National level on different attributes of these crops. Data obtained included the sub-division of the European Forest Types (EFT) of conifer into conifer/conifer mixtures and broadleaf into broadleaf/broadleaf mixtures. These, along with the reported conifer/broadleaf mixtures published in the NFI results give a more complete breakdown of the different types of mixed crops.

While the NFI contains a vast amount of data on a wide range of parameters, 11 were selected to best describe the attributes of mixed crops at National level. These include species mixture type on the stocked forest area by:

1. ownership
2. forest sub-type
3. even-uneven aged
4. tree distribution
5. mixture
6. nativeness
7. development stage
8. forest establishment type
9. number of tree species
10. number of non-tree plant species
11. humus form

The extraction of further information on different aspects of mixtures is possible but, for the purposes of this review, it was confined to the eleven parameters.

Data tables and graphs are presented in Appendix 1 in the same format as the NFI published results. Key statistics, however, are summarised in Table 8.

TABLE 8: Key Statistics on mixtures from the NFI 2012.

Attribute	General	Mixture		
		Conifer/Conifer	Broadleaf/Broadleaf	Conifer/Broadleaf
Area	Similar areas of pure and mixed forests in the National forest estate - 337,000 ha (53%) pure and 300,000 ha (47%) mixed.	Conifer/conifer mixtures comprise 127,731 ha or 20% of the total forest area and 43% of the mixed forest area.	Broadleaf/broadleaf mixtures 83,000 ha or 13% of the total forest area and 28% of the mixed forest area	Conifer/broadleaf mixtures 88,807 ha 14% of total forest area and 30% of mixed forest area.
Ownership	There are 128,856 ha (38%) mixed crops in public ownership and 171,008 ha (58%) in private hands.	Conifer/conifer mixtures 55,632 ha in public and 72,099 ha private ownership.	Mixed broadleaves 21,211 ha in public and 62,114 ha private ownership.	Conifer/broadleaf mix 52,013 ha (59%) public and 36,795 ha (41%) private ownership.
Age	Mixtures are 63% even aged and 37% uneven aged.	Even-ages dominate conifer/conifer mixtures at 91.5% (116,889ha).	Uneven ages dominate broadleaf/ broadleaf mixtures at 80.3% (66,890ha)	Even ages dominate conifer/broadleaf mixtures at 62.6% (55,581ha)
Tree distribution	Tree distribution of mixed crops tends to be either regular (56%) or random (42%) with very few groups (2%).	Conifer pure and conifer/conifer mixtures tend to have a regular tree distribution - 97% and 84.3% respectively.	Broadleaf /broadleaf mixtures tend to have a random tree distribution - 82.2% compared with 17.8% regular distribution.	Conifer/broadleaf mixtures are 52% regular, 44% random and only 4% in groups.
Mixture type	Uniform mixture type (where one species is present) is most prevalent (53%). Individually mixed (where more than one species present - 37.8%) and group mixtures (groups of trees of each species, which include line mixture) 9.2%.	Conifer/conifer mixtures have 82% individually mixed and 18% group mixed (lines mixes are included in groups)	Broadleaf/broadleaf mixtures are generally individually mixed i.e. more than one species present, with species mixture occurring in a random manner (91.3%).	Conifer/broadleaf mixtures are mostly individually mixed 68% - compared with 32% for groups mixed (which included line mixtures).
Nativeness	Mixed crops comprise 48% non-native species and equal amounts of native species (26%) and those of mixed nativeness (27%).	Conifer/conifer mixtures are 99% non-native.	Broadleaf/broadleaf mixtures are mostly native 81% (67,303ha).	Conifer/broadleaf mixtures are dominated by species of mixed nativeness - 74% (65,585ha).
Development stage	48% of the mixed crops are in the thicket, small pole and pole stages (141,311ha).	65% of conifer/conifer mixtures are in the thicket, small pole and pole stages (82,870 ha)	13% of the broadleaf/broadleaf mixtures are in the thicket, small pole and pole stages (10,812ha). 61% of broadleaf/broadleaf mixtures are multi-storeyed (50,000ha)	54% of conifer/broadleaf mixtures are in the thicket to pole stages (47,629ha).
Establishment	Afforestation accounts for 54% of mixed crops, reforestation 26% and semi-natural establishment 20% make up the remainder.	Conifer/conifer mixtures are mostly in the afforestation establishment type (98,096 ha or 77%) with only 23% in restock.	Broadleaf/broadleaf mixtures are evenly distributed between afforestation (17%) and reforestation (15%) but most are in the semi-natural establishment type (68%).	Areas for conifer/broadleaf mixtures are similar for afforestation 48,816 ha and reforestation 37,590ha. Only 2.7% (2,401ha) are in the semi-natural establishment category.
No. of tree species	In the mixtures that contain broadleaves, there is a higher number of tree species present than in the conifer mixtures.	Only 3% of the conifer/conifer mixtures have 5 or more tree species	12.2% of the broadleaf/broadleaf mixtures have 5 or more tree species.	12.1% of the conifer/broadleaf mixtures have 5 or more tree species.
No. non-tree plant species	The Conifer/broadleaf mixtures lie midway between the pure conifer (75.7%)and pure broadleaf (91.7%) stands for 6 or more non-tree plant species.			88.7% of conifer/broadleaf mixtures have 6 or more non-tree plant species present.
Humus formation	Mixed crops are intermediate between conifer and broadleaf crops in terms of the different types of humus formation. 10% of conifer crops have mull formation, conifer /broadleaf crops have 17% while broadleaves have 29%.			

3.1.3 Private Plantations

Introduction

A National programme for the restoration of forest cover in Ireland, after centuries of over exploitation, was started by the State in the mid-1920s. Extensive afforestation of marginal agricultural land with conifer species was undertaken with the objective of providing a sustainable supply of timber from home grown sources. For the next five decades, State forests continued to form the greater part of the afforestation effort, but from the mid-1980s, arising from the Western Development Package, private forestry emerged as an important factor, driven by improved establishment grants to a point where, by 1989, it became more significant than public afforestation (Malone 2008). Afforestation moved from the hills and bogs to more fertile and sheltered sites on farmland. The planting of broadleaves was facilitated through generous Grant and Premium Schemes and mixed species plantations were encouraged, particularly as a means of providing shelter for broadleaves and early returns from conifer nurses. Today, public forests comprise 38% mixed species while the private forests 58%.

In order to gain further insight into mixed plantations in the private sector, the IFORIS (Integrated Forest Information System) was interrogated for data on mixtures under the different Grant and Premium Categories (GPCs).

Methodology

Species categories
Detailed data on mixtures in the different GPCs are available from 2006-2017. Earlier data with less information are also available from 1989 but it was decided to present the 2006-17 data as it is more comprehensive and gives a better insight into the mixtures. There are 47 tree and shrub species listed that are eligible for grant aid under the afforestation schemes. Many (30) are minor species with small areas and these were reclassified as “Other Broadleaves” or “Other Conifers” in order to reduce the number of species codes. The different lodgepole pine provenances (NC and SC) were grouped together as were the birches and sessile and pedunculate oaks (Table 9).

Using the reclassified species codes, data were obtained on mixtues from the GPCs through the IFORIS system. Results are presented in summary tables and graphs below.

TABLE 9: Reclassification of species codes.

Species Name	Species Code	Species Code Reclassification	Area (ha)
Sitka spruce	SS	SS	139,944
Norway Spruce	NS	NS	18,609
Japanese larch	JL	JL	14,369
Ash	Ash	Ash	13,744
Lodgepole pine (NC)	LPNC	LP	10,837
Pedunculate oak	PO	PO	9,302
Alder	Ald	Ald	8,545
Additional Broadleaves	ADB	ADB	7,085
Sycamore	SYC	SYC	5,381
Scots pine	SP	SP	3,511
Hybrid larch	HL	HL	2,110
Beech	BE	BE	1,173
Douglas fir	DF	DF	1,092
Birch	BI	BI	1,076
European larch	EL	EL	736
Lodgepole pine (SC)	LPSC	LP	356
Norway maple	NM	OB	256
Cherry	CH	OB	207
Serbian spruce	SerbS	OC	145
Western red cedar	WRC	OC	122
Sessile oak	SO	SO	119
Spanish Chestnut	SC	OB	63
Corsican pine	CP	OB	48
Other conifer	OC	OC	34
Western Hemlock	WH	OC	20
Hazel	HAZ	OB	14
Downy birch	DBI	BI	9
Lime	Lime	OB	8
Rowan	ROW	OB	8
Monterey cypress	MC	OC	8
Monterey pine	MP	OC	7
Red oak	RO	OB	7
Leyland Cypress	LeyC	OC	6
Grand fir	GF	OC	4
Austrian pine	AP	OC	3
Lawson Cypress	LC	OC	3
Holly	HOL	OB	2
Southern beech	SBE	OB	2
Coast Redwood	CR	OC	1
Hawthorn	HAW	OB	0.6
Goat willow	GW	OB	0.5
Guelder rose	GROSE	OB	0.3
Silver birch	SBI	BI	0.2
Italian alder	IALD	OB	0.1
Rusty willow	RW	OB	0.1
Poplar trichobel	POP	OB	0.1
Eucalyptus glaucescens	EUC	OB	0.0
Total Area (ha)			**238,966**

No. of species per parcel

The extent of species diversity in the afforestation programme from 1998 can be seen by the indicator "No. of Species per Parcel". In total, 70% of the area established comprises between 2 to 4 species with the greater proportion (41%) occurring as two species (Table 10).

TABLE 10: Number of species per parcel.

No. of species per parcel	Area (ha)	Percentage
1	65,468	27%
2	98,520	41%
3	50,811	21%
4	18,134	8%
5	4,588	2%
6	792	<1%
7	492	<1%
8	55	<1%
9	43	<1%
10	18	<1%
Total	**238,921**	**100%**

Species by GPC

Another measure of species diversity is the area established under the different GPCs. While the GPCs largely define the species to be planted, there is variation which is likely to be attributable to local site and soil conditions or to enhance plantation design (Table 11 and Figure 2).

TABLE 11: Area of species established under the different GPCs.

GPC Class	ADB	ALD	ASH	BE	BI	DF	EL	HL	JL	LP	NS	OAK	OB	OC	SP	SS	SYC	Grand Total
1 - Unenclosed	931	728	133	7	50	9	6	120	1,575	5,491	151	27	7	31	178	23,314	54	32,812
2 - Sitka spruce/ lodgepole pine	115	41	60	5	4	9	5	12	210	3,905	142	79	33	2	32	38,409	42	43,104
3 - 10% Diverse mix	3,900	1,591	264	29	694	54	73	1,188	9,716	1,482	252	239	19	180	270	76,177	107	96,235
4 - Diverse	638	254	135	16	52	988	214	754	2,690	294	17,945	74	47	97	1,317	1,727	117	27,359
5 - Broadleaf (except oak & beech)	1,033	4,590	13,078	212	70	13	35	28	137	20	75	528	467	38	115	217	5,045	25,700
6 - Oak	257	42	68	186	73	19	352	7	36	2	25	8,182	24	4	1,465	60	13	10,815
7 - Beech	58	3	3	718	1	50	1	5	0	16	27	1	0	61	3	3	950	
8 - Alder	63	1,204	3	0	56	0	1	23	1	7	5	1	1,365					
9 - NWS Est (Scenarios 1-3)	62	28		68	220	15	0	53	445									
10 - NWS Est (Scenario 4)	24	60	17	15	2	13	131											
11 - Agroforestry	0	5	0	0	6													
Grand Total	**7,081**	**8,541**	**13,744**	**1,173**	**1,084**	**1,092**	**736**	**2,110**	**14,369**	**11,193**	**18,607**	**9,419**	**616**	**351**	**3,511**	**139,912**	**5,381**	**238,921**

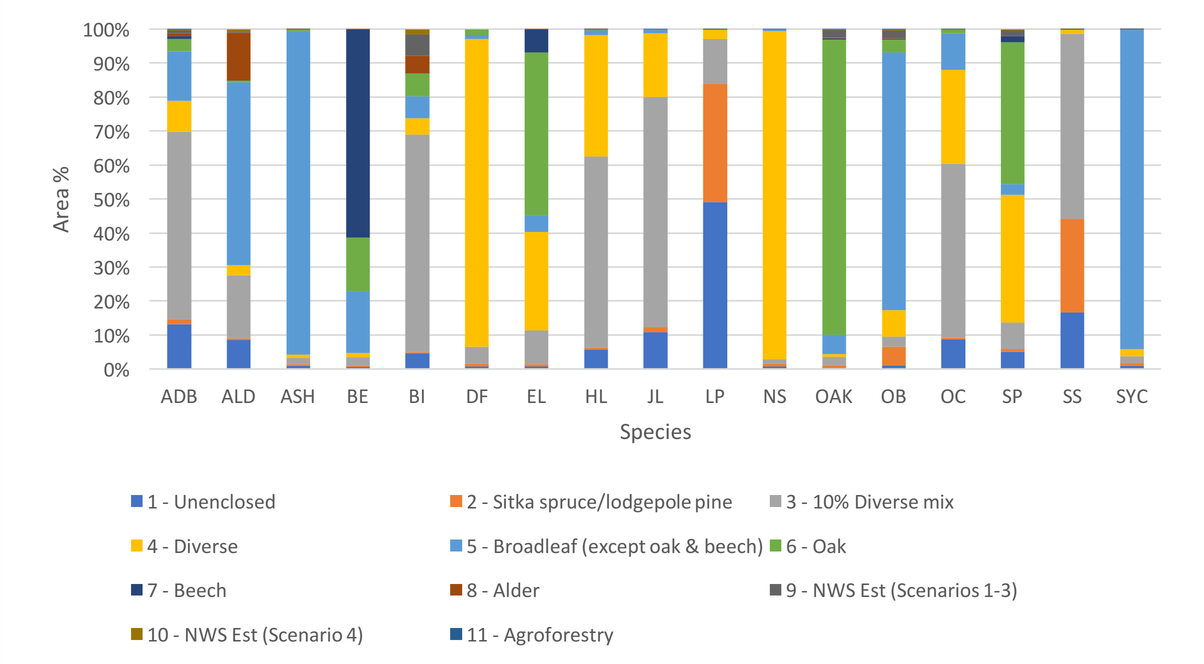


FIGURE 2: Breakdown of species established under the various GPC's

Mixture types by species

Information on four different mixture types is available from the GPCs – Group, Intimate, Row and Pure (Table 12 and Figure 3).

TABLE 12: Area (ha) of main species in mixed stands established in GPCs 2006-17.

Species	Group	Intimate	Row	Pure	Total (ha)
Sitka spruce	5,946	14,589	1,708	13,860	36,103
Norway spruce	489	313	122	3,720	4,645
Lodgepole pine	26	409	63	101	599
Scots pine	187	225	332	255	998
European Larch	29	57	80	90	256
Hybrid larch	85	348	14	260	708
Japanese larch	210	1,600	54	361	2,225
Douglas fir	21	71	13	156	261
Other conifers	23	91	3	94	211
Oak	533	767	947	2,036	4,282
Beech	24	49	52	128	253
Ash	331	397	45	1,878	2,651
Sycamore	34	52	5	199	291
Birch	189	297	68	468	1,022
Alder	538	649	90	2,277	3,554
Additional broadleaves	718	1,232	196	1,530	3,677
Other broadleaves	18	20	8	41	88
Total (ha)	9,401	21,168	3,801	27,454	61,824

In total, mixed crops amount to a significant proportion (34,370ha) 56% of the total GPC area for the period for which detailed information is available (61,824ha).

Intimate mixtures are by far the most common mixture type employed (21,168ha), followed by Group mixtures (9,401ha) with Row mixtures being the least used (3,801ha).

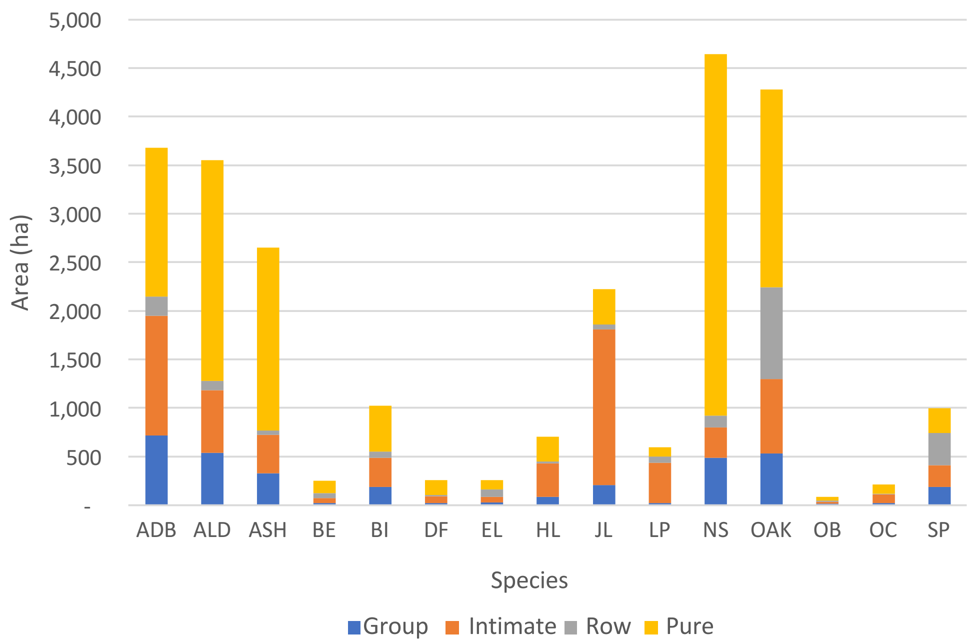


FIGURE 3: Area of mixture types by species.

Sitka spruce has been graphed separately (Figure 4) as the area is so large that it distorts Figure 3. The species with the largest areas are ranked in the different mixture types as follows:

Group:	Sitka spruce, additional broadleaves, Norway spruce and oak.
Intimate:	Sitka spruce, additional broadleaves, Japanese larch, alder and oak.
Row:	Sitka spruce, oak, Scots pine.
Pure:	Sitka spruce, Norway spruce, alder, oak, ash and additional broadleaves.

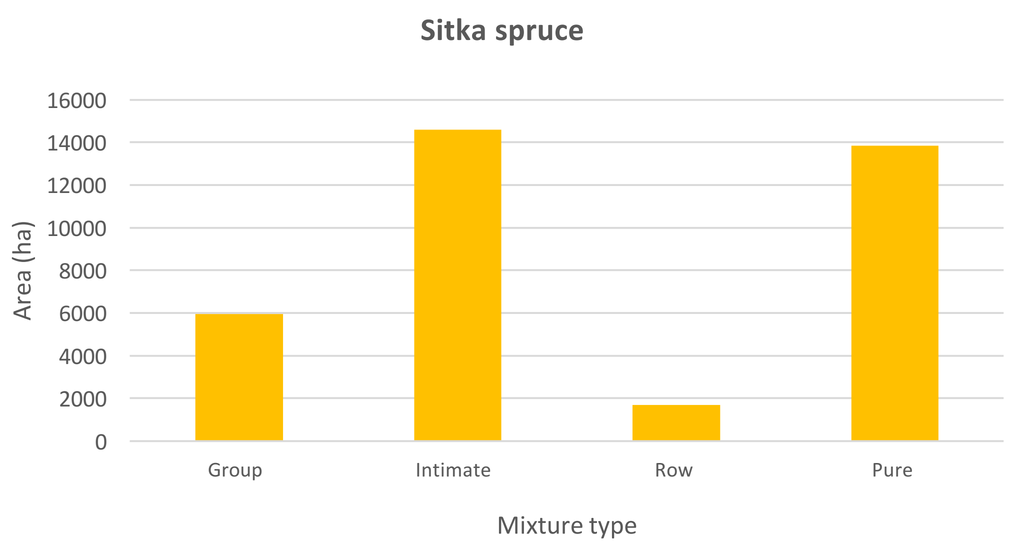


FIGURE 4: Area of Sitka spruce in the different mixture types.

Mixture type by year

The areas of Group and Row mixtures planted have remained quite steady over the 11-year period but there has been a significant decline in the area of intimate mixtures with a corresponding rise in pure crops (Table 13 and Figure 5). The reason for the decline in intimate mixtures has been the removal of the SS/JL mixtures which was traditionally an intimate mixture. GPC3 used to be a 20% mix but is now 10% mix with other broadleaves and minor conifers. These are generally planted around the plantation edge or in groups. Table 14 and Figure 5 show these data broken down further by GPC.

TABLE 13: Area (ha) of main mixture types established in GPCs 2006-17.

Completion Year	Group	Intimate	Row	Pure	Total (ha)
2006	637	3,667	579	2,487	7,369
2007	420	2,621	380	1,407	4,828
2008	373	1,341	195	812	2,720
2009	434	1,475	245	641	2,795
2010	706	2,367	346	1,395	4,814
2011	783	1,050	87	3,298	5,217
2012	906	1,632	190	2,570	5,298
2013	1,053	1,975	265	3,060	6,353
2014	1,055	1,830	249	3,383	6,517
2015	969	1,154	205	2,992	5,320
2016	937	1,316	384	3,601	6,237
2017	1,130	740	675	1,809	4,354
Total (ha)	9,401	21,168	3,801	27,454	61,824

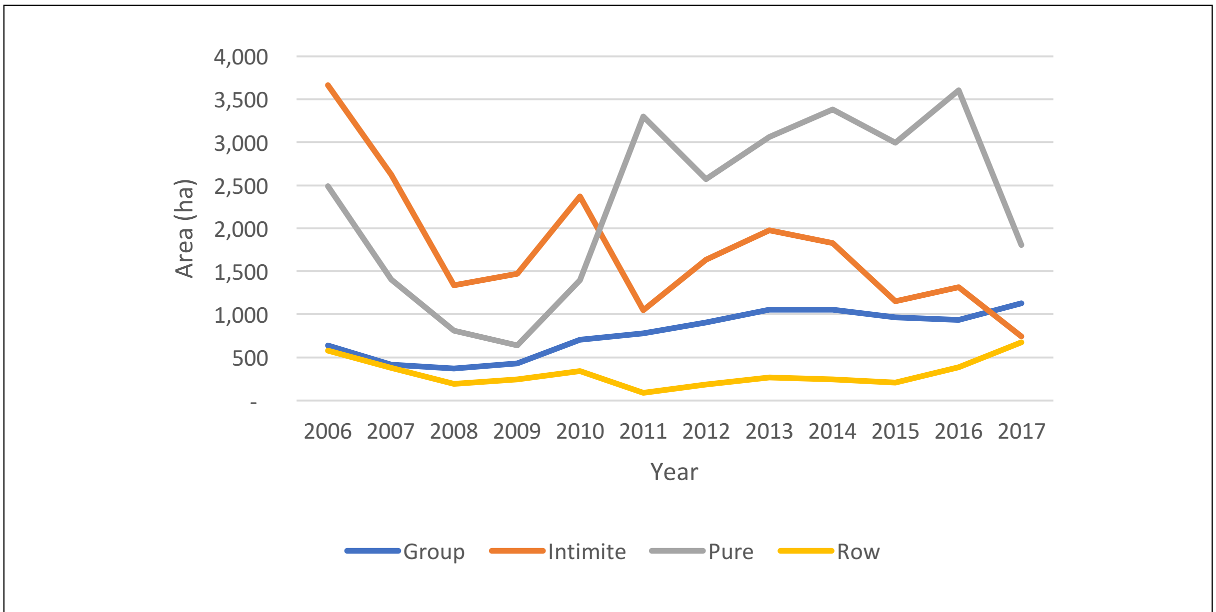


FIGURE 5: Establishment of mixture types over time (2006-17).

Mixture type by GPC

TABLE 14: Mixture type by Grant Premium Category (GPC).

Grant and Premium Category	Group	Intimate	Row	Pure	Total
Unenclosed	440	1,707	214	735	3,096
SS/LP	14	42	0	33	89
10% Diverse	6,604	16,854	1,826	15,325	40,609
Diverse	653	578	158	4,802	6,191
Broadleaf (excl. oak & be)	794	766	90	3,425	5,075
Oak	371	773	1,401	1,997	4,542
Beech	15	71	72	121	279
Alder	176	181	34	973	1,364
NWS (Scenario 1-3)	271	134	3	36	444
NWS (Scenario 4)	65	61	3	2	131
Agroforestry	0	1	0	5	6
Forestry for fibre	0	0	0	0	0
Total (ha)	9,403	21,168	37,801	27,454	61,826

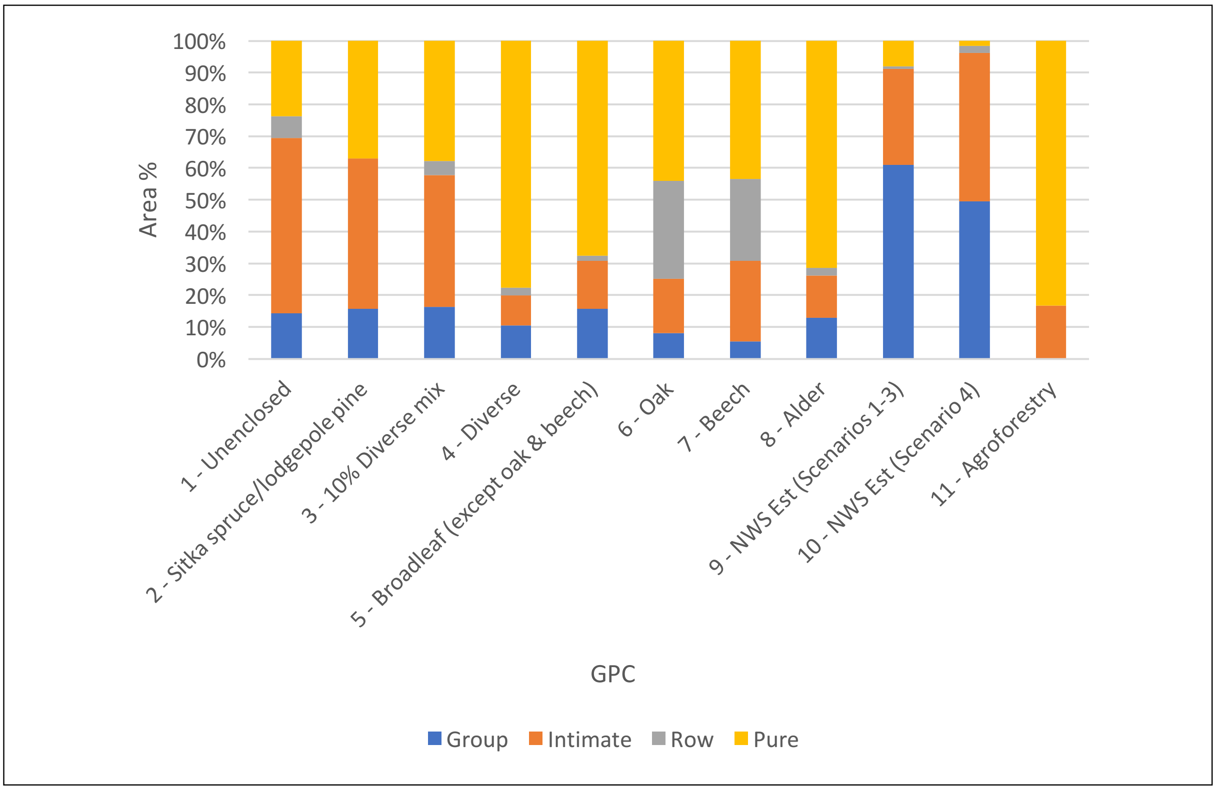


FIGURE 6: Mixture type by GPC.

Mixtures of main species

Five conifer and five broadleaves, which represent the main species occurring in the parcels, were selected to show the area of other species growing with them. The information was classified into percentage classes occupied by the main species. The latter, which had the largest areas, were then graphed to show the percentage of the main species in the mixture. This gives an idea of the species ratio in the mixture. Graphs for Sitka spruce are shown in Figure 7 with the graphs for the other 9 species presented in Appendix 2.

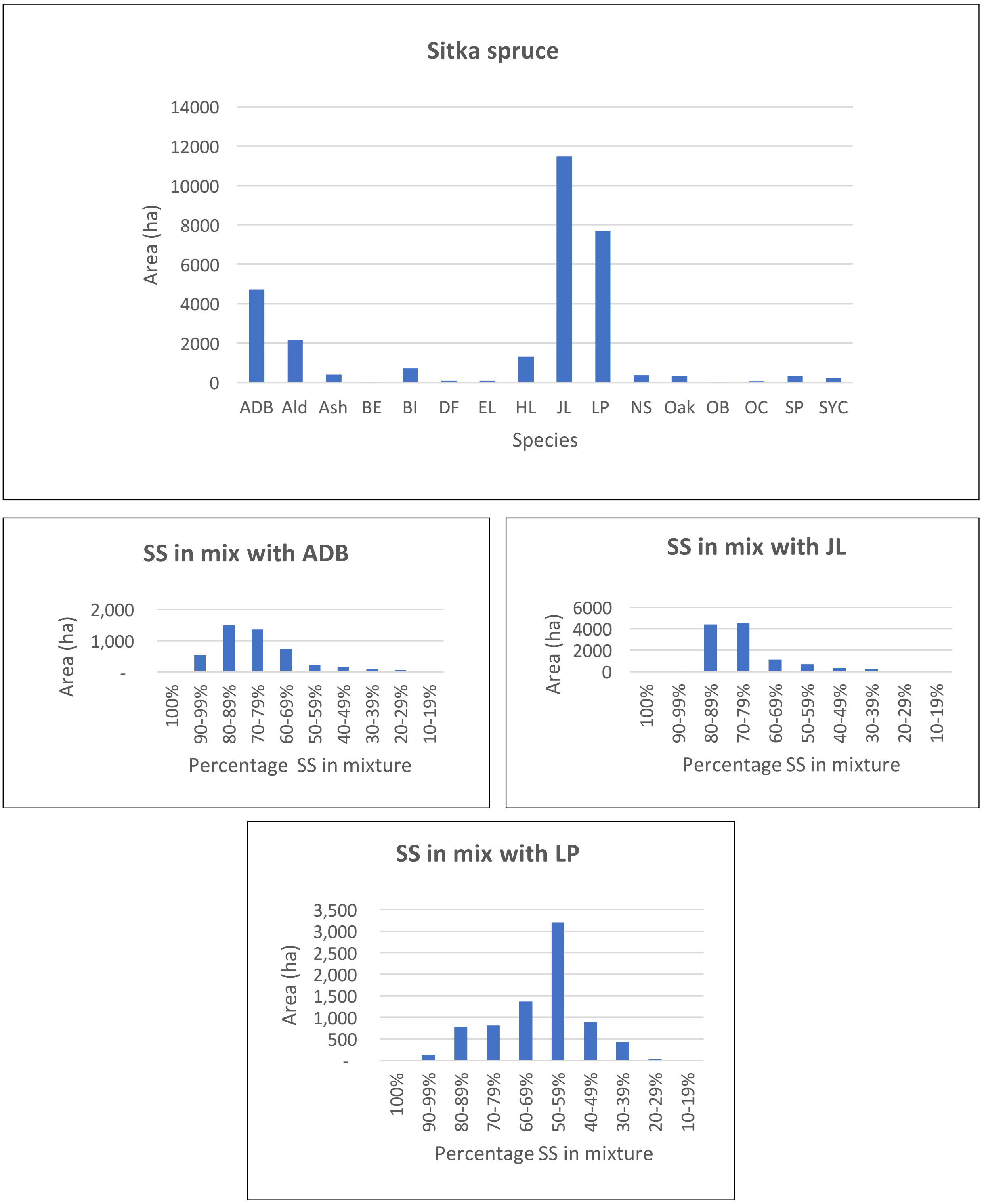


FIGURE 7: The breakdown of Sitka spruce in mixture with other species (four graphs).

Figure 7. The species mixtures identified in the analysis above were ranked in order of area. The top mixtures in area are listed below (Table 15 and Figure 8). Sitka spruce, being the main species, is represented in 6 of these mixtures with SS/JL, SS/LP and SS/ADB having the largest areas.

TABLE 15: Species mixtures ranked by area from the GPC data (2006-17).

Mix type		Area (ha)	
SS/JL		11,490	
SS/LP		7,683	
SS/ADB		4,726	
SS/Ald		2,163	
Ash/Syc		1,603	
Oak/SP		1,358	
SS/HL		1,323	
SS/Bi		726	
Syc/Ash		556	
Ash/Ald		484	

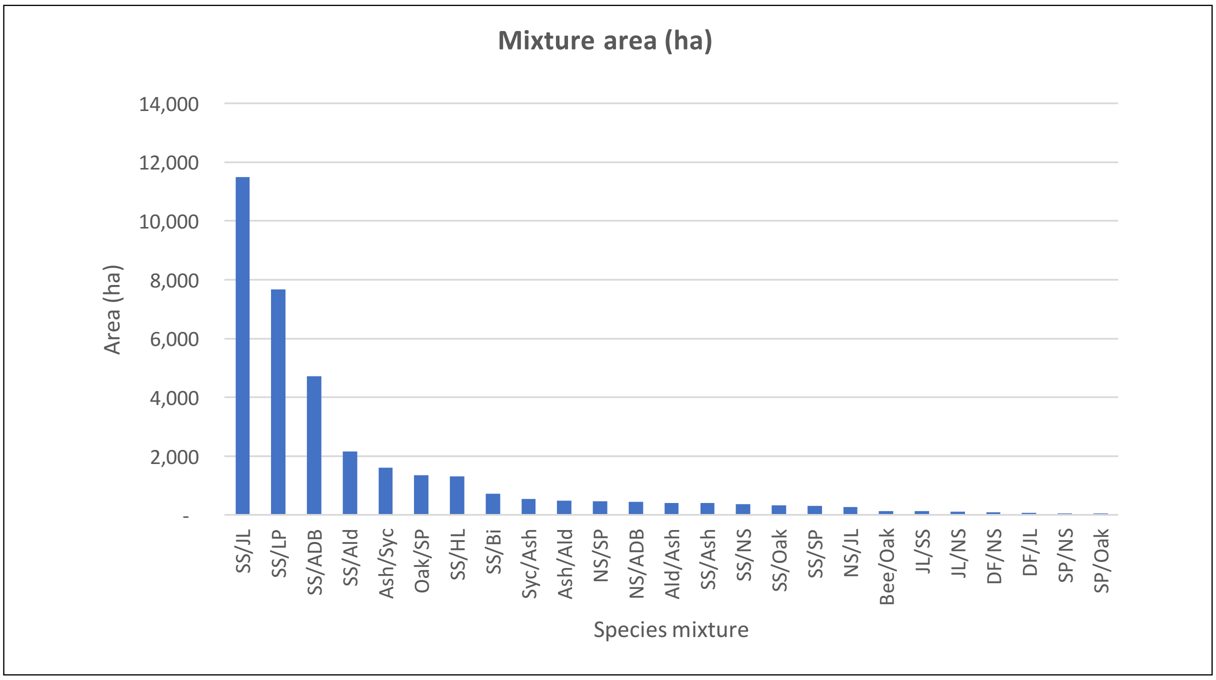


FIGURE 8: Species mixtures ranked by area from the GPC data (2006-17).

3.1.4 State (Coillte) Forests

The data making up the inventory information in this Section are based on an original dataset supplied by Coillte Inventory Section. A "mixture" is defined in the Coillte Inventory as any woodland where a second species makes up greater than 20%. The dataset is made up of compartments and sub-compartments from conifer high forest (CHF), mixed high forest (MHF) and broadleaf high forest (BHF) and includes intimate and non-intimate mixture types.

Within the three land use types (CHF, MHF and BHF), there are a total of 67,321 ha of mixed forest in the Coillte estate (approximately 15% of the entire Coillte estate). This total is broken down as follows (Table 16).

TABLE 16: Mixtures in the Coillte estate.

Mix type	Area (ha)
Broadleaf/broadleaf	8,241
Conifer/broadleaf or Broadleaf/conifer	15,813
Conifer/conifer	43,267
Total	67,321

The oldest recorded mixture in the Coillte estate dates back to an oak/beech mixture where the oak was planted in 1720. The database includes mixtures planted up to the current year (2018). Although there doesn't seem to be a specific policy in Coillte on mixtures, some mixtures are still being planted and approximately 1,500 ha of mixtures have been planted in the Coillte estate since 2011. Mixtures involving Sitka spruce, Scots pine, alder, birch and oak make up 76% of the total in that period. Very few mixtures which include lodgepole pine (45 ha using all provenances) have been planted since 2011.

Using the definitions outlined above, there are 22,000 stands defined as mixtures within the Coillte estate. Many mixture types are represented by relatively small areas so, for the purposes of this report, only those mixture types greater than 450 ha are shown in the tables below. The break-down is as follows:

Main mixture types (overall)

The ten mixtures with the greatest area in the Coillte estate are given below in Table 17. Note that the primary species in the mixture is given firstly.

These overall figures are broken down further into the main broadleaf/broadleaf, conifer/broadleaf (and broadleaf/conifer) and conifer/conifer mixtures in the following tables.

Broadleaf/broadleaf

The main mixtures (>450ha) in this category are given in Table 18.

Conifer/broadleaf and broadleaf/conifer

The main mixtures (>450ha) in this category are given in Table 19.

Conifer/conifer

The main mixtures (>450ha) in this category are given in Table 20.

3.2 Mixtures in British Forests

The United Kingdom (UK) comprises the countries of England, Northern Ireland, Scotland, and Wales. In 2017, forests amounted to 3.17 million ha of the land area of the UK, equivalent to 13.0 per cent (Anon., 2017). This figure has increased from a low of around 5 per cent of the land area in 1905 and the increase reflects the effects of a major afforestation programme carried out for much of the last century. Conifers account for 51 per cent of the growing stock, but this varies from 26 per cent in England to 74 per cent in Scotland (Anon., 2017). 28 per cent of the area is made up of public forests, managed by state forest organisations (Forest Enterprise England, Forest Enterprise Scotland, Natural Resources Wales, and Forest Service Northern Ireland).

TABLE 17: Largest mixtures (by area) in the Coillte estate.

Mix type	Area (ha)
SS/LP	16,630
SS/JL	10,905
LP/SS	4,937
SS/Bi	2,720
Bi/SS	1,064
JL/SS	1,037
NS/Bi	900
SS/NS	807
DF/SS	705
Bi/NS	687

TABLE 18: The main broadleaf/broadleaf mixtures in the Coillte estate.

Mix type	Area (ha)
Ald/bi	637
Oak/bi	612
Be/ash	542
Oak/be	490
Be/oak	480

TABLE 19: The main conifer/broadleaf mixtures in the Coillte estate.

Mix type	Area (ha)
SS/bi	2,720
Bi/SS	1,064
NS/bi	900
Bi/NS	687
SS/ald	686
Oak/SP	535
SS/OB	508

TABLE 20: The main conifer/conifer mixtures in the Coillte estate.

Mix type	Area (ha)
SS/JL	10,905
SS/LPN	8,647
SS/LPS	7,342
LPS/SS	3,160
LPN/SS	1,146
JL/SS	1,037
SS/NS	807
DF/SS	705
SS/LPL	641
LPL/SS	631
NS/SS	630
SS/HL	607
DF/JL	506
SS/DF	462

The twentieth century afforestation programme involved the creation of extensive areas of single species plantation forests, often composed of non-native species. Thus, Sitka spruce is now the commonest tree species in Great Britain (Mason, 2007) and is the most important species for the timber processing sector, especially in Scotland. Throughout the last century, the deliberate creation of mixed stands was relatively limited and was largely confined to the use of conifers to nurse broadleaves in lowland Britain and to the planting of 'nutritional' mixtures on poorer soils in the uplands (Kerr *et al*., 1992).

Perhaps because of the relative lack of importance of mixtures in British forests, estimates of the extent of mixed forests in Britain vary considerably (Table 21).

TABLE 21: Recent estimates of the area of mixed stands in British forests.

Year	Area of mixtures (K ha)	Percentage forest area	Notes	Reference
1988	209.6	26	Forestry Commission forests only	Kerr *et al*. (1992)
1998	244.1	10	NIWT report	Anon. (2013)
2010	1,247.0	44	MCPFE indicator 4.1	MCPFE (2011)
2011	93.9	2	NFI	Anon. (2013)

Some of this variation is due to difference in the ways of defining a mixed species stand. In 1988, a stand was classed as mixed if more than one species occurred within a sub-compartment, even if the various species were planted in pure blocks (Kerr *et al*., 1992). The MCPFE 2011 report considers a stand to have more than one species if an admixed species represents > 5% of the basal area of the stand. The 1998 and 2011 National Forest Inventory reports consider a stand to be mixed where no single species occupies more than 80% of a stand (Anon., 2013). The considerable discrepancy between the 1998 and 2011 figures is almost certainly due to the latter only providing data on 'mainly conifer' and 'mainly broadleaved' mixtures. This seemingly ignores conifer-broadleaved mixtures which amounted to about 75,000 ha in upland Britain (Mason, 2006) with a similar estimate for the area of this type of mixture in lowland Britain (WLM, unpublished data).

The 2011 report (Anon., 2013) indicated that over 80% of the identified mixtures (81.6 K ha) occurred in private woodlands with only around 12 K ha found in Forestry Commission forests. Around 50% of the mixtures were reported from England with lower proportions present in both Scotland and Wales. The data suggest that the amount of 'mainly conifer' and 'mainly broadleaved' mixtures is quite similar at 48.8 K ha and 45.2 K ha respectively (Anon., 2013, Table 8).

Partly because of this variation, it can be difficult to obtain good estimates of the main species grown in mixture and the types of mixture that are employed. The most recent woodland map arising from the British NFI does not allow easy breakdown of the main species found in mixture (Anon., 2013). Kerr *et al*. (1992) indicated that 51% of broadleaves on the public forest estate were being grown in mixture compared with only 25% of conifers. The percentage of conifers occurring in mixture was highest for Scots and lodgepole pines (30 and 38% respectively), compared with 19% for Sitka spruce.

Section 4. Performance of Mixtures

4.1 Ireland

4.1.1 Species Mixtures in Irish Forestry Literature

A literature review was undertaken to gather documented information on the performance of mixtures in Ireland. The dearth of both published and grey literature on mixtures reflects the policy and practice of establishing and managing single species plantations from the early days of afforestation until relatively recently. It is only in latter years that mixed species plantations have been established to any great extent, encouraged by the afforestation grants GPC 6 & 7.

Much of the current knowledge on the performance and management of species mixtures has been gained either through personal experience, forestry lore or guidance from abroad. Also, mixture types are often described in the literature, but details of their performance are seldom given. For example, Horgan *et. al.* (2004) give a useful listing of potential mixture types involving pure conifers, pure broadleaves and conifer/broadleaves. As many of these have yet to be tested in Ireland, however, it is not known how they will perform on different sites.

In conducting this review, it was decided to focus on the performance of mixtures reported in Irish forestry literature based on experimental data, or on sites where stand history has been recorded.

The mixtures established for which information is available have a number of objectives:
- Nutrient nursing
- Protection
- Self-thinning
- Crop development
- Soil enrichment
- Disease risk reduction

Nutrient Nursing

Mycorrhizae
The beneficial effects of mixed species on the nutrition of crops in Ireland was first shown scientifically by OCarroll (1978). This was demonstrated in an experiment established with Sitka spruce, Japanese larch and lodgepole pine in intimate and band mixtures on an impoverished Old Red Sandstone site in Avondhu forest, Co. Cork.

Periodic assessments of mean height and height increment of the Sitka spruce showed that there were no differences between treatments up to the 10th year. In the following 6-year period the height increment of the spruce mixed with larch was significantly greater than that either of the pure spruce or the spruce mixed with lodgepole pine. The pine did not significantly improve spruce growth, compared with that in pure spruce plots, until the assessment of mean height at 18 years, when a significant increase was associated with nursing by the pine.

Foliar analysis showed that the nitrogen content of the spruce had been significantly increased in the plots mixed with larch. There was also a significant increase in the intimate mixture with pine, but not in the band mixture and there was a significant increase in foliar phosphorus only in the plots mixed with larch. The differences in foliar potassium levels were not statistically significant, although their trend in general is similar to that for nitrogen and phosphorus.

Further work was undertaken to investigate the nursing effect at Avondhu as part of an EU funded collaborative project with British researchers working on the same phenomenon (Carey e*t al*., 1988). The results showed that the total nitrogen content of the larch and spruce came to 307kg/ha compared with 110kg/ha in the pure spruce plots. The spruce in the mixture plots contained 210kg of the 307kg of nitrogen present in the treatment.

The nursing effect appeared in one way or another to be closely related to root activity. The extra nitrogen in the mixed plots came from the soil and, in addition, there was a rapid turnover of nitrogen in the mixture plots. The results suggested that it was possible that the improved nitrogen status of the spruce in mixed stands may be due to direct transport of nitrogen from either the nurse species, the soil or both.

There were strong indications of substantial differences in the fungal flora associated with spruce mycorrhizae from pure and mixed stands. Differences in other associated fungi were also evident. The mycorrhizae hypothesis was further investigated at Avondhu, initially by Heslin *et al*. (1990), followed by further work by McElhinney and Mitchel (1991, 1993, 1995) and McElhinney (1995). This work included the influence of ectomycorrhizal fungi on the response of Sitka spruce and Japanese larch to forms of phosphorus; an evaluation of in vitro methods for the production of ectomycorrhizal fungus inoculum and phosphatase activity of four ectomycorrhizal fungi found in the Sitka spruce and Japanese plots. The results showed greater diversity of mycorrhiza species under the mixture plots than in the controls and provided more evidence of the role of ectomycorrhizal fungi in the utilisation of organic P substrates in the soil.

While providing scientific data on the effects of mycorrhizae, the practical implications of the results were not discussed and reported to the forest industry. Also, further work was not undertaken to test the possibility of inoculating transplants with suitable forms of mycorrhizae to enhance survival and subsequent early growth on nutrient deficient sites.

A nursing effect of Sitka spruce by Douglas fir was also recoded in a field experiment established at Ballyhoura Forest in 1976 - again on a poor Old Red Sandstone soil. The effect was first noted eight years after the establishment in plots of Sitka spruce adjacent to Douglas fir. Height, leader length and diameter of the spruce were measured in lines parallel and adjacent to the Douglas fir to determine the spatial progress of nursing. Foliar analysis indicated that the effect was nutritional, rather than due to shelter. The authors recommend that Douglas fir/Sitka spruce mixtures should be considered on similar soils, the main benefits being the extended species choice, increased diversity and reduced need for fertilisation (McCarthy and Horgan, 2003).

Nutrient cycling

The enhancement of nutrient cycling is another effect often reported for mixed forests. A recent assessment of a field trial (KTY 14/00) established under the BOGFOR programme in 2000 showed that, on a cutaway peatland site, Sitka spruce planted with birch in alternate rows at the same time, had an improved growth performance (c. 35% for both DBH and height and a 38% increase in site index) compared to pure Sitka spruce on the same site. The growth of the pure spruce was stunted, showing the characteristic P and K deficiency symptoms, based on visual observations. In contrast, the spruce in the mixed species plots (planted at the same time as the birch) showed no signs of a decrease in growth, no visual needle deficiency symptoms or signs of suppression by birch at this stage of canopy development. There was no evidence of a reduction in exposure or frost stress in mixed species treatments. The nutrient status of the spruce was investigated to assess if the apparent nursing effect by birch was related to nutritional factors. The mean foliage concentration of macronutrients and trace elements of the spruce needles confirmed a significant treatment effect for P and iron (Fe). The levels of P in the spruce needles sampled from the alternate birch/spruce row treatment (planted at the same time) was c. 33% higher than levels from all the other treatments. This observation is consistent with the significantly higher productivity of Sitka spruce, compared to that in the other treatments (Black *et al*., 2017).

Protection

Shelter

One of the benefits attributed to mixtures is the provision of side shelter - particularly to broadleaves. Experience has shown that, in the absence of good topographic shelter, nurse species can make a positive contribution.

Conifers are often used in band and intimate mixtures in various configurations with the view to providing side shelter to protect the target final crop (broadleaves). While it is generally accepted that there is a positive effect, it has not been reported or demonstrated to any great extent in this country.

A field trial (NMT 81/98) was established by Coillte in 1998 to explore the feasibility of establishing oak and ash in a matrix, consisting of both fast growing and more compatible nurse species. Though essentially a lowland site, exposure to south westerly winds from the Shannon estuary was very severe. This was manifested in the birch by a very pronounced lean away from the prevailing wind, whilst the alder suffered a high percentage of leader breakage. Notwithstanding this and having regard to the hostile nature of the site, the oak looked promising when last assessed with a good choice of final crop trees in each group. The nurse species had little impact on the ash, which, although making vigorous growth, continues to suffer from broken leaders. The trial was last assessed in 2012 (NATFOREX accessed 2018).

A more recent survey of mixed plantations found that potential crop tree candidates in oak/Norway spruce band mixtures and in oak/European larch band mixtures were of better quality than those in alternate line mixture types (Guest and Huss, 2012). This was attributed to the combination of shelter offered by a significantly taller conifer nurse and higher intraspecific competition within the oak, resulting from the band planting.

Within the BOGFOR research programme, different mixed species plantations were established to investigate nursing and sheltering effects on cutaway midland peatlands (Renou-Wilson *et. al.*, 2008). Results showed that oak performed better in mixture with fast-growing species such as alder and hybrid larch or underplanted in a natural birch woodland, compared to where it was planted in the open. The survival of oak was not significantly different between trees grown under shelter and those grown in the open (average survival for each treatment varied between 84% and 86% after four growing seasons). Oak growing in the open, however, were significantly smaller than under birch, from the second growing season onwards. There was no significant difference between the height of oak growing directly under the birch canopy compared to growing with birch side shelter. Height increment under birch was greater than in any other oak plantations on cutaway peatlands.

Norway and Sitka spruce growing in the open were smaller than under shelter. Both species were also affected by the type of shelter, and from year one, trees were significantly taller when growing directly under the birch canopy compared to those growing in the ‘side shelter’ plots. Across all the BOGFOR trials, Sitka spruce grew best under the naturally regenerated birch.

The trials showed that nurse crops can greatly improve the performance of most species, but an important consideration is that nurse crops (natural or planted) should reach a sufficient height and density before underplanting with the final crop species (Renou-Wilson *et. al.*, 2008).

Frost protection

Nurse crops can be used to provide an overhead screen to help alleviate late spring frost damage to sensitive species. However, these mixtures have not been planted to any great extent in Ireland, with preference being given to the selection of species that are frost hardy on frost prone sites.

The performance of Sitka spruce in mixture with Japanese larch in the Avondale plots is recoded by Clear (1944) in which he stated that “Another lesson to be drawn from this plot is that the nurse species had little or no effect in mitigating frost damage until it formed canopy.”

The efficacy of mixtures in protecting against frost was demonstrated again in the BOGFOR trials on the cutaway midland peatlands. These areas are very prone to frosts and many trial plantations failed because of damage due to late spring frosts (Jones and Farrell, 1997a and 1997b).

In the BOGFOR trials, Norway spruce did not suffer from frost damage under birch, while damage to Sitka spruce was reduced under the birch canopy compared to the open areas. Some Sitka spruce trees were damaged by frost where the canopy was sparse.

It was also observed that frost damage was absent in oak growing under birch shelter while trees suffered severe leader die-back in the open (Renou-Wilson et. al., 2008).

Self-thinning mixtures

Mixtures of Sitka spruce and lodgepole pine have been used for many years, particularly on poor and exposed sites for both nutrient nursing and to reduce the risk of crop failure. However, one of the main benefits with this mixture is its ability to self-thin. On poor sites, vigorous south coastal provenances of lodgepole pine will dominate the mixture but the use of slower growing north coastal origins allows the spruce to develop and eventually suppress the pine. On unstable fertile sites, the spruce can compete successfully with the south coastal origins which it eventually suppresses and goes on to form stable productive stands (Horgan *et. al.* 2004). Examples of such stands are to be seen in Coillte forests in the Cork region.

Differences in growth rate of Sitka spruce provenances offer the opportunity to create provenance mixtures that are more variable than pure seed lots. A high within-stand variability facilitates the self–thinning process, which has applications on high-risk windthrow sites, where no thinning regimes are adopted.

Self- thinning mixtures of a slow growing Alaskan provenance in various ratios with the fast growing QCI and Washington provenances are being tested in a research field trial (KFN1290) in Kifinnane, Co. Cork. The trial is now 28 years old and treatment effects are clearly evident. Although the Alaskan provenance has been suppressed, it has kept the branch sizes down on the more vigorous origins and left them spaced at intervals, similar to a second thinning stage. The trial is registered on the NATFOREX database but has yet to be assessed and the results published.

At a time when devastating winter storms are forecast to become more intense and frequent as a result of climate change (Black *et al*., 2010), self-thinning mixtures have considerable potential where crop stability might be compromised on such sites.

Crop development

Species mixtures

The performance of species mixtures recorded in Irish forestry literature is confined to a few publications and mostly concerns broadleaves as the target final crop species. Apart from the reports on the species plots at Avondale published by Forbes (1923) and Clear (1944) there were no subsequent publications on mixtures for a 34-year period, until OCarroll (1978) published a paper on the nursing of Sitka spruce by Japanese larch and lodgepole pine. This was followed by a paper by Carey *et. al.* (1988) ten years later. It was not until the new Millennium that the performance of species mixtures began to be reported on and discussed again in the literature.

In reviewing the performance of species mixtures, it was decided to focus on the nurse species and their effect on the target final crop. Table 22 lists the published performance of species used as a nurse in field trials, observation plots and surveys.

TABLE 22: Published performance of nurse species in mixed crops in Ireland.

Nurse species	Performance in mixtures	Reference
Larch	Douglas fir, Corsican pine, Spanish chestnut and ash will all grow sufficiently fast to preserve themselves from injury when mixed with larch (European).	Anon (1907)
	Avondale - larch too fast for most of the broadleaf trees. Requires early attention in the way of thinning and side pruning. Avondale - European larch had a positive effect on the performance of hornbeam. Avondale - Compatible with western red cedar, Lawson cypress and redwood species. Avondale - Japanese larch suppressed Sitka spruce in mixture but the latter made a remarkable recovery when the larch was removed in thinnings.	Forbes (1923)
	Japanese larch suppressed Norway spruce in a mixture in which the latter was to play the role of a filler.	Clear (1944)
	Well managed European larch/beech mixtures have developed into excellent stands of pure beech at Mullaghmeen, Ballyarthur and Kilbora.	Huss *et al*. (2016)
	European larch may still be considered a suitable nurse crop species for establishing oak, provided a robust planting pattern is used.	Guest and Huss (2012)
Scots pine	Avondale - Scots pine as a nurse has not proved satisfactory, its growth being either too fast or too slow for most species.	Forbes (1923)
	It is doubtful that Scots pine should be used as a nurse crop species for establishing oak.	Guest and Huss (2012)
	Scots pine/larch is a mixture of intolerant species and has little to recommend it silviculturally. There are few instances of crops being raised successfully with this mixture.	Clear (1944)
Norway spruce	Avondale - Too vigorous for oak and beech.	Forbes (1923)
	Avondale - Norway spruce suppressed all broadleaves.	Carey (2010)
	Poor development of oak in mixture with Norway spruce planted at Killane, Co. Wexford and Camross, Co. Laois	Huss *et al*. (2016)
Lodgepole pine *North coastal*	Suitable for nutrient nursing and self-thinning mixtures on organic and mineral soils.	Carey *et. al*. (1988)
South coastal	Suitable as self-thinning mixture on fertile lowland sites	Horgan *e. al*. (2004)
European silver fir	Avondale - Not effective as a nurse species due sensitivity to frost.	Clear (1944)
Hornbeam	Avondale – a mixture of oak and hornbeam was unsuccessful because the hornbeam outpaced the oak and suppressed it. Useful as an understory in minimising epicormic shoots.	Clear (1944)
Beech	Avondale - beech overtopped and suppressed the oak when planted at the same time.	Carey (2010)
Ash	Avondale - the ash outgrew the oak in mixture, leaving the latter as a stunted understory.	Clear (1944)
Birch	Both silver and downy birch are capable of rapid early growth to provide oak with shelter during the establishment phase.	Guest and Huss (2012)
	When compared to pure Sitka spruce treatment, the DBH and height of Sitka spruce was ca. 35% higher in the plots planted in alternative lines with birch. The spruce showed no signs of a decrease in growth, visual needle deficiency symptoms or suppression by birch after 17 years on a cutaway midland bog.	Black *et al*. (2017)
Alder	Species commonly planted but currently mostly planted pure.	GPC data. (*ibid)*
	Potentially suitable as nurse species on soils on which oak is often planted.	Guest and Huss (2012)

In addition to the stands mentioned in the references above, there exists approximately 18 replicated field trials in the Coillte estate which address the issue of mixed species performance, particularly on ORS podzols and gleys (see Table 23 in Section 4.1.3). Assessments of species performance have been taken and the data stored in the NATFOREX database, but the results have not been written up and published. These trials are a valuable resource and further research on mixtures should include a review of existing data, assessment of current growth and development, writing up and publication of results. These are long term trials and many have treatments of a sufficient area to enable them to maintain their integrity well into the rotation. A programme of maintenance (access, thinning, etc.), however, needs to be planned and implemented.

Soil enrichment

There are few published data showing the effects of tree species mixtures on soil enrichment in Ireland. The National Forest Inventory (2012), however, has assessed the humus layer in the National forest estate. The different types of humus are an indicator of soil biological activity, which in turn, is an indicator of soil health and sustainability.

The NFI assessed the different types of humus under four categories – mull, moder, mor or no humus. Mull is a well humified organic matter, which is produced in very biologically active habitat. The porous, crumbly humus rapidly decomposes and becomes well mixed into the mineral soil, so that distinct layers are not apparent. Bacteria, earthworms, and larger insects are abundant, and the pH is alkaline.

The opposite extreme is a mor-humus formation, or raw humus condition, occurs in soil that has few micro-organisms or animals, such as earthworms, to decompose the organic matter that lies on the soil surface. Below this surface-litter layer is a distinct, strongly compacted humus layer; a layer of mineral soil underlies the humus. Fungi and small arthropods are the most common organisms. Mor soils are usually acidic.

A moder-humus formation is intermediate between mor and mull extremes. A moder formation contains more organic material than a mull formation, but this material is not as well mixed with mineral components. No humus development indicates that the litter layer may not have formed yet or could be removed due to surface run off or flooding.

The results from the inventory (Figure 9) show that mixed forests are intermediate between the pure conifer and broadleaf forest types in terms of mull and mor formation. Moder formation was similar in the pure conifer and mixed forests. The presence of broadleaves, with their rapid breakdown of litter, is likely to have had an influence in developing the humus content of mixed stands. However, the extent to which the matching of species to soil type e.g. conifer to acid soils and broadleaves to the more fertile types, however, is not known.

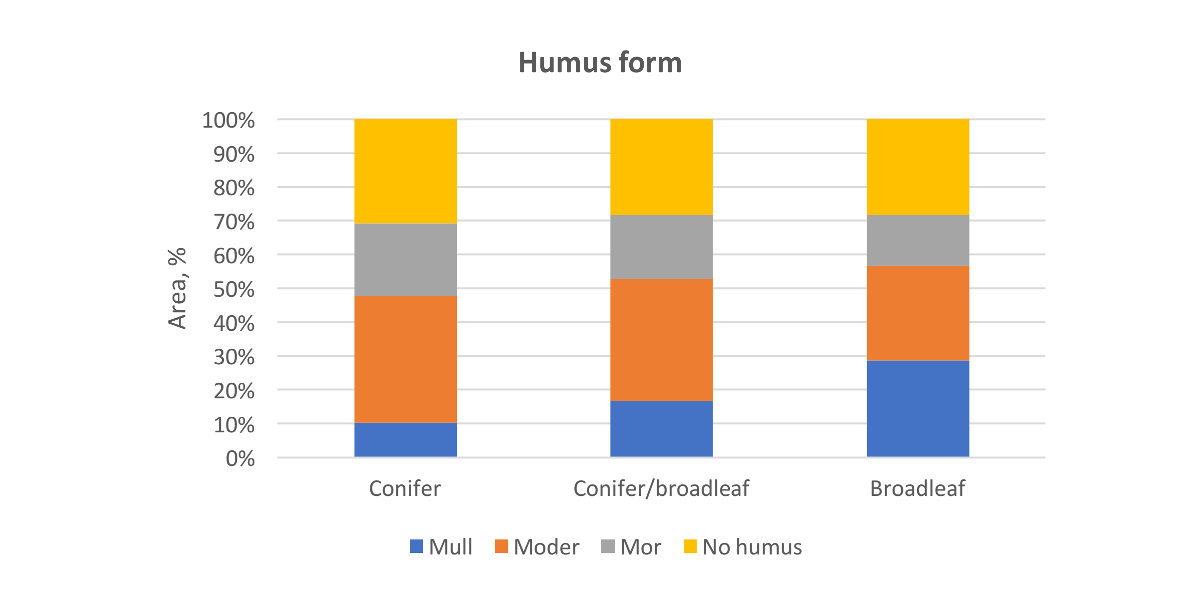


FIGURE 9: Humus formation under different forest types in Irish forests (NFI 2012).

Disease risk reduction

It is generally accepted that species mixtures will spread the risk of plantation failure in the event of insect pest or disease outbreaks. Examples of this are found in Sitka spruce/Japanese larch mixtures that have been widely planted in Ireland, primarily to introduce diversity into spruce stands, enhance landscape values or to benefit from the nursing effects of the larch on the spruce on poor sites (Walsh *et. al*., 2017). This mixture has shown the benefit of mixed crops in the face of an outbreak of the virulent pathogen *Phytophthora ramorum* which has recently caused widespread damage to Japanese larch. While the larch can be severely damaged, the spruce remains unaffected and still has the potential to form productive crops. Looking at this mixture in another way, however, one could argue that the mixing of the larch with the spruce, in an effort to reduce risk, has, in fact caused increased damage to the overall crop – compared to a crop of pure spruce.

Similarly, the ash disease (*Hymenoscyphus fraxineus*) is now becoming widespread in this country, causing dieback in young ash plantations and threatening the future commercial viability of the species here (Anon, 2018). Again, ash plantations growing in mixture with other species are at less risk of significant economic damage than pure ash crops, although this has yet to be quantified.

Another example of the benefits of mixtures is shown by the research undertaken in Northern Ireland during the 1990s when growing willow for biomass was being investigated. Research showed that growing willow in mixed or polyclonal stands could result in significant increases in growth and dry matter yield. One of the factors contributing to these increases was the effect of reducing the onset, build up and impact of disease. The results of experiments showed that all clones increased growth and dry matter yield when grown in polyclonal plots. In polyclonal plots disease was recorded later than in monoclonal plots. Disease build up, as measured by % leaf infection, was more rapid in monocultural plots in the early parts of the season, at which stage, leaf fall produced an apparent reduction in disease levels (Dawson and McCracken, 1993 and 1998).

Conclusion

The management of mixed species crops is becoming a necessary skill for Irish foresters/forest owners who have, until recently, been used to the management of single species plantations. The necessity to significantly increase planting of broadleaves, which often require shelter on afforestation sites, has meant that the establishment of mixed crops has progressed at a rate ahead of research and the skill base/experience of practitioners. While some indication of the performance of mixtures is contained in Irish forestry literature, the published works and guidance on mixtures mentioned above are inadequate to provide the silvicultural support necessary to meet the needs of the industry at present. Species combinations, appropriate nurse species, tree distribution, relative performance of species in response to soil type and exposure, time of thinning, etc. are factors which make the management of mixed crops complex, with often variable results on different sites. Properly designed replicated field trials established across the main site types, testing a range of species combinations, mixture types, thinning regimes, etc. - along with a network of observation and permanent sample plots are required to provide the necessary scientific and practical information to inform policy and demonstrate best practice, rather than having to rely on limited local experience or guidance from abroad, untested in Irish forests.

4.1.2 Survey of Practitioners

Introduction

One of the requirements of the project was to carry out a survey on mixtures among practitioners on the ground. After initial discussions with experts in this area (particularly Dr. Áine Ní Dhubháin, Forestry, UCD), it was decided to use SurveyMonkey to carry out the survey and a draft survey compiled. This draft was edited by Dr. Ní Dhubháin and by the COFORD Working Group on Mixtures in late January 2018. Changes suggested by the Group were taken on board and the survey was distributed on February 18^{th} with a ten-day window given for completion. The survey was made up of 15 questions in total, ranging from assessing background experience of participants to drawing down information on specific mixtures that participants found particularly easy or difficult to manage.

The survey was initially distributed individually by e-mail to 253 individuals or organisation. Included in this first trawl were:

- All names listed on the 21st December 2017 DAFM Register of Foresters and Forestry Companies (177 in total). This included small and large companies and individual forest consultants
- Forestry co-ops
- Forest harvesting companies
- Forest organisations e.g. Crann, IFA Forestry, Pro-Silva, Woodlands of Ireland, etc.
- Sawmills – major sawmills only included
- Forest Service Inspectors
- Teagasc forestry staff (Research and Advisory)
- Coillte - Resource staff from all BAU's

Note that, because the survey was completely anonymous, we were not able to break down the answers into specific replies from e.g. Forest Service Inspectors, Coillte staff, etc.

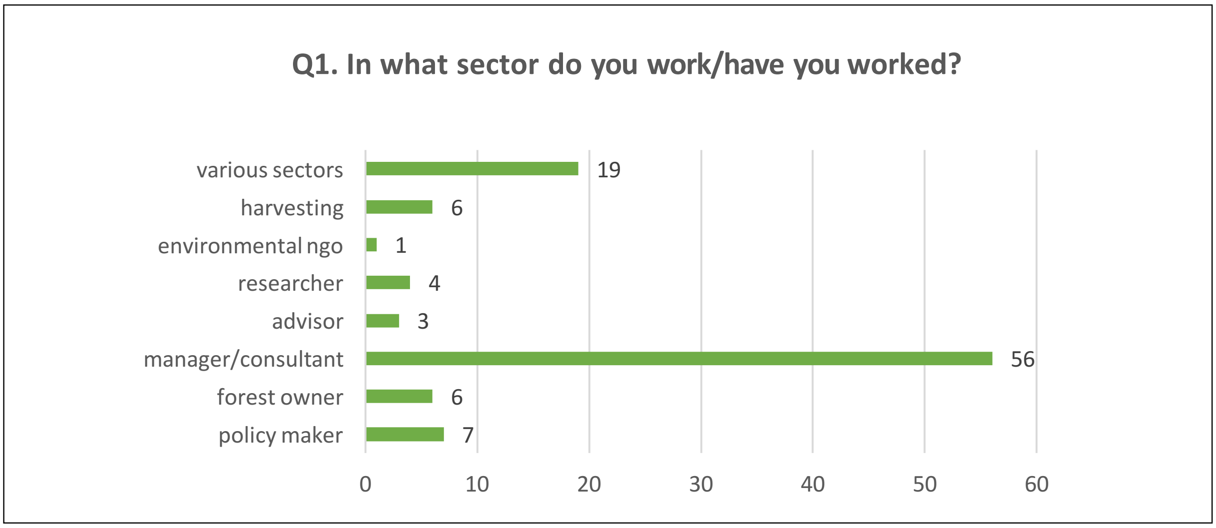
Within three days, fifty replies had been returned and, on February 21st, the survey was distributed to all members of the Society of Irish Foresters to include interested parties who may not have been included on the original list as described above.

By the end of the survey, there were 102 respondents. Results presented below are based on this total. The fact that the totals in some answers may not equal 102 is because not all respondents answered all questions. Participants took, on average, 16 minutes to complete the survey (double the time anticipated when the survey was being distributed).

Results are presented below with individual responses to some specific questions given in Appendix 3.

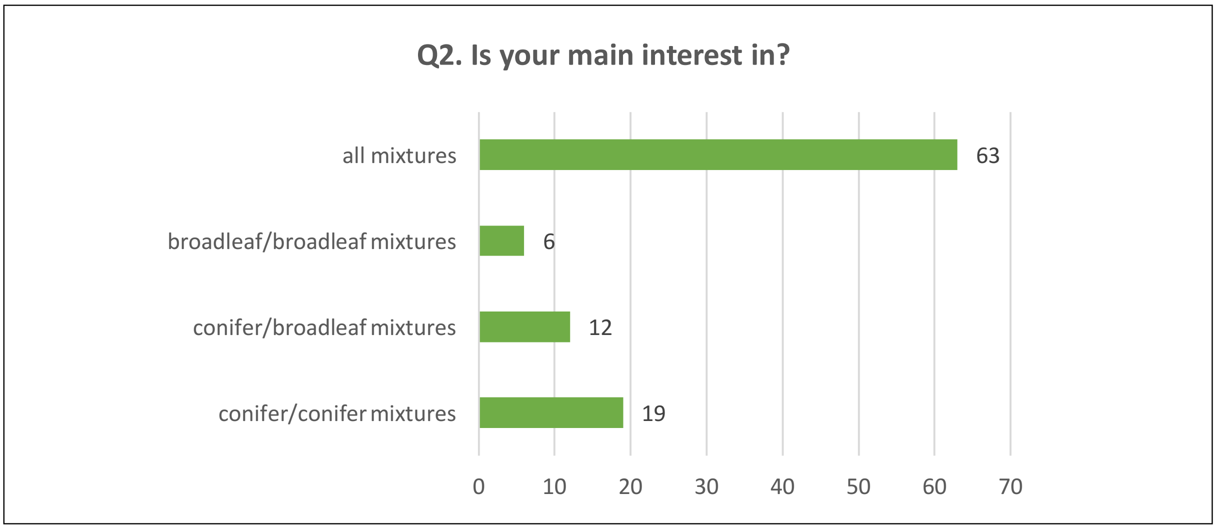
Results

QUESTION 1: In what sector do you work/have you worked? (tick one)



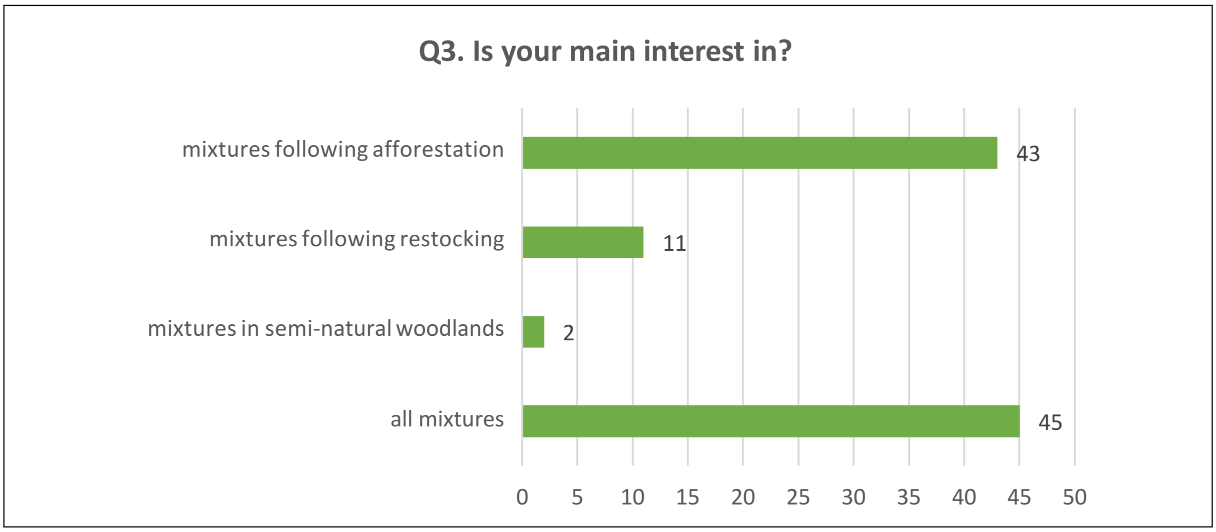
As anticipated, over 50% of respondents were forest managers/consultants with 19% classifying themselves as working (or having worked) in "various sectors". Very few (6 in total) respondents were forest owners. This was expected – given that the survey was only sent to registered foresters or members of the Society of Irish Foresters. Interestingly, six replies came from respondents who said they worked primarily in the harvesting area.

QUESTION 2: Is your main interest in? (tick one)



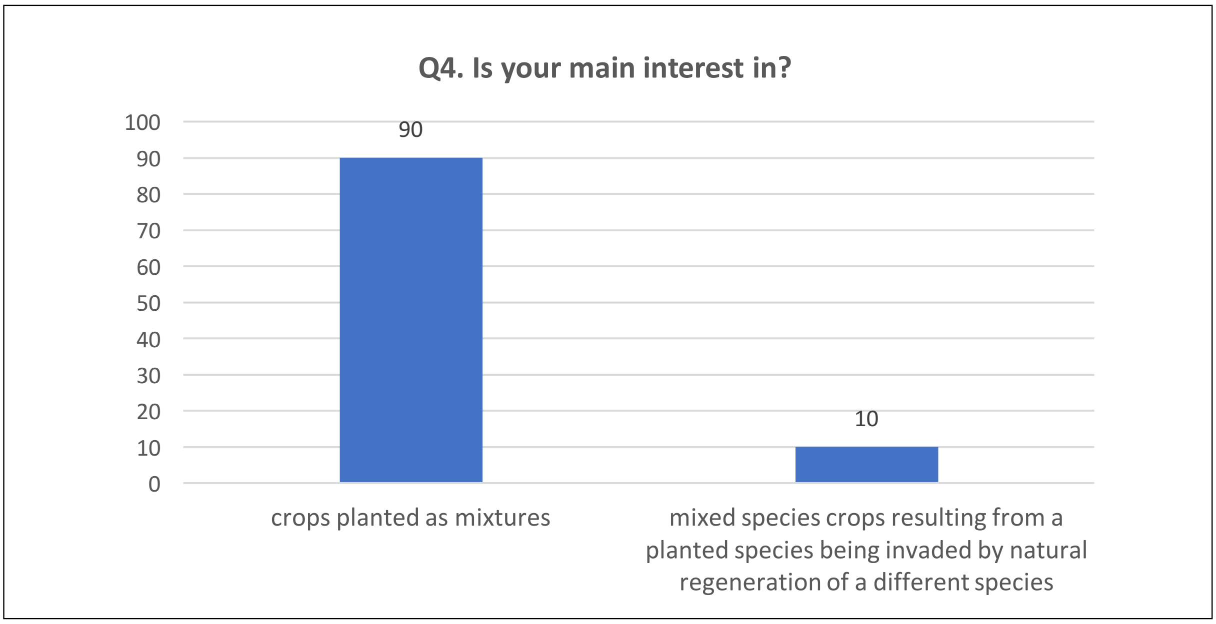
Results here were a little surprising as, in advance, it had been anticipated that most interest would be in conifer/broadleaf mixtures. Most respondents were interested in all types of mixtures with nineteen replies nominating conifer/conifer mixtures as their area of greatest interest.

QUESTION 3: Is your main interest in (tick one)?



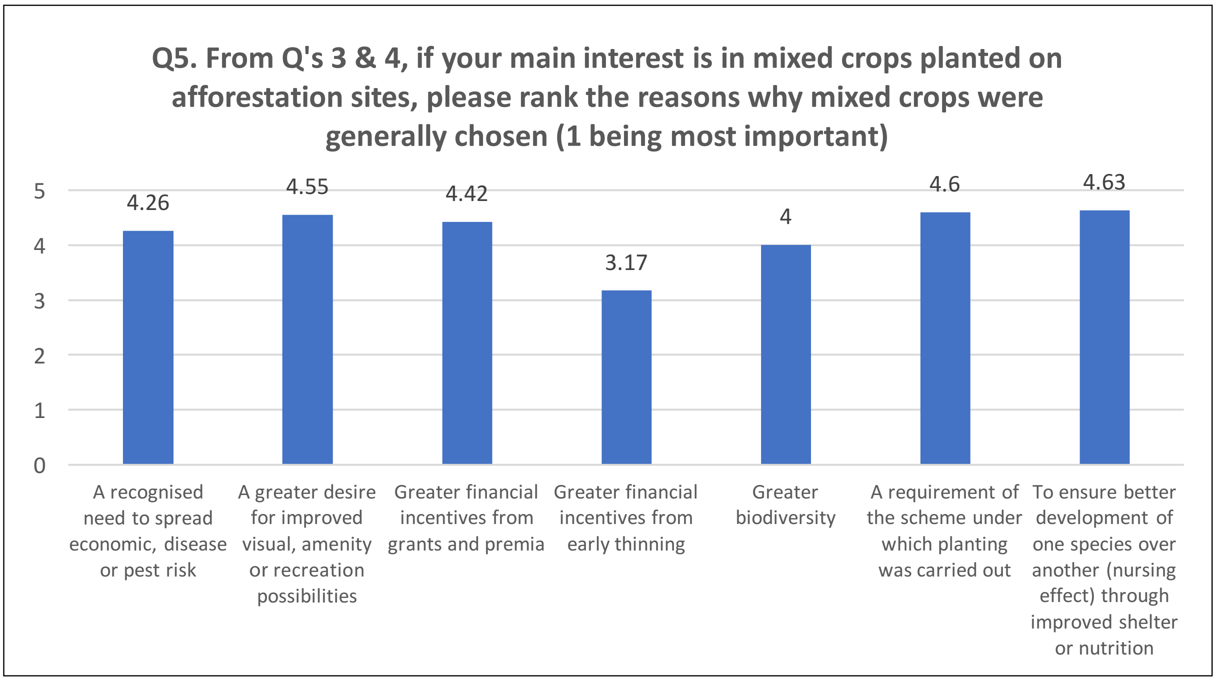
An interesting result here also in that, in advance, we anticipated that most participants in the survey might only be interested in mixtures following afforestation. Almost half of respondents, however, were interested in all mixtures and 11% were interested specifically in mixtures following restocking.

QUESTION 4: Is your main interest in? (tick one)



Although somewhat related to Question 3, there is a slightly different emphasis here. Given the range of sites planted in this country, it might be expected that sites which are invaded by natural regeneration (right hand column above) would mostly be sites in the restock phase rather than afforestation sites. Whatever the breakdown, most respondents were interested in crops which were planted as mixtures.

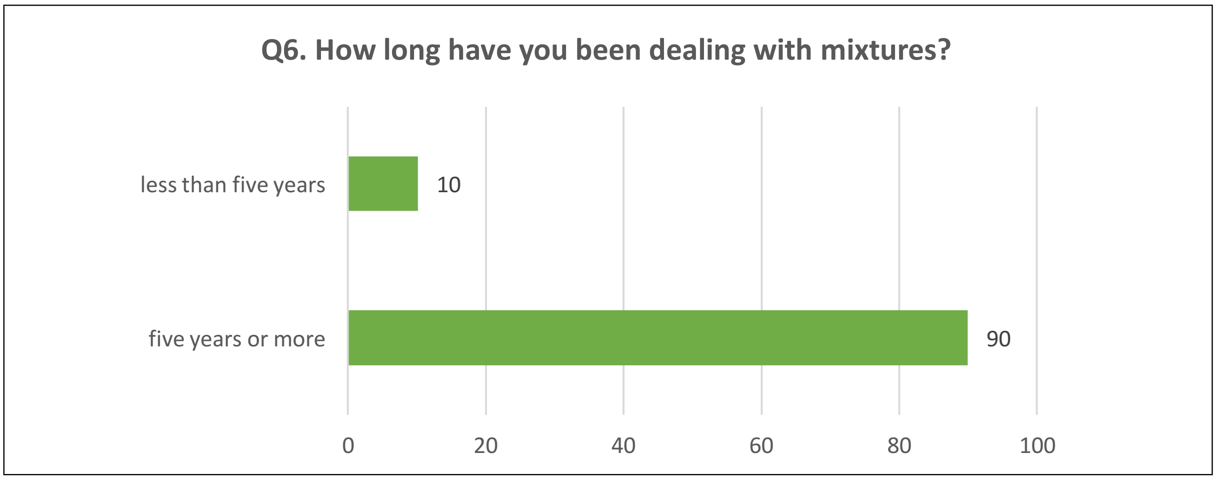
QUESTION 5: From Q's 3 & 4, if your main interest is in mixed crops planted on afforestation sites, please rank the reasons why mixed crops were generally chosen? (1 being most important)



Although 1 corresponds with the most important reason in the above, in Survey Monkey, weights are applied in reverse. In other words, the respondents' most preferred choices (which they rank as #1) have the largest weight and score, and their least preferred choice (which they rank in the last position) has a weight/score of 1.

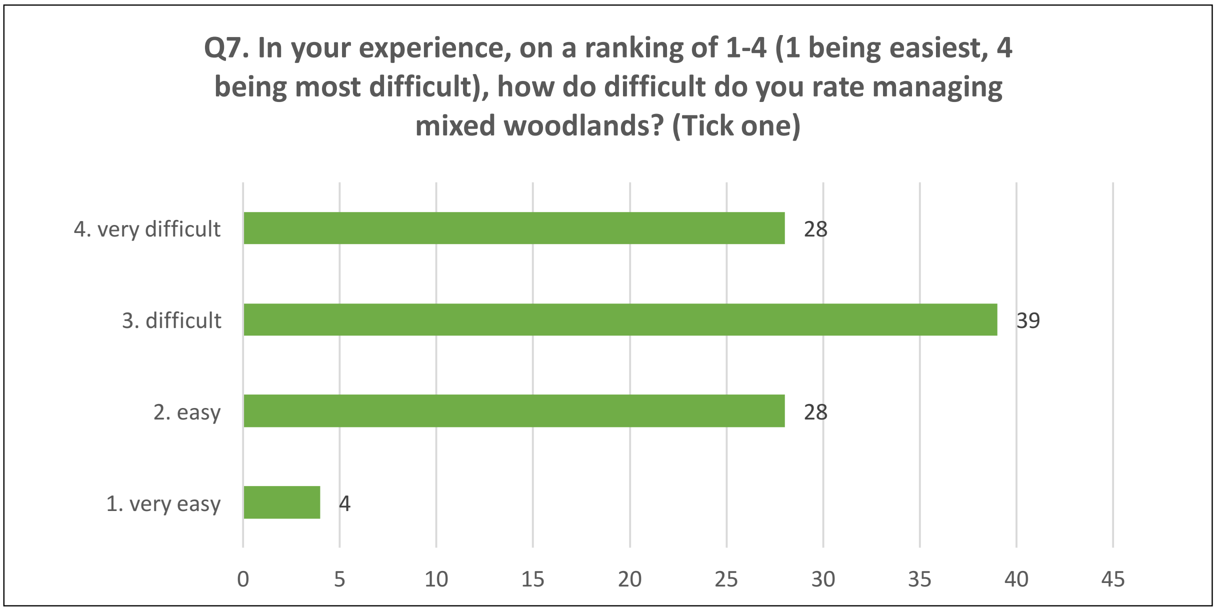
From the Question 5 graph above, therefore, the **most important reason** given by respondents as to why mixtures were generally chosen was "to ensure better development of one species over another (nursing effect) through improved shelter or nutrition" (score of 4.63). This was closely followed by a "grant scheme requirement" (4.6) and to improve "visual, amenity or recreation possibilities" (4.55). The reason respondents suggested as being of **least importance** was "greater financial incentives from early thinning" (score of 3.17).

QUESTION 6: How long have you been dealing with mixtures?



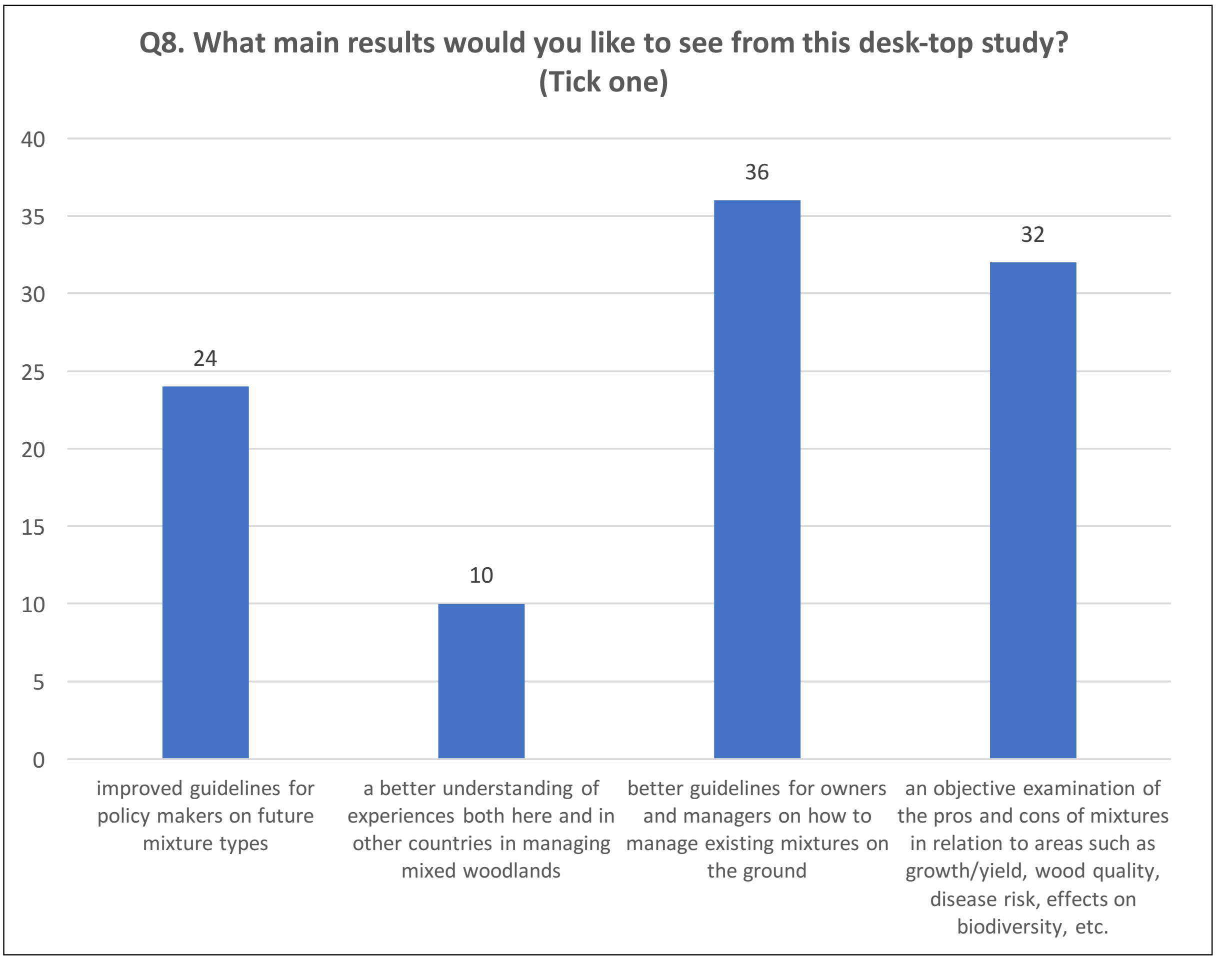
Of the one hundred people who responded to this question, 90% have been dealing with mixtures for more than five years. Respondents were generally experienced practitioners and, as we will see later, were still looking for guidance on how to manage these crops.

QUESTION 7: In your experience, on a ranking of 1-4 (1 being easiest, 4 being most difficult), how difficult do you rate managing mixed woodlands? (tick one)



Despite the experience of people on the ground (from the answers to the previous question), over two thirds of respondents found mixtures either difficult or very difficult to deal with. Only 4% found them very easy to deal with.

QUESTION 8: What main results would you like to see from this desk top study? (tick one)

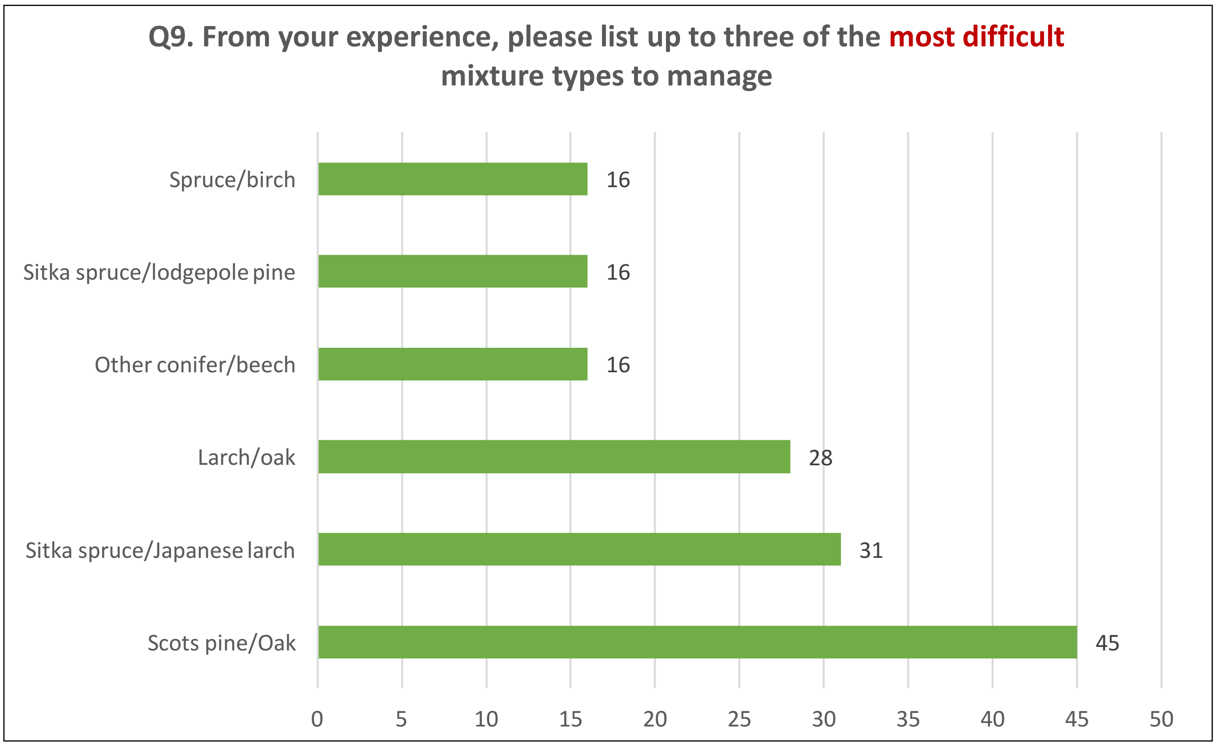


The difficulty in managing mixtures (expressed in Q7) resulted in a call for better guidelines for owners and managers in this question. Respondents put less importance on improved guidelines for policy makers or an examination of the pros and cons of mixtures and put least importance of all in the study of a better understanding of others experiences of managing mixed woodlands.

Answers to this question can be compared to a recent EU-wide survey of forest managers (including some from Ireland and the UK) on mixtures (Coll, 2018). In the wider EU survey, forest managers felt that the greatest knowledge gaps were in correct species choice in the face of changing climate and natural disturbance. This was not specifically highlighted in the Irish survey.

The question ranked third most important by the EU study was similar to the highest ranked in this study – how to manage existing mixtures to ensure that the desired species is maintained throughout the entire rotation. The second most important area highlighted in the current study (pros and cons of mixtures) was also ranked as very important in the wider EU survey and was further broken down into its constituent parts in the latter.

QUESTION 9: From your experience, please list up to three of the most difficult mixture types to manage (1 is most difficult........). When naming the mixture type, please give the actual species, arrangement (line, intimate, etc.), GPC and planting year.



The data shown in the Figure above are a bringing together of what respondents ranked as their top three most difficult mixtures to manage. In most cases, respondents nominated the species mix and the arrangement but did not mention the GPC or planting year.

The top three most difficult mixtures to manage were SP/oak, SS/JL and larch /oak. The other mixtures that respondents found difficult to manage were other conifers/beech, SS/LP and spruce/birch. The last mentioned here (spruce/birch) is interesting in that, unlike all the others, the mixture results from a broadleaf crop (birch) naturally invading a planted spruce (Sitka or Norway) crop.

Other mixtures were also nominated as being difficult to manage but the above six categories made up 75% of all those nominated. Some other mixture types suggested by respondents as being difficult to manage were:

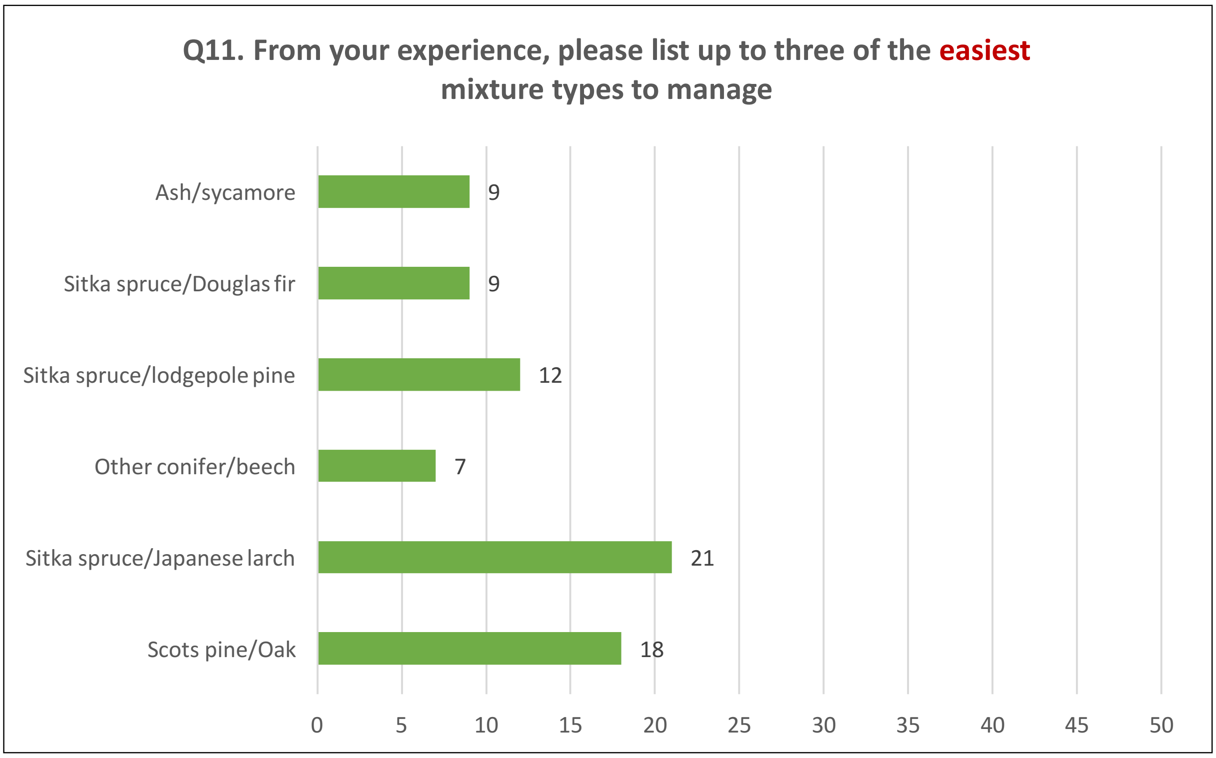
- Groups of broadleaves in a matrix with conifers
- Ash in mixture with other broadleaves
- Mature broadleaf mixtures
- Oak/Norway spruce

QUESTION 10: For the mixture type you ranked as most difficult in Q9, why is it difficult to manage?

Although most respondents nominated crops as being difficult to manage, fewer of them gave information as to why they found particular mixtures difficult. For the main difficult mixtures (from Question 9), some of the main reasons are given in Appendix 3 as direct quotes from the respondents themselves.

QUESTION 11: From your experience, please list up to three of the easiest mixture types to manage (1 being the easiest.......). When naming the mixture type, please give the actual species, arrangement (line, intimate, etc.), GPC and planting year.

The answers to Q7 earlier suggested that most respondents found mixtures difficult to deal with. As mentioned earlier, the type of respondents who find mixtures difficult to deal with are across the range - forest companies, consultants, FS Inspectors, Coillte staff, Teagasc Advisors, etc. When it came to Question 11 on what mixtures respondents found easy to deal with, the overall number of crop types nominated was less (as expected) – 142 ("easy") compared to 202 ("difficult"). The crops which respondents found easiest to deal with are shown in the Figure below.

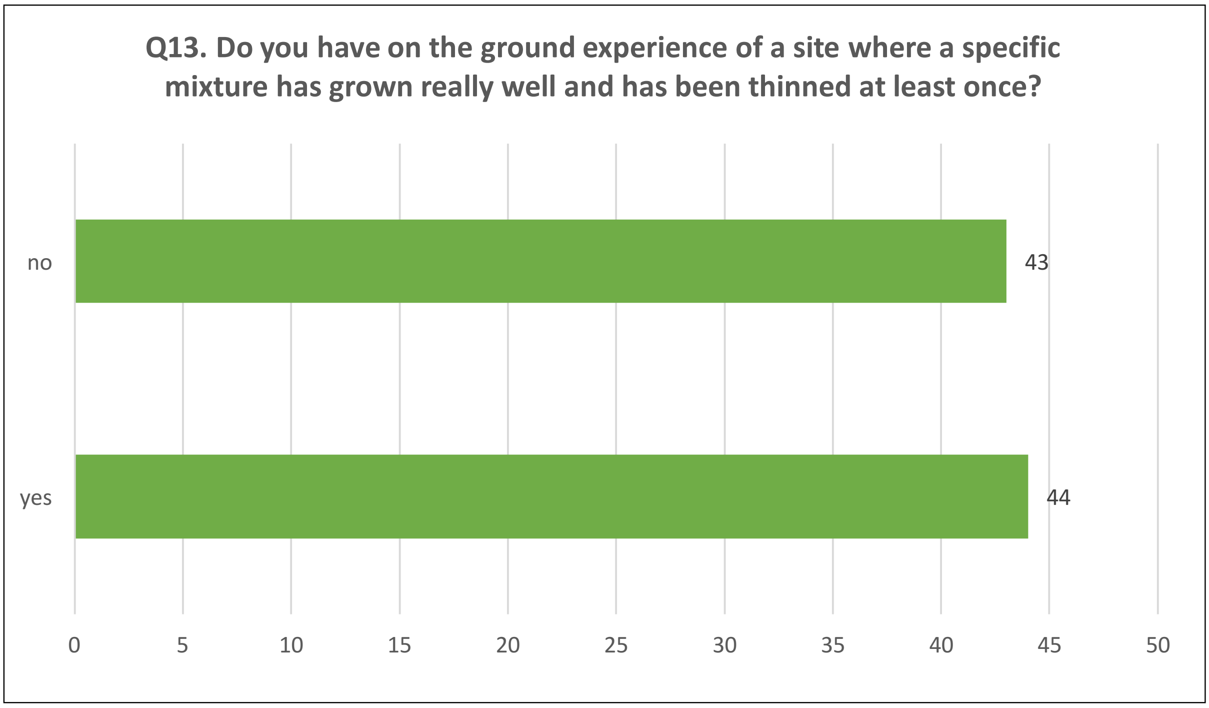


Three of the four easiest crops to manage as listed above have also been included in the most difficult crops to manage. This may seem contradictory, but simply comes down to the fact that what some respondents found difficult, others found relatively easy. This may have been due to the differences between similar mixture types across a range of sites or some managers getting in early to manage crops which others came to when it was already too late. Some companies and individual managers now have a policy to manage certain mixtures in a very specific way e.g. completely removing JL in SS/JL crops within the first two thinnings.

QUESTION 12: For the mixture type you ranked as easiest in Q11, why is it easy to manage?

Responses here were fewer and shorter than those given in Question 10. Some of the main reasons are given in Appendix 3 as direct quotes from the respondents themselves on why they found certain crops relatively easy to deal with.

QUESTION 13: Do you have on the ground experience of a site where a specific mixture has grown really well and has been thinned at least once?



Although many respondents found mixtures either difficult or very difficult to manage (see earlier questions), the almost 50/50 split in answers to this question is encouraging. There are crops where mixtures have worked and which have passed the first thinning stage. Some of these may prove useful in future years as demonstration areas.

QUESTION 14: If you answered yes to the previous question and you are interested in showing the woodland to the Project Team, please complete the details below. Note that the Project Team may not be able to visit all the crops nominated.

Of the forty-four respondents who answered yes to Q13, twenty-seven nominated crops for the Project Group to visit. These nominated crops were in:

Leinster	14
Munster	7
Connaught	5
Ulster	1

They comprised of a range of mixture types – from Scots pine/oak to Sitka spruce/Douglas fir and beech/Douglas fir to oak/European larch/Spanish chestnut. Because of time and budget restrictions, the Team decided to only visit a number of nominated crops and these were located in Counties Meath, Offaly, Dublin, Carlow, Wexford, Cork, Waterford and Kilkenny.

At most sites, the Team met with the Manager and sometimes also the owner. These site visits were extremely useful and informative and full details of the sites and crops visited are given in Appendix 4.

QUESTION 15: If you have any further comments on mixtures which might help the Project Team, please insert them below

Replies to this question were received both from respondents who nominated crops for field visits and those who didn't. Topics covered ranged widely but a sample of some of the replies is given below:

"Generally, mixtures must be managed. We have a good idea when interventions should take place and there is an onus on the Forest Service to contact woodland owners to encourage them to engage in management of their woodlands."

"I don't believe foresters are micro assessing sites correctly prior to planting - there is a tendency to plant a field with one species, regardless of the potential to use alternative species in small sections with shallower soil / wetter soil / a variation in soil type. Diversifying planting in this way would reduce the need for / pressure for mixtures which are applied in a blanket manner when one or more of the species in mixture is unsuited. There is insufficient flexibility in the grant and premium scheme to cater for this due to mapping and plot size conventions."

"There is a lot of alder planted in the West, some good some bad, some healthy some not. It would be interesting to try and find a suitable broadleaf species that could be planted under these alder after a heavy thinning to try and change it into a ccf as the most common line of thought is to clear it out and replant it with ss."

"As part of this study, potential new mixture types that have been planted in the UK might be investigated to see if we might be able to expand the species mixtures we could employ in Ireland. Also, dissemination of the results of this study to the sector is very important and those industry/sector websites that are most used should be employed in this regard."

"I have been involved in harvesting of mixtures since 1990 and have yet to witness a valuable broadleaf crop even at 40 years of age [apart from hurley ash]. In a clear-fell of 40 year old Alder, approx. 100 m^3 of 2.5 m lengths, min top diam of 20 cms , was rejected by saw-millers , primarily because of the elliptical nature of the logs .The logs were sold as firewood !!! Perhaps, because of the length of the conifer rotation the Broadleaf mixture is severely disadvantaged. This could suggest a pure Broadleaf stand, and a rethink of intimate mixtures."

"Broadleaves need more management time with less return in the early years. Private forest owners generally leave broadleaves to survive on their own and concentrate on the conifers. The message should be that broadleaves can be improved and will respond to thinning/ pruning intervention - not to close the gate on the plantation- even if a small number of final crop trees can be salvaged - there will be some commercial value to the crop - along with the bio value etc,"

4.1.3 Research on Mixtures

Mixed plantations are increasingly becoming a significant part of the National forest estate, driven by the need to create more species diversity and the increased planting of broadleaves. While many plantations have been established with mixed species in recent years, there are relatively few formal research field trials and demonstration plots on mixtures in this country. Those that exist are currently under the management of either Coillte or Teagasc.

Coillte

The Coillte field trials which contain mixed species treatments can be categorised under three main initiatives:

- Avondale: experimental plantings of tree species on tillage land
- R&D programme: field trials established in the past under the Coillte Silvicultural R&D programme
- BOGFOR project: forest research programme on cutaway midland bogs

Avondale

Background

In 1903, a forest experimental station was established by the State at Avondale, under the management of Arthur Forbes, with the view to determining the most suitable tree species for Ireland's forestry programme. Although many tree species introductions had been made by landlords during the eighteenth and nineteenth centuries, there was no scientific information available at that time on the best species or on how they should be managed. Forbes set about establishing an extensive area of species trials at Avondale and, between 1905 and 1913, 49 ha of land were planted in 104 different plots, with 84 tree species: 46 coniferous and 38 broadleaf. A further 16 rare species brought the total planted to 100. Some species were planted pure, others in mixture with nurses, mainly larch and Norway spruce. Most of the planting took place between 1905 and 1907. Although "*fairly good tillage land not usually devoted to tree planting*" the Avondale experiment plots provided a wealth of information on species adaptability and suitability. (Carey, 2010).

For many years, Avondale plots were regarded as not truly representative of the land being afforested. However, with afforestation currently taking place on better quality land, the Avondale plots have a new relevance, particularly to today's farm forestry.

Mixtures in Avondale

In Avondale, the use of mixtures was adopted across the plots to reduce the cost of plants and secondly to minimize the risk of frost damage to the nursed species. It was anticipated that frost might be a problem on the site and this proved to be correct in that some of the more susceptible species, including Sitka spruce and European silver fir, were damaged in the early years after planting.

Pure crops of all the important species were planted side by side with the same species in mixture, with a view to noting their development under both conditions. Larch and Norway spruce were mainly used to nurse the broadleaf species. Scots pine was used as a nurse for most of the more unusual pines and European silver fir for the fir section. Beech was used with larch and oak, ash with oak, walnut and American ash, hickory and tulip tree. In most cases, larch outgrew all other species, which necessitated cutting back of the side branches of the larch. Norway spruce had the same effect in some instances. European silver fir and ash failed as nurse species due to frost damage. Plot layouts are shown in Carey (2010).

In the 1950s, mixtures were further established when it was decided to underplant some of the original plots with shade tolerant species. A number of the plots, notably the elms, some of the Corsican pine plots, in addition to the Scots pine, eastern white pine and Monterey pine plots were underplanted with a variety of species, the most common being western hemlock, Lawson cypress, Douglas fir, grand fir and western red cedar. Corsican pine was underplanted with beech in 1957. The beech has grown poorly. In general, Douglas fir also grew poorly when underplanted, whereas the shade-tolerant western hemlock grew well.

The Avondale plots now provide living proof for growers of what to expect from the various species, tested over a period of one hundred years. This is particularly so in the case of the broadleaf species. The plots are relatively small in area (0.4ha), but they represent the largest areas and number of species tested on a single site in Ireland over the last 100 years, apart from the JFK Park at New Ross in Co Wexford, established in the 1970s. Unlike Avondale, however, no mixtures were established in JFK in the 1970s planting. More recently, however, Kelly (2013) reported that five plots of mixtures of two species were planted in JFK, starting in 2001. Species included Scots pine, sessile oak, European silver fir, Italian alder, hybrid larch, Norway spruce and Macedonian pine.

The performance of the various species and mixtures in Avondale at 20 and 40 years was reported by Forbes (1923) and Clear (1944) respectively. Although some of the original plots and trees initially planted no longer survive, having either failed or blown down or been replanted with other species, the bulk of the plots still exist. These provide a large amount of information on the performance of different tree species and their mixtures under Irish conditions. This information is highly relevant, not only for the evidence it provides on the successful species, but also on those that proved to be unsuccessful and warrant further investigation (Carey, 2010).

Detailed information on plot layout, establishment and species performance in Avondale has been reported in various reports and papers (Forbes, 1913 and 1923, MacOscair, 1978, Carey, 2004 and Carey 2010).

Coillte R&D Programme

Background

Over the years, research activities undertaken by the Forest Service and subsequently Coillte have resulted in an extensive network of experimental trials on many aspects of forest management. These trials have provided scientific data to assist in developing best forest practice and have also acted as demonstration areas for communicating research results.

The trials are a unique National resource, in that they contain a wide range of silvicultural and management treatments that have been carried out to strict specifications. In addition, they are properly documented and treatment effects have been measured.

Considerable investment has been made over the years in the development of the plot network and the gathering of data. To secure these data in a central location where they could be archived and made readily accessible to researchers and practitioners alike, the NATFOREX (National Resource of Field Trials and a Database for Research and Demonstration) database was established between 2007 and 2013. The database developed by UCD and funded by COFORD gives a useful inventory of the resources available and silvicultural and management treatments. It also facilitates reviews of knowledge gained to date and helps to show areas where new trials may be required.

A search of the NATFOREX database for this project produced a list of 18 field trials that contain mixed species (Table 23). The trials test a range of treatments aimed at achieving productive conifer and broadleaf crops. Treatments include nursing mixtures to:

- improve crop nutrition on poor soils,
- provide shelter to ensure the successful establishment and development of broadleaves; and
- improve stand structure through the use of provenance mixtures.

Details of the individual trials can be accessed through the hyperlinks under Experimental Code in Table 23. In addition, the Team visited six of the trials listed in the table below (and some trials not listed) during April 2018. Further details and images from the field visit to the trials are given in Appendix 4.B.

TABLE 23: Field experiments from the NATFOREX database which contain mixtures.

Experiment Code	Thematic Area	Research Area	Affor./Restock	Site	Species
ADH0588	Crop Nutrition	The nursing effect of various species influenced by Ulex and sludge	Restock	ORS podzol	Japanese larch Lodgepole pine Scots pine Sitka spruce
ADH1690	Crop Improvement	Provenance/ mixtures	Restock	ORS podzol	Lodgepole pine Sitka spruce
ADH2493	Crop establishment	Conifer/broadleaf mixtures	Afforestation	Gley	Ash Norway spruce Sessile oak Western red cedar
BHA3893	Crop Nutrition	Nursing mixtures	Restock	ORS podzol	Douglas fir Japanese larch Sitka spruce
BHA8597	Crop Nutrition	Ulex gallii as a source of biological nitrogen fixation	Restock	ORS podzol	Japanese larch Sitka spruce
BHA8999	Crop Improvement	Mixture demonstration area	Restock	ORS podzol	Lodgepole pine Sitka spruce
BHA9201	Crop Establishment	Species/Mixture observation area	Restock	ORS podzol	Downy birch Hybrid larch Lawson cypress Macedonian pine Rowan Silver birch Western red cedar
BHA9503	Crop Establishment	Species/mixtures/ fertiliser trial	Restock	ORS podzol	Alder Beech Corsican pine Douglas fir Downey birch Grey alder Hybrid larch Italian alder Japanese larch Lawson cypress Macedonian pine Red oak Rowan Scots pine Sessile oak Silver birch Sitka spruce Western hemlock Western red cedar

BNO8600	Crop Establishment	Species/mixtures demonstration/ observation trial	Restock	Brown podzol	Beech Corsican pine Douglas fir European larch Hybrid larch Japanese larch Macedonian pine Norway spruce Scots pine Sessile oak Sitka spruce Spanish chestnut Sycamore Western hemlock Western red cedar
BTR2594	Crop Establishment	Pure and mixed-species trial	Restock	ORS podzol	Douglas fir Hybrid larch Japanese larch Monterey pine Sessile oak Sitka spruce Spanish chestnut Western hemlock Western red cedar
BTR3297	Crop Establishment	Pure and mixed-species trial	Restock	Variable - gleys, podzols and free draining soils.	Hybrid larch Japanese larch Red oak Scots pine Southern beech (N procera) Western red cedar
CQN1708	Crop Establishment	Reconstitution of unthrifty oak	Afforestation	Grey brown podzol	Beech Common walnut Pedunculate oak Walnut crosses (J. major x J. regia) Walnut crosses (J. nigra x J. regia) Wild cherry
KFN1290	Crop Improvement	Provenance experiment, self-thinning mixtures.	Afforestation	Gley	Sitka spruce

TABLE 23: Field experiments from the NATFOREX database which contain mixtures (Continued).

Experiment Code	Thematic Area	Research Area	Affor./Restock	Site	Species
MDT0202	Crop Establishment	Species/mixtures and fertiliser trial	Restock	ORS podzol	Beech Corsican pine Douglas fir Downey birch European larch Grey alder Hybrid larch Italian alder Japanese larch Lawson cypress Macedonian pine Monterey pine Red oak Rowan Scots pine Sessile oak Silver birch Sitka spruce Western hemlock Western red cedar
NMT8198	Crop Establishment	Nurse species composition and spatial arrangement	Afforestation	Gley	Ash Common alder Downy birch Pedunculate oak Scots pine Silver birch Western red cedar
NMT8301	Crop Improvement	Appropriate nurse species for oak	Afforestation	Gley	Common alder European larch Grey alder Norway spruce Pedunculate oak Scots pine Sycamore Western red cedar
NMT8104	Crop Establishment	Group planting	Afforestation	Gley	Hornbeam Norway spruce Pedunculate oak Silver birch Western red cedar
RLC0788	Crop Establishment	Reforestation techniques site prep and SS/JL and SS/LP(NC)	Restock	ORS podzol	Japanese larch Lodgepole pine Sitka spruce

During the period when the NATFOREX project was undertaken (2007-13), the trials were visited and their condition assessed. Any maintenance work required was carried out on key trials to improve access, signage and labelling, and also to update the thinning and management status of the trials and to implement and continue the experimental treatments. New data were also collected where required for the development of the stand and the research objectives of the specific trial.

No further wor K has been carried out on the trials since the end of the project (2013). Coillte currently has no research unit as staff have either retired or been reassigned. There is, therefore, a danger that these field trials could fall into disrepair. As many of the treatments in the trials will only show their effects in the later development stages of the crop, it is essential that maintenance and monitoring of these experiments be carried out as they still have much useful information to yield.

BOGFOR

BOGFOR was a multi-disciplinary programme undertaken in the early 2000's by UCD in collaboration with Board Na Mona and Coillte. The primary objective of the programme was to examine the forestry potential of industrial cutaway peats in the midlands (Renou-Wilson *et. al*., 2008). It was designed to develop new approaches to the challenges and problems of establishing a tree crop on these sites.

An extensive series of field trials was established over the period 1999-2008 examining a range of silvicultural issues, including the performance of species mixtures, particularly to protect against spring frost damage. Table 24 lists the BOGFOR trials that have mixed species treatments and that still exist.

TABLE 24: BOGFOR field trials that have mixed species treatments.

Site Name	Expt. Name	Type of expt.	Area (ha)	Comment
Blackwater	KTY 14/00	Nursing trial	4.0	Birch nursing SS
Blackwater and Tumduff	KTY 20/02 and CLE 3/00	Alder/spruce mixture	1.7	Alder thinned and underplanted with SS and NS
Tumduff	CLE 3/00	Species trial	4.0	Oak (pure and mixed with HL and SP)
Tumduff	CLE 5/00	Underplanting of birch	8.2	Birch thinned and underplanted with NS, SS and oak
Tumduff	TLM 35/96	Species trial	2.0	JL/Syc and JL/beech mixtures included

Unfortunately, most of the demonstration areas and experimental sites established under the BOGFOR programme have not been actively managed since the programme was terminated. The trials still exist but are in need of essential silvicultural intervention to ensure correct development of mixed species canopies. However, they can still yield useful information.

Details of the trials have been published in key reports from the Programme (Renou-Wilson *et. al*., 2008 and Black *et. al.,* 2017).

Teagasc Trials

Teagasc field trials that include mixed species treatments were mostly established under the 5-year B-SilvRD project funded by COFORD (Table 25). The project (2010 – 2016) established medium to long-term silviculture trials designed to address issues concerning establishment, provision of shelter, thinning and spacing in plantations of mixed species, in which broadleaves are the target species. The trials are continuing to be manged and monitored and results communicated to the industry and stakeholders. The trials are established on fertile farmland owned by Teagasc and by private individuals.

TABLE 25: Teagasc field trials with mixed species treatments.

Trial	Location	Est. year	Treatments
Oak: birch establishment	Johnstown Castle, Co. Wexford Kilmacthomas, Co. Waterford	2012/13 2013/14	Pure oak Bands 3:3 oak:birch Anderson squares
Oak: SP shelter in advance of establishment	Charlestown, Co. Mayo	2012/13	Oak / Scots pine Pure oak: 2010/11 Oak: SP control: 2010/11 / 2010/11 Oak: SP 2yr: 2012/13 / 2010/11 Oak: SP 4yr: 2014/15 / 2010/11
Oak: SP thinning trial	Johnstown Castle, Co. Wexford	2015/16	Remove all SP; Remove alternate SP lines; Remove 2 from 3 SP lines; Control (no SP removed).
Ash: sycamore spacing trial	Teagasc, Kinsealy	2010/11	Ash and sycamore in a Nelder fan layout

Status of Field Trials

Currently, a total of twenty-seven replicated field trials and one mature demonstration area (Avondale) that contain mixed species treatments continue to exist (Table 26). Seventeen of the trials are concerned with two specific site types viz. unenclosed restock sites on ORS podzols and cutaway midland bog. Forests on these areas are mostly owned by Coillte and the trials may have limited application to farm forestry. Only 10 trials and the Avondale plots could be considered to be on sites that are similar to the mixed plantations established under the afforestation programme in recent years. As there is an urgent need to address the challenges of these plantations, there is currently a serious deficiency of field trials designed to test and demonstrate various silvicultural treatments in relation to mixtures. Apart from the Teagasc trials, most enquire immediate maintenance.

TABLE 26: Site types of existing mixture experiments.

Site type	No. of trials
Farmland	4
Surface water gleys	6
Unenclosed ORS podzols	11
Cutaway raised bog	6

The Coillte trials are the remnants of a once active silvicultural research programme which has now been disbanded, but if the trials are maintained, they should continue to yield useful information. Being part of a large forest estate, they occupy only a very small area. Unless active interest in shown by the industry in these trials, however, there is a risk of their falling into disrepair or being subsumed into and managed like the surrounding commercial plantations.

Similarly, the long-term future of the Teagasc trials needs to be secured as changing ownership and owners' management objectives are potential risks to their existence. Continuity of funding, however, is perhaps the greatest risk to the existence of trials of both organisations.

British experimental evidence

For a variety of reasons, not least the emphasis upon single species stands in the afforestation programmes of the last century, there has been relatively little formal experimentation in Britain to examine the effects of species mixtures on wood production. The most important long-term experiments formed part of a series of some 20 trials laid down between 1955 and 1962 which contained a range of two species mixtures, together with pure plots of the constituent species planted in three replicates with 0.2 ha plots of each treatment: none of the experiments have been thinned. The mixtures were planted in a 50:50 mix using an alternate 'chequerboard' design so that the admixed species could be expected to survive until well beyond canopy closure.

This experimental series appears to be almost unique in northern Europe in that it potentially allows statistically valid and long-term investigation of the growth of tree species in pure plots and in mixture. Unfortunately, many of the experiments were lost to neglect or windthrow so that only eight survived to canopy closure after which measures of productivity could be made. Summary details of performance of different two-species mixtures in these experiments are shown in Table 27. All the effects reported below are based on measurements of basal area rather than of stem volume and while it is reasonable to assume a direct relationship between these parameters, it is possible that differences in stem taper could affect the actual outturn from the mixtures (Pretzsch, 2009, Chapter 9).

TABLE 27: Species mixtures planted in British long-term experiments and the extent of overyielding (O) or neutral (N) performance of the mixture.

Forest	Species mixture	Age	Overyielding or neutral
Gisburn [1]	Scots pine/common alder	20	N
Gisburn [1]	Scots pine/sessile oak	20	N
Gisburn [1]	Scots pine/Norway spruce	20	O
Gisburn [1]	Scots pine/Sitka spruce	20	O
Gisburn [1]	Common alder/sessile oak	20	N
Gisburn [1]	Common alder/Norway spruce	20	O
Gisburn [1]	Sessile oak/Norway spruce	20	N
Ceannacroc [2]	Scots pine/birch	55	N
Hambleton [2]	Scots pine/birch	48	N
Dunraven [3]	Sitka spruce/western hemlock	56	O
Margam [3]	Sitka spruce/western hemlock	59	O
Speymouth [3]	Scots pine/western hemlock	58	O
Bickley [3]	Lodgepole pine/Japanese larch	48	N

References are: 1 – Mason and Connolly (2014). 2 – Mason and Connolly (2016). 3 – Mason and Connolly (in prep.)

Overyielding was found in six out of the fourteen species combinations that are represented in the series. Given that mixture effects often become more evident with the increasing age of a stand (Zhang *et al*., 2012), it is probably sensible to consider the results from the comparatively young stands at Gisburn separately from those in the other experiments listed where the trees are at least half the normal rotation age in Britain for the species concerned. Preliminary analysis of results in the older experiments suggests that, where light demanding, pioneer species (e.g. Scots pine, birch, lodgepole pine, Japanese larch) have been mixed together, there was no positive interaction between the species so that competition was the driving process. However, where species of different shade tolerance (Scots pine, Sitka spruce, western hemlock) have been mixed, there is overyielding in the mixture. In two of these cases (Dunraven and Margam), this is probably due to competitive reduction, but at Speymouth, it is thought that facilitation is causing the positive interaction, analogous to the case of nutritional mixtures between pines and larches with Sitka spruce on nutrient poor soils in northern Britain (Mason and Connolly, 2018).

One of the interesting features of the Gisburn site is that it provides a contrast between several different two-species mixtures all growing on the same site, as opposed to the other experiments listed in Table 27, where there is only one mixture combination planted at each site. Only three out of the seven mixture combinations at Gisburn had shown evidence of overyielding by year 20, and all of these are thought to be caused by a facilitation effect, either through interaction with a nitrogen fixing species (common alder) or because specialist mycorrhiza associated with Scots pine are able to degrade proteins in the soil, resulting in an enhancement in the pool of organic nitrogen which is then accessible to generalist fungi present on Norway or Sitka spruce roots (Ryan and Alexander, 1992). In two out of the three mixture combinations where overyielding has occurred, one species has benefitted at the expense of the other, thus Norway spruce at the expense of common alder, Sitka spruce at the expense of Scots pine (Mason and Connolly, 2014, their Figure 4). However, in the case of the Norway spruce/Scots pine mixture, both species appear to have benefited from the mixture.

Another benefit of the design used in the experiments listed in Table 27 is that, in those mixtures where overyielding has occurred, the presence of pure plots of each species provides a sound basis for understanding the species interactions that have caused the productivity gains. This is relevant to the nutritional mixtures widely planted on nutrient poor soils in Ireland and northern Britain during the extensive afforestation programmes in the last decades of the past century (Carey *et al*., 1988, Morgan *et al*., 1992). A recent attempt to estimate the degree of overyielding in long-term pine/Sitka spruce nutritional mixture experiments in northern Scotland was hampered by the lack of pure plots of the nurse species replicated into the experimental design, so that the performance of the nurse had to be estimated from nearby sample plots (Mason and Connolly, 2018, supplementary data). Within the limitations of this approach, after 42-47 years, transgressive overyielding occurred in the pine/spruce mixtures in three experiments located on sites of 'very poor' soil nutrient regime, but no evidence of overyielding was found in the same mixture when planted on a more fertile site (Mason and Connolly, 2018).

In summary, results from long-term British experiments that have investigated the effect of mixtures upon stand productivity have either provided evidence of overyielding or neutral interactions. There have been no cases where underyielding has been identified. Overyielding appears to occur in those cases where the different growth strategies of the component species result in competitive reduction (e.g. the Sitka spruce/western hemlock combinations in Table 27) or where the presence of one species (e.g. common alder, Scots pine) appears to facilitate the growth of a more 'sensitive' one, particularly on nutrient poor sites. Neutral interactions in mixture appear to be found either on more fertile sites or where the component species share similar growth strategies (e.g. combinations of light demanding species).

4.1.4 Site visits

As already mentioned under the Practitioners' Survey earlier, respondents were asked if they were interested in showing their mixed woodland (or a mixed woodland they knew of) to the Project Team. Twenty-seven respondents nominated crops for the Project Team to visit, with most crops (78%) located in either Leinster or Munster.

Given the tight time deadlines and budgets for the project, it was agreed with the Working Group that the Project Team only visit a proportion of the nominated sites. Over a six-day period in April 2018, twenty-one sites were visited in counties Meath, Offaly, Dublin, Carlow, Wexford, Cork, Waterford and Kilkenny. The sites/crops visited were either operationally planted mixtures or experimental trials. The former crops were generally shown to us by the owner, manager or local Forest Service Inspector while the latter (in the Cork/Waterford area) were shown by Ted Horgan (ex. Coillte).

These site visits were extremely useful and informative for the project and full details of the sites and crops visited (including photos) are given in Appendix 4.A (operational sites) and 4.B (research trials). Although all site visits were very brief and not all site/crop details were available on all sites, there were some general lessons from these site visits. These were:

Owners' knowledge

- Managers often understand the necessity of getting in early to thin mixed crops more than owners do. Many crops will fail as mixtures if owners are not educated in this area.
- Even if owners and managers do understand the necessity of getting in early, some are reluctant to do so because it can be a loss-making exercise. Recent changes in the Woodland Improvement Grant structure should help in this regard.

Stand quality

- Some excellent quality oak stands, originally planted in mixture, were visited. The seed source of a particularly fine stand at Kildalkey (Meath) stand is of Dutch origin (see photographs in Appendix 4.A).
- Mixture performance is very variable across sites and is dependent on a number of factors that need to be determined e.g. site conditions, silvicultural treatments, etc.

Species combinations

- 15 species mixture combinations were seen – all at the first thinning stage or later. These included: SS/JL, SS/LP, SS/DF, NS/oak, NS/WRC, SP/oak, JL/syc, EL/oak, EL/be, WH/DF, WH/HL, LC/HL, WRC/oak, Oak/cherry and oak/hornbeam. Between operational plantings and field trials, there are sufficient stands available to provide useful data on a wide range of mixture combinations. A properly designed survey of both operational and experimental crops is however, required. Many crops, nominated as possible site visits to the Project Team, could not be visited because of project budget and time constraints.
- It is difficult to predict how some specific mixtures will perform on any given site and it is the relative growth rates of the individual species that determine the potential success or failure of any mixture.
- Where larch was used in the mixture, management intervention had to happen very early in the rotation – as early as 7-8 years old on some sites.

- A low percentage of a target species in a mixture is likely to result in pure performance of the target species. For example, SS in intimate mixture with 10% DF was seen at Tulla, Co. Offaly where the SS was out-competing the DF. A more robust design would have been required if a higher percentage of DF was expected in the final crop.

Mixture type

- Mostly line mixtures were seen on the ground with some group mixtures in the Coillte field trials. Line mixtures seen were generally alternate single lines and these resulted in particular problems for managers.

Wind stability

- Significant windthrow due to storm damage was observed in two oak stands soon after thinning. Both stands had been mechanically thinned, which may or may not have influenced their stability. On one of these sites (Kildorrery, Cork), however, strips of Italian alder were unaffected by the windthrow that had devastated the surrounding oak.
- NS and oak in a 3:3 line mixture performed well on a moist site (Moanmore, Kilkenny) until one of the outer 2 lines of NS was removed. The remaining NS lines were then blown in a storm and had to be removed, leaving an 8 m gap between the external lines of oak, resulting in a profusion of epicormic shoots on the oak.

Field trials

- The Coillte trials are at an interesting stage where the performance of a range of species mixtures can be seen. Maintenance, assessment and reporting, however, are urgently required.

Thinning

- Timely thinning resulted in excellent oak stands - Kildalkey, Mallow and Enniscorthy are good examples.
- All of foresters who hosted the field visits were experienced and had the necessary understanding of the competitive effects of conifer nurse species. All realised that, if the target species was not allowed the freedom to grow, then it would be out-competed very quickly by the nurse.

4.2 Performance of Mixtures in Britain

Conifer-broadleaved mixtures

The use of faster growing conifers such as Scots pine and larch to nurse slower growing broadleaves such as oak and beech has a long history in British forestry, dating back to at least the second half of the eighteenth century when extensive planting of Scots pine in mixture with broadleaves was reported on various private estates in Scotland (Anderson, 1967). European larch and Norway spruce were also used as nurse species for broadleaves (Anderson, op. cit.). Apart from any ‘nursing’ effect, one reason for the growing of these mixtures was the desire to obtain earlier revenues from the conifers which would be removed in early thinning. The growing of conifer nurses in mixture with broadleaves was evidently widespread in Britain until recent times. For example, Guillebaud (1930) reported that quality stands of oak in the Forest of Dean, dating from the second half of the nineteenth century, had originally been planted in mixture with European larch. Evans (1984) noted that the use of conifers to aid the establishment of broadleaves had been ‘almost universal’ in Britain.

Kerr and Evans (1993; their Table 3.4) outlined best practice for these nursing mixtures, where oak, beech and ash were the main broadleaves to be grown in mixture. Norway spruce and European larch were recommended nurses for all the broadleaved species, Scots pine was recommended for use with oak and beech, while Corsican pine and western red cedar were recommended for use with beech, primarily on calcareous soils. They gave a rule of thumb that, to ensure compatible growth rates, the anticipated yield class of the nurse should not be more than twice that of the broadleaves, except for larch where the ratio should not be more than 1.5 times. Both strip and group mixtures could be used, provided the pattern of planting was sufficiently robust to allow for mixture success even with some period of neglect. This was felt to mean that the broadleaved strips should be a minimum of three rows wide, while group mixtures should involve 12-25 trees in each broadleaved group.

Despite the long tradition of these conifer-broadleaved mixtures in British forestry, by the end of the last century their use had become much less common, partly because of concerns about the landscape impacts of mixing conifers with broadleaves, the so-called 'pyjama stripe' effect (Kerr and Evans, 1993). There was also evidence of delayed removal of the conifer nurses resulting in suppression of the broadleaved component and concerns over the progressive 'coniferisation' of native broadleaved woodland. This concern was heightened by a strategy briefly adopted in Forestry Commission forests in eastern England in the early 1970s of removing (either manually or chemically) the broadleaved element of such mixtures to favour the conifers. Reflecting widespread concern over these issues, in 1985 a new policy was introduced favouring broadleaved woodland, with associated grants which only supported the establishing of pure broadleaved stands. In subsequent years, while there have occasionally been specific grants for conifer-broadleaved mixtures (e.g. under the Scottish Rural Development Programme in 2014), their use is often constrained to specific situations.

There is some experimental evidence that, on nutrient poor soils, nursing mixtures of pines or larch admixed with more demanding broadleaves such as oak and beech can result in both improved growth and form of the broadleaves (Gabriel et al., 2005). However, there appears to have been limited operational uptake of this type of mixture, possibly reflecting some of the policy constraints on the use of conifer-broadleaved mixtures discussed above.

In various forests of upland Britain, spontaneous mixtures of conifers and broadleaves can be found to be developing where native broadleaves (e.g. birch, rowan, oak) colonize felled areas that have been replanted with conifers such as Sitka spruce and Scots pine (Mason, 2006). Limited experimental evidence suggests that these mixtures will eventually self-thin towards a conifer dominated stand, although the stocking of the conifers may be lower than would have been anticipated due to partial suppression of some conifers during the establishment phase. Traditionally, the broadleaved component would have been removed as part of a cleaning or pre-commercial thinning operation, but cost pressures have resulted in a greater acceptance of this 'ephemeral' broadleaved element.

One relatively new form of conifer-broadleaved mixture is the establishment of mixed woodlands of Scots pine and various upland broadleaves as part of grant schemes supporting the creation of new Native Pinewoods in Highland Scotland from 1988 onwards (McIntosh, 2006). Initially this allowed the inclusion of substantial areas of native upland broadleaves within a native pinewood, but this guidance has been refined in recent years. Thus, currently up to 15 per cent of Native Scots woodland being funded under the Scottish Woodland Creation Scheme can consist of native broadleaves, typically birch, rowan or aspen (Scottish Government, 2018). These broadleaves tend to be planted in discrete mosaics ('groups') rather in intimate mixture with the pine, according to soil and vegetation features of the site. To date, most of the issues arising from this mixture have involved trying to obtain satisfactory establishment on exposed sites of poor nutrient status, sometimes subject to deer browsing.

Conifer-conifer mixtures

Many of the early accounts of woodland creation in Britain suggest that the planting of mixtures of conifer species appears to have been comparatively rare, although Steven (1927) reported that intimate mixtures of Scots pine and European larch were fashionable in Scotland in the nineteenth century. The early part of the twentieth century saw a greater emphasis on pure stands of conifers so that, as noted by Anderson (1950), mixtures were recommended only on less fertile soils, or where a 'sensitive' species needed protection against frost or wind exposure. A major discovery in the 1920s and 1930s was that species like lodgepole pine, mountain pine, Scots pine and Japanese larch could be used to 'nurse' more productive species like Norway and Sitka spruce (Zehetmayr, 1960) on the impoverished sites available for afforestation, often characterised by heather vegetation. This nursing process typically involved two stages. The first stage involved the first 8- 10 years after planting when the nurse species showed normal growth while that of the nursed species could be very slow with nutrient deficient foliage. The second stage involved a transition in the growth of the nursed species from the 'checked' condition to one of vigorous growth with good foliage colour. The presumption was that the height growth of the nursed trees would rapidly catch up with that of the other species in the mixture so that a mixed closed canopy stand developed. It was also anticipated that the nursed species would outcompete the nurse during the 'stem exclusion' phase (sensu Oliver and Larson, 1996).

For a period in the 1940s and 1950s, such nursing (or nutritional) mixtures (typically of lodgepole pine and Sitka spruce) were widely planted in upland afforestation schemes, especially on sites where heather check was anticipated to be a problem for the spruce. One problem experienced with these mixtures was that if the height growth of the nurse was too vigorous (e.g. with south coastal provenances of lodgepole pine), the nurse would suppress the admixed species before the latter could benefit from improved nutrient status (Garforth, 1979). Furthermore, by the 1960s, advances in site management techniques (e.g. improved cultivation, use of herbicides, site adjusted fertiliser regimes) were able to remove many of the limiting factors to establishing pure stands of Sitka spruce across much of upland Britain. As a result, interest in nutritional mixtures declined for a decade or more. However, they again became of interest in the 1970s and 1980s during programmes of afforestation of peat dominated soils on infertile lithologies in northern Scotland. On these sites, establishment of pure Sitka spruce required costly fertiliser and herbicide inputs while the low productivity of pure stands of lodgepole pine, the main alternative species for these site types, was unattractive to private investors. Experimental evidence indicated that productivity of nutritional mixtures on these sites could be equal to or even exceed that of pure spruce and that these mixtures could be established without expensive fertiliser inputs (Mason and Connolly, 2018). The identification of Alaskan origins of lodgepole pine as having early growth rates compatible with that of Sitka spruce was another factor which made the use of nutritional mixtures attractive to forest managers. When coupled with the relatively low purchase price of the land, the productivity potential of nutritional mixtures of pine and spruce made forestry investment in the peatlands of northern Scotland commercially attractive.

Several patterns of these nutritional mixtures were trialled varying from alternating row mixtures to one where the different species were mixed in alternating plants along each planting row. A common form of this intimate mixture involved alternating groups of three plants of each species along the row. The commonest proportion was a 1:1 mixture of the pine (or larch) nurse to spruce, although both 1:3 and 3:1 mixtures were also used. The reason for favouring the intimate within row pattern of mixture was that this was felt to ensure maximum benefit from the nurse during the establishment phase (e.g. rapid root contact between the different species) while permitting the spruce to exert maximum competitive pressure on the pines following canopy closure.

The rapid expansion of private forestry in northern Scotland during the 1980s that was based upon widespread use of nutritional mixtures proved to be very controversial given the high conservation value of the peatland habitats for various bird species (Warren, 2000). The result was a government decision in 1988 to withdraw the favourable tax regime that had encouraged private forestry investment in this region, with a consequent rapid decline in planting on these nutrient poor soils. As a result, interest in nutritional mixtures of conifers declined again, although it has recently begun to increase as areas that were originally planted with such mixtures are felled and must be restocked. However, the damaging impact of *Dothistroma* needle blight on lodgepole pine is also limiting current use of these mixtures.

Planting of other mixtures of conifer species has been rare (Wilson and Cameron, 2015), although current grant schemes do allow for the planting of mixtures of conifer species as part of diversification strategies, for example in the ‘Diverse conifer’ component of the Scottish Woodland Creation Scheme (Scottish Government, 2018). In a recent review of the potential benefits of growing Sitka spruce in mixture with other conifers, Wilson and Cameron (2015) highlighted potential gains in resilience to pests and diseases, comparable productivity to pure spruce stands, the use of shade tolerant admixed species to enhance stand structural diversity, combined with limited environmental and amenity improvements. Among the alternative conifers considered for potential admixing in this review were: Douglas fir, western hemlock, western red cedar, Pacific silver fir, grand fir, and noble fir. The reported benefits must be set against increased costs of establishment, higher palatability of the admixed species to browsing, and possible marketing difficulties for stands containing a mixture of species. While none of these disadvantages are insuperable, the potential difficulties of creating and managing such mixtures mean that they are only being planted on a trial basis.

Broadleaved-broadleaved mixtures

As noted by Kerr and Evans (1993), the planting of mixtures of broadleaves became more common following the advent of the Broadleaved Policy in 1985, in addition to increased policy emphasis being given to the establishment of native broadleaved woodlands. These native woodlands are commonly divided into a number of different types known as the National Vegetation Communities (NVCs). Each NVC is based on the dominant tree species in the type. The 16 NVC woodland communities composed of broadleaves generally contain a mixture of tree species even if past management has resulted in a simplification of the species composition and structure (Harmer *et al*., 2010). Thus, planting of native broadleaves will normally contain a mixture of species with no single species representing more than 75 per cent of the stand (e.g. Scottish Government, 2018). The general perception has been that mixtures of broadleaves are less difficult to manage because of more compatible growth rates and functional traits (Kerr and Evans, 1993). However, there is little evidence of any systematic evaluation of the performance of broadleaved mixtures, possibly reflecting that these are often planted for environmental reasons and that management for timber production is of lesser importance.

Conclusion

The history of the use of mixtures in British forestry over recent decades has been rather complicated. The traditional two uses of mixtures identified by Kerr *et al*. (1992) (e.g. nursing mixtures of conifers and broadleaves; nutritional mixtures of conifers) have both proved controversial, largely for wider environmental reasons rather than for silvicultural considerations. Since these environmental issues have been reflected in forest policy, it seems unlikely that nursing mixtures of conifers and broadleaves will ever become as 'universal' in lowland Britain as they were until the 1980s (Evans, 1984). It is possible that nutritional mixtures of conifers will increase in importance as increasing areas of planted forests on nutrient poor soils in upland Britain are felled and have to be restocked, coupled with the desire to limit input of synthetic fertilisers as part of sustainable forest management. Thus, Smith and McKay (2002) recommended that nutritional mixtures be considered for the restocking of any site where nitrogen had been used in the first rotation to establish a pure Sitka spruce stand.

In contrast, a number of 'new' types of mixture have been recommended or are developing. These include conifer-broadleaved mixtures that are developing through natural colonisation of conifer restocking sites, and the establishment of mixtures that are intended to mimic the pattern found in native woodland types across Britain. Lastly, there is a clear policy aspiration to increase the use of species mixtures of all kinds in British forests as exemplified in recent guidance on the use of mixtures as part of a strategy for diversifying Welsh forests (NRW, 2017). Experimental and/or practical information on best practice for use in the design and management of these 'new' mixtures is sparse.

Section 5. Guidance on the management of mixtures

5.1 Review of current guidance

5.1.1 Documented guidance

Guidance available to Irish forest managers/owners on mixtures is very limited and is found in five main publications:

1. Forest Service Forestry Schemes Manual (Anon 2015a)
2. A Guide to Forest Tree Species and Selection and Silviculture in Ireland (Horgan *et. al.,* 2004)
3. Broadleaf Forestry in Ireland (Huss *et. al*., 2016)
4. Silvicultural Guidelines for the Tending and Thinning of Broadleaves (Short and Radford 2008)
5. Native Woodland Establishment GPC9 & GPC10 Silvicultural Standards (Anon 2015b)

1. Forestry Schemes Manual

Published by the Forest Service, Department of Agriculture in 2015, this booklet is mostly concerned with the administration of afforestation and other ancillary grant schemes. It provides detailed information on the silvicultural standards required for plantation establishment and the administration of the grants and premiums. Guidance on mixed plantations is very limited. Grant and Premium Categories give specifications regarding the species composition of plantations, including the configuration, plant spacing and stocking in a table. Tables show the suitability of Sitka spruce in mixture with Douglas fir, Japanese larch, hybrid larch, lodgepole pine (NC and SC) on various soil types, and the compatibility of conifer species in intimate and line mixtures. On broadleaf and conifer mixtures, the manual refers the reader to the book “A Guide to Forest Tree Species Selection and Silviculture in Ireland” (Horgan *et. al*., 2004).

There are only brief references to the establishment of mixed plantations with no discussion, rational or recommendations given for their use; nor the standards necessary for their management. As the main document concerned with plantation establishment in this country, the manual gives considerable detail on cultivation, drainage, planting, genetic material, etc. but lacks sufficient guidance on mixtures.

2. A Guide to Forest Tree Species and Selection and Silviculture in Ireland

Published originally in 2003 by COFORD and written by a multi-disciplinary team of experienced forest researchers this is the first forestry textbook to address the issue of mixed species plantations in Ireland in recent years. It discusses the reasons for mixtures, guidelines for their use and recommended conifer/conifer, broadleaf/ broadleaf and conifer/broadleaf mixtures. It provides comments on recommended species mixtures on suitable sites and gives layout options for group and band mixtures.

This is a useful publication. It draws on the experience of the researchers and also that from abroad. However, some of the mixtures recommended have yet to be planted on scale in this country and their performance determined over different site types.

3. Broadleaf Forestry in Ireland

A later publication (2016) than the previous book, this discusses, in one section, mixed plantations from the point of view of the establishment and management of broadleaves as the target final crop species. Topics covered include the advantages and disadvantages of mixed forests, types of mixtures, guiding principles of establishment, main species in mixture types, nurse crops and management issues. It points out the lack of experience in dealing with broadleaf mixtures in Ireland and the need for further research on mixture types under differing site conditions.

The publication gives a useful discourse on the theoretical background to mixed species crops but could not be considered to be a practical guide to the establishment and management of mixtures.

4. Silvicultural Guidelines for the Tending and Thinning of Broadleaves

This 30-page booklet, published by Teagasc, is a practical guide to the tending and thinning of broadleaf plantations. It covers not only pure broadleaf crops but also a number of broadleaf /conifer mixtures. It is clearly written and well-illustrated with photographs and diagrams and gives clear guidance to practitioners on how to go about these operations. Focusing on broadleaves it is, however, incomplete - particularly with regard to conifer mixtures.

5. Native Woodland Establishment (GPC9 & GPC10) Silvicultural Standards
This publication is similar to the Forestry Standards Manual but is concerned specifically with the establishment of native woodland under GPCs 9 and 10. Detailed guidance is given under a Native Woodland framework on the appropriate woodland type to be established on a site. The framework sets out the prescribed species mixture, composition and layout, designed to initiate the development of the relevant native woodland type. It provides good guidance for the purpose of establishing mixed species native woodlands for nature conservation but does not address the management of commercial plantations for timber production.

Other media
Video is becoming a popular medium for education and training and Teagasc have produced one on the thinning of broadleaves (available at the Teagasc Forestry YouTube Chanel). However, there are no specific videos dealing with the issues concerning mixed species plantations.

Comment
Published guidance on the establishment and subsequent management of mixed species plantations is both scarce and not readily available to practitioners. The material that exists is inadequate to provide them with the required practical information to successfully manage mixed species plantations. Articles in textbooks are often not known, or readily accessible to those seeking information. Guidelines in booklet form such as those published by Teagasc on the Thinning of Broadleaves, or COFORD Connect Notes are an ideal way of providing material in an easily accessible fashion.

Given the immediate need to inform and upskill the industry on the issue of species mixtures, other forms of communication should be considered apart from the written word. A communications programme specifically addressing the issue of mixtures should be considered. A model to consider is the programme carried out by COFORD on Wood Energy. This included workshops, seminars, demonstrations, field days, information notes and a website, woodenergy.ie., which contains a wealth of information on all aspects of wood energy.

5.1.2 Education and Training

In addition to the documented guidance outlined above, the subject of mixtures is also currently covered in forest education in this country. For this study, contacts in the two main third level institutions involved in forest education (UCD and WIT) were contacted and asked about the coverage of the subject in their syllabus.

UCD
Forestry students coming through UCD get approximately 2-3 hours exposure to the subject of mixtures. This takes place mainly in 3rd year in two modules - Forest Establishment and Silviculture of Forest Stands. These modules are co-ordinated by Drs. Conor O'Reilly and Áine Ní Dhubháin. The students are also expected to consider mixtures in their project for the Establishment module and are provided with some reading material about mixtures. They are also expected to consult text books, including the COFORD Guide to Forest Tree Species Selection and Silviculture in Ireland (Horgan *et al*., 2004). The module descriptor can be viewed at the link below which gives an overview of what is covered http://www.ucd.ie/students/course_search.htm.

The Establishment module is heavily weighted towards the project, which accounts for 60% of the marks. The lectures are only pointers, combined with some discussion. Therefore, the students are expected to dedicate a significant amount of time to independent learning, to include the consideration of mixtures, particularly in completing the project. Thinning of mixtures is covered very briefly in the Silviculture module.

In addition to in-class teaching, mixtures are also covered in field visits, particularly in one field visit where Dr. Ian Short (Teagasc) pays particular attention to the subject.

WIT
The subject of mixtures is covered in two lectures in Silviculture by Dr. Nick McCarthy. The emphasis is very much on the additional management required where mixtures are used. This is taken up again in field visits where

poorly managed or neglected mixtures are visited. In addition, it is covered in first year (Forest Establishment) where mixture types (line, block, intimate, conifer-conifer, broadleaved-broadleaved and conifer-broadleaved), compatibility and mixture spacing is examined. It is also part of Forestry in the Environment in second year - in terms of species diversity requirements and GPC categories. It is then looked at again in Sustainable Forest Management in third year, with an emphasis on nursing and nutrient supply and then again later in third year in Commercial Forest Practices, under Forest Service requirements.

5.2 Recommendations

5.2.1 Basic principles regarding mixtures

a) Decide on the reasons for selecting a mixed rather than a pure crop e.g. timber production, landscape, amenity, biodiversity, nature conservation, etc. Be clear about the silvicultural requirements of mixed crops, timber yields and products, financial costs and returns, etc. if growing for timber production.
b) Choose species mixtures that are suited to the site type.
c) Select a mixture design that is robust i.e. multiple line mixtures or groups which will enable target species to develop properly and prevent the nurse dominating the mixture. Choose a design that will facilitate thinning.
d) Periodically monitor the plantation’s development, particularly during the first 5-10 years.
e) Ensure timely intervention/thinning if the nurse becomes too dominant.
f) Total removal of the nurse is often not necessary. If the crop is stable, some of the nurse trees can be left to form a mixed plantation and produce quality timber.
g) After first thinning, select Potential Crop Trees (PCTs) and prune.
h) Introduction of shade bearing species e.g. beech, hornbeam, western red cedar, etc. to control epicormic shoot in pure oak plantations can be carried out at this stage.
i) Subsequent thinnings should concentrate on providing the PCTs sufficient space to develop.

5.2.2 Management recommendations

The species mixtures covered in the tables below (Tables 23, 24 and 25) are the mixtures listed in Tables 5.3 (conifer/conifer), 5.4 (broadleaf/broadleaf) and 5.5 (conifer/broadleaf) of the COFORD publication “A Guide to Forest Tree Species Selection and Silviculture in Ireland” (Horgan et al., 2004). In the third column of each of the three tables below, updates (where available) on the original 2004 recommendations are given – based on available new data or findings since that time.

Note: All recommendations given in the three tables below are based on currently available best silvicultural practice. They do not take into account current Woodland Improvement Grants, costs of thinning (either to recycle or to remove) or markets for small material. These additional factors change over time and the woodland owner/manager must balance these financial issues with his/her long terms objectives for their woodland.

Plant health notes on larch and pines

The two notes below are taken from information supplied by the Forest Service (DAFM) and should be taken into account when designing new mixtures or managing existing ones.

1. Hybrid larch (*Larix* x *eurolepis*) & European larch (*Larix decidua*) (Larch species):

Due to the very damaging outbreaks of *Phytophthora ramorum* in Japanese larch, this species continues to be an unapproved species for grant aid. Hybrid larch and European larch are also susceptible to the disease and will no longer be accepted species for grant aid post June 2017. In the interim with regard to applicants who are applying to plant hybrid larch or European larch, the location of the proposed planting will be taken into account by the Forest Service in relation to its proximity to current outbreaks of the disease in Japanese larch and wild rhododendron and the latest scientific knowledge of the disease.

2. Pinus species (Pine species):

Applicants wishing to plant pine species should be aware of the potentially damaging disease, red band needle blight (Dothistroma needle blight caused by the fungus *Dothistroma septosporum* and listed in the EU Plant Health Directive as *Scirrhia pini*). This disease is causing significant damage to pine species in Great Britain and has also been detected in Northern Ireland.

Conifer/Conifer mixtures

Data from the NFI suggest that conifer/conifer mixtures make up 55,632 ha in public and 72,099 ha in private ownership in Ireland. The main conifer/conifer mixtures in the Coillte estate include various mixes of SS, LP and JL. Although the primary objective of many of these mixtures originally was to enhance the performance of the more site-demanding species, they have been used increasingly to diversify risk and, in the case of the SS/JL mixtures, to enhance the landscape value of upland spruce plantations. Unfortunately, due to recent disease outbreaks, larch is currently not being planted in this country. Guidance on potential conifer/conifer mixtures on suitable sites is provided in Horgan et. al. (2004), and reproduced here in Table 28.

TABLE 28: Potential conifer/conifer mixtures on suitable sites (Horgan et. al. 2004).

Species Mixture	Comments (original text from Horgan et. al. 2004)	Current management recommendation and/ or lessons learned since Horgan et al. (2004) was published
Sitka spruce (inter provenance mixtures)	Mixtures of different Sitka spruce provenances, e.g. Alaska/Washington (if Alaskan material is available), result in high stand variability, thus facilitating the self-thinning process. This has much merit on unstable sites, where thinning operations could otherwise induce windblow.	The details of the mixture (proportion of each provenance and spatial arrangement) depend on crop stability, potential markets for small material and rotation length but the mixture provides the owner/manager with a "plant and close the gate option" for specific sites.
Sitka spruce/ lodgepole pine (south coastal)	In the past, this mixture was very popular on infertile soils, but in nearly all cases the lodgepole suppressed the Sitka spruce. However, on fertile sites, the Sitka spruce later dominates (having kept pace in the earlier years), and goes on to ultimately, suppress the lodgepole pine. As is the case of the Sitka inter provenance mixtures, it has application on unstable sites.	Apart from species diversification, this mixture has fewer advantages over the SS/SS inter provenance mixtures (above). In a 28-year-old experiment, established on a restock site in Cork (ADH 16/90), the pine is currently taller than the spruce. The pure spruce plots in the experiment have already been thinned.
Sitka spruce/ lodgepole pine (north coastal or inland)	On nutrient-poor mineral soils, the lodgepole pine out-performs the Sitka spruce for about the first ten years, then the desired nursing effect generally begins to manifest itself in improved growth of the Sitka spruce, which goes on to suppress the pine.	Should be used more on suitable sites as the mixture leads to stability and reduced branchiness in the final spruce crop. Mixtures of Sitka spruce and various lodgepole pine provenances (inland, north and south coastal) are to be found in a 28-year-old experiment in Cork (ADH 16/90).
Sitka spruce/ Japanese larch	Early dominance by the larch, often poses problems for the spruce on nutrient-poor mineral soils. However, after about ten years, nursing by the larch begins to take effect, becoming evident in improved growth of the spruce. This usually leads to a reversal of dominance later in the rotation.	Not a mixture currently used because of disease issues. Originally proposed for nursing SS on nutrient-poor mineral soils but extended in use over the last 10-15 years and has been used on many wet mineral fertile sites to improve landscape design. This has resulted in the JL growing faster than the SS, with resulting poor form in the larch and damage to individual spruce in the vicinity of the larch. Larch now being removed in first two thinnings, leading to subsequent pure spruce crops.
Sitka spruce/ Douglas fir	Nursing of Sitka spruce by Douglas fir is a recently discovered phenomenon, (first observed in 1985 at Mallow forest, Co Cork). This performance has since been replicated at a number of sites, demonstrating conclusively that on free-draining mineral soils, nutritionally marginal to pure Sitka spruce, planting in mixture with Douglas fir enables the spruce to be grown successfully. Early dominance by the Douglas fir is usually reversed later in the rotation.	Very similar results to SS/JL mixtures above. This mixture has potential on poor, free-draining mineral sites but the owner/grower must weigh the advantages/disadvantages of potential markets for small DF compared to small JL removed in early thinnings. The DF is also more prone to windblow than the JL if the site is moist. If used on sites suited to the DF and where a DF crop is the end objective, the individual good DF trees have to be freed from spruce competition. On good sites, the difference in rotation lengths between the two species can lead to the spruce having to be removed before the fir is at an optimum size. The mixture is included in a trial in Cork (BTR 25/94) where the spruce has outgrown the fir after 24 years.

TABLE 28: Potential conifer/conifer mixtures on suitable sites (Horgan et. al. 2004). Continued.

Species Mixture	Comments (original text from Horgan et. al. 2004)	Current management recommendation and/ or lessons learned since Horgan et al. (2004) was published
Sitka spruce/ western hemlock	This mixture occurs in the native range of both species, the west coast of North America. The western hemlock benefits from the microclimate created by the Sitka spruce during the establishment phase. The pliant, pendulous leading shoot of the hemlock is not easily whipped, and it has very strong powers of recovery after being suppressed.	Some advisors advocate introducing hemlock to spruce crops where it is intended moving towards a continuous cover forest (CCF) system. This must be carried out with care, however, as hemlock can become invasive over time. The mix may have benefits where woody vegetation such as laurel or rhododendron need to be controlled.
Sitka spruce/ western red cedar	This mixture occurs in the native range of both species, the west coast of North America and may have application here on heavy soils, where species options are limited.	Probably a better choice (compared to SS/WH) where a move to CCF systems are intended.
Norway spruce/Scots pine	This mixture was very popular in the past, when Scots pine was used as a nurse to Norway spruce on frost-prone sites. However, on damp sites the spruce has a tendency to dominate, whilst frosty or infertile conditions favour the pine.	Given the nature of our changing climate, Scots pine is rarely used now to nurse Norway spruce crops from frost and it is only in exceptional circumstances that NS is affected by late spring frost. Apart from species diversity, pure crops of either species (the choice of either depending on soil and site) are probably a better choice.
Norway spruce/ European larch	On sites suitable to both species this mixture works well, but where soil conditions are heavy the Norway spruce usually becomes dominant.	In a similar way to NS/SP mixtures, the optimum site/soil for each of these two species is quite different (see original comment in this row). European larch is currently not being planted here.
Douglas fir/ Japanese larch	These species are generally compatible. However, Japanese larch is much more flexible in terms of site suitability. These stands have a high amenity value.	This mixture is currently not being planted because of disease issues in larch. Where already growing well and disease free, some larch can be removed in early thinnings where markets exist for larch poles. Best quality DF should be favoured as thinnings progress.
Douglas fir/ Hybrid larch	Mixtures of these species are generally compatible, although Douglas fir is much more site specific. By judicious thinning, the final crop composition is easily manipulated to favour the most promising species or indeed the best stems of both species.	As above.
Western hemlock/ Douglas fir or western red cedar	These species often grow in mixture or in close association in their native range. Drier areas favour the Douglas fir and western hemlock, with western red cedar becoming dominant on the banks of watercourses and on marshy valley bottoms.	Also included in trial BTR 25/94 where, after 24 years, the hemlock crop is good (light branched) and has outgrown the DF.
Scots pine/ European larch	Mixtures of these species were much favoured in the past. The larch, being valuable in small sizes for the production of fencing stakes, was gradually removed as thinnings, leaving the pine to form the final crop. Although generally compatible, on fertile sites the larch has a tendency to dominate, whilst infertile or frosty conditions favour the pine.	More suited to similar sites than either species in mixture with spruce. This mixture is currently not being planted because of disease issues in larch. Where already growing well and disease free, some larch can be removed in early thinnings where markets exist for larch poles, resulting in a final crop of pure pine or larch/pine mix.
Japanese larch/western hemlock or western red cedar	These form plantations with a high amenity value, as well as a nursing effect and early returns from the larch, in combination with enhanced production from the hemlock or cedar. The pliant, pendulous leading shoot of the hemlock is not easily whipped, and it has very strong powers of recovery after being suppressed. By virtue of its narrow crown and shade tolerance, western red cedar is well set to cope with the early dominance of the larch.	Mixture currently not being planted because of disease issues in larch but silviculturally works well as a mixture. Objectives for ultimate clearfell or CCF management will determine how the various species are managed e.g. larch crowns will require room while hemlock will recover from being confined in the understory for long periods.
Hybrid larch/ western hemlock or western red cedar	These form plantations with a high amenity value, as well as a nursing effect and early returns from the larch, in combination with enhanced production from the hemlock or cedar.	As above but improved form and faster growth of the hybrid larch (compared to Japanese larch) may influence management objectives and techniques.

Broadleaf/Broadleaf mixtures

Data, already presented from the NFI, show that there are 21,211 ha of broadleaf/broadleaf mixtures in public ownership and 62,114 ha in private ownership in this country. Generally, broadleaf mixtures have fewer problems with compatibility and visual impact than conifer/broadleaf mixtures, affording a more flexible attitude to design. Table 29 shows broadleaf mixtures with recognised potential on suitable sites.

TABLE 29: Potential broadleaf/broadleaf mixtures on suitable sites.

Species Mixture	Comments (original text from Horgan et al., 2004)	Current management recommendation and/ or lessons learned since Horgan et al. (2004) was published
Birch in mixture with oak, beech, ash, Spanish chestnut and/or cherry	Birch, because of its frost-hardiness, is ideal as an overhead screen against spring frost damage for more delicate species during the establishment phase. However, unless already present on the site, the birch needs to be planted well in advance of the other main species. When it reaches a height of about 6 m, the main species is introduced as an understorey following a heavy thinning of the birch. These plantations must be carefully watched to prevent whipping of the main crop leaders by the birch. Further thinning of the birch, as required, can provide additional relief to the main crop.	The birch in this mixture can be difficult to establish on farmland afforestation sites and mixtures with birch often result from situations where naturally regenerating birch invades restock sites (either before or after restock planting takes place). A good example of planting oak under an already existing canopy of birch exists in Offaly (experiment CLE 5/00). On this site, the oak was planted when the birch (naturally regenerated) was already up to 10 m tall. The trial was established in 2000.
Alder in mixture with oak, ash, and cherry	On heavier soils, common or grey alder can be substituted for birch as an overhead screen. Alder's ability to make direct use of atmospheric nitrogen can be beneficial to the ash on many sites.	Care must be taken with this mixture as alder growth is unpredictable. If it grows well, the target crop (ash and cherry particularly) will require their crowns to be opened up early. If the alder dies early on, then there should be sufficient light for all the crop species mentioned.
Oak/beech	It is not recommended to mix these species at planting. It's best to introduce beech as an understorey at the time of first thinning of the pure oak crop. Beech will benefit from the microclimate created by the oak, while controlling epicormic shoots in the oak.	In addition to the planting of beech after thinning in pure oak (as recommended across), underplanting with beech is also being used in some crops where oak had originally been planted in mixture with Scots pine or European larch and where the conifer was removed at an early stage. The beech is planted is an attempt to prevent epicormic shoots developing in the oak.
Oak/hornbeam	On heavy soils, following thinning of an oak crop, hornbeam can be introduced as an understorey to control lateral branch development, epicormic shoots and undesirable undergrowth.	Similar to the above but for heavier soils. Hornbeam can grow faster than beech and may need to be cut back if too vigorous.
Beech/ash	Following a number of thinnings to the ash, beech is best introduced as an understorey to control unwanted vegetation, to act as a soil-improver and as a successor crop to the ash.	This mixture may have increased relevance where an ash crop may have been affected by disease but where some healthy trees remain.
Beech/ sycamore	Although this mixture is initially compatible, the beech tends to suppress the sycamore later in the rotation.	Not suitable in areas of high grey squirrel populations. No additional guidance available at this point.
Beech/alder	Italian alder may be used as a nurse to beech on alkaline soils.	No additional guidance available at this point.
Ash/sycamore	These species are generally compatible. The ash, however, is more site specific, and is also more sensitive to frost and exposure than the sycamore.	Not suitable in areas of high grey squirrel populations. No additional guidance available at this point.
Ash/Spanish chestnut	These species have many similarities, i.e. sensitivity to frost, exposure and growth rates. However, ash prefers soils with a higher pH and also a higher soil moisture regime than does Spanish chestnut.	Not suitable in areas of high grey squirrel populations. No additional guidance available at this point.
Spanish chestnut/ sycamore	Growth rates of these two species are compatible. Sp. chestnut, sensitive to frost and exposure, should benefit from the syc. nurse.	Not suitable in areas of high grey squirrel populations. No additional guidance available at this point.

Conifer/Broadleaf mixtures

There are 52,013 ha of this mix in public ownership and 36,795 ha in private ownership, according to the NFI (data presented earlier in this report). These mixtures are usually established with one or more of three main objectives in mind:

a) the production of quality broadleaf crops
b) the production of cost effective pure broadleaf crops
c) production of visually appealing crops.

Ideally, conifer/broadleaf mixtures should be of robust design, i.e. band or group, where each species is able to survive with the minimum intervention. To be fully effective in the provision of side shelter, so essential to the satisfactory establishment of quality broadleaf crops, the conifer nurse should, in some instances, be planted ahead of the broadleaf species. This can be difficult to manage when it comes to Afforestation grant payments but recent changes in the Woodland Improvement Grant Scheme means that there may be new opportunities in this regard. Alternatively, both species can be planted at the same time, and if, after 2-3 years the general form of the broadleaf crop is less than satisfactory, it can be 'stumped back' (cut back to within 10 cm of ground level). The resultant vigorous regrowth will not only have improved form, but also benefit from the side shelter now available from the conifer nurse. However, it should be remembered that not all broadleaves lend themselves to stumping back. It works very well in the case of oak, ash, Spanish chestnut and sycamore, but not for beech. Table 30 lists conifer/broadleaf mixtures with recognised potential on suitable sites.

TABLE 30: Potential conifer/broadleaf mixtures on suitable sites.

Species Mixture	Comments (original text from Horgan et al., 2004)	Current management recommendation and/or lessons learned since Horgan et al. (2004) was published
Norway spruce/oak	Traditionally Norway spruce was used to nurse oak. However, this practice has been questioned, due to the slow early growth of Norway spruce compared to oak. Oak responds to chemical vegetation control more positively in terms of enhanced growth than Norway spruce. This can result in the oak being twice the height of the Norway spruce four to five years after planting. In later years, the spruce is usually too vigorous for the oak.	Not used very much on the ground for the reasons given across. A good example of such a mixture in Kilkenny was highlighted by Guest and Huss (2012). The crop was planted in 1992 with alternating three row bands of oak and Norway spruce. The robust nature of the bands meant that, even though the Norway spruce was 2.5 m taller than the oak after 15 years, the authors felt that, with judicious gradual removal of the spruce over time, the oak would continue to grow well. On a recent visit (2018), however, it was noted that all the spruce had been removed, resulting in large gaps (8 m) between the remaining rows of oak.
Norway spruce / ash	Prior to the advent of chemical vegetation control these species were regarded as having compatible growth rates. However, due to their very differing responses to chemical vegetation control, this is no longer the position, at least in the earlier years. Mixtures of these species are therefore not recommended.	No additional comment.
Scots pine/ oak	Well-managed oak, pedunculate in particular, can make rapid height growth in the early years. Therefore, to be in a position to provide the necessary side shelter to the oak at establishment, and to avoid the danger of suppression by the oak, the Scots pine should ideally be planted 2-3 years ahead of the oak. All authors agree Scots pine is not ideally suited to heavy soils that are often considered as good pedunculate oak sites.	This is not a good mixture on many sites because, in the early years, the pine does not provide any shelter for the oak and from about year 10-12, the pine begins to dominate the oak. Unless the crop is well managed (i.e. most, if not all of pine, removed) at this point, the oak could be lost. A good example of a well-managed crop of this type exists in Co. Meath. This crop was planted in 2000 and had most of the pine removed by 2012. Band mixtures of these two species are a much better option where the Scots can be removed more gradually, giving room to, but also providing some shelter to, the oak.
Scots pine + European larch/ oak	Provided the soil and site are suitable, these mixtures have the advantage of yielding an early return from the thinnings of the conifer, whilst also providing a space in which beech or hornbeam can be introduced as an understorey to control the occurrence of epicormic shoots. The larch is removed in earlier thinning, whereas the Scots pine may be allowed to grow until half way through the oak rotation. These mixtures are also much cheaper to establish than pure oak. However, such mixtures need careful and skilful management.	This mixture is similar to the SP/oak above but uses a line of European larch instead of every second line of Scots pine. It has an advantage over using only pine in that the larch gives earlier shelter to the oak but requires even earlier intervention because of the more rapid early growth of the larch. By year 8-10, the larch may need to be removed completely but perhaps at a size where it produces rustic stake material (if straight enough). Woodlands owners/managers have three options when it comes to early opening of such stands. The choice will depend on size of tree, markets for small material, availability of suitable equipment and stand objectives. The three options are: 1. Fell and remove thinned material 2. Fell and leave harvested trees on site (fell and recycle) 3. Kill trees (lines or individuals) using a herbicide and leave standing

TABLE 30: Potential conifer/broadleaf mixtures on suitable sites. Continued.

Species Mixture	Comments (original text from Horgan et al., 2004)	Current management recommendation and/or lessons learned since Horgan et al. (2004) was published
Scots pine/ beech	To be in a position to provide the necessary shelter to the beech at establishment, Scots pine should ideally be planted 2-3 years ahead of the beech. A better system is to introduce beech as an understorey, after the Scots pine has been opened up by a number of thinnings.	A better mix than SP/oak in that the pine will provide some shelter to the beech earlier than it will to the oak. Options early in the rotation are also better in that the beech can tolerate being overtopped by the pine longer than the oak would, giving the owner/manager more time in which to intervene successfully. Alternatively, band mixtures of three rows of each species, are a better option.
Corsican pine/beech	This is a frequently used mixture on calcareous soils, the Corsican pine being less liable to lime-induced chlorosis than other compatible species.	Risky to plant here at the moment because of Dothistroma in the Corsican pine.
European larch/oak	Generally compatible, however European larch is not ideally suited to heavy soils that are often considered as good pedunculate oak sites.	A common mixture as alternate lines but which requires early and timely management on most sites. The larch can be 1-3 m taller than the oak after only 5-9 years (Guest and Huss, 2012). Another issue which may arise after early intervention on these sites is windblow in the oak after the larch has been removed. This was observed recently (2018) on two sites. Both sites had been thinned mechanically and it is not yet known whether this was partly responsible for the oak toppling.
European larch/beech	On some soils, the rapid early growth of the larch can pose problems for the beech. On the other hand, the beech is likely to outgrow and suppress the larch later in the rotation. A better system is to introduce the beech by underplanting half way through the rotation of the European larch.	Options early in the rotation are better than larch is mixed with beech in that the beech can tolerate being overtopped by the larch longer than the oak would, giving the owner/manager more time in which to intervene successfully. Alternatively, band mixtures of three rows of each species are a better option.
European larch/ash	Where the soil and site is suitable to both species, compatibility between these species is generally good. Nevertheless, to be effective in the provision of side shelter so essential for quality ash production, the larch would need to be planted 3-4 years ahead of the ash. However, care is needed to ensure that the larch does not restrict crown development in the ash, which once lost is not easily increased again.	Neither species are currently being planted because of disease issues
European larch/ sycamore	Where the soil and site is suitable to both species, these mixtures are successful. Nevertheless, there is a need for vigilance to prevent dominance by either species.	Not currently planted because of larch disease issue.
European larch/Spanish chestnut	It is recommended to plant the Spanish chestnut in groups in a matrix of European larch, stump back the Spanish chestnut about 2-3 years after planting and reduce the resulting coppice to a single stem one year later.	Not currently planted because of larch disease issue.
Hybrid larch/ sycamore or ash	Hybrid larch provides early side shelter and controls heavy branching in the broadleaf species, whilst also providing early returns from thinnings. However, timely intervention is required to favour the broadleaf species from undue competition from the larch.	Although not currently planted because of larch disease issue, a good example of a similar crop exists in Offaly on a cutover site. The crop (JL/sycamore) was planted in two row strips of each species and is currently 22 years old. The sycamore badly needs to be opened up and freed from excessive larch competition.
Western hemlock/oak	Western hemlock can be planted as an understorey in semi-mature oak (60-80 years old) stands to control lateral branch development, epicormic shoots and undesirable undergrowth. It is envisaged that both species would be harvested simultaneously.	Useful to control epicormic shoots in the oak but care must be taken that hemlock regeneration doesn't invade the site or adjoining sites.
Western hemlock/ash	Western hemlock can be introduced as an understorey to control undergrowth and to provide a successor crop.	Similar to above.
Western red cedar/ash	Its narrow crown makes western red cedar the ideal nurse species, to be effective in the provision of side shelter to the ash, ideally it needs to be planted 3-4 years ahead of the ash.	Alternatively, the cedar could possibly be introduced into existing ash crops where disease has killed some of the broadleaf crop but where healthy trees remain.

TABLE 30: Potential conifer/broadleaf mixtures on suitable sites. Continued.

Species Mixture	Comments (original text from Horgan et al., 2004)	Current management recommendation and/or lessons learned since Horgan et al. (2004) was published
Western red cedar/ beech	Provided the soil and site is suitable to both species, this mixture should be successful. The narrow crown of the western red cedar enables it to provide the necessary shelter without endangering the beech. Ideally it needs to be planted 2-3 years ahead of the beech.	No additional comment.
Western red cedar/ oak	Its narrow crown makes western red cedar the ideal nurse species, but, in common with some other nurse species, ideally it needs to be planted 2-3 years ahead of the oak. Western red cedar can also be introduced as an understorey where it will also control lateral branch development and undesirable undergrowth.	Probably a better choice than hemlock for introducing under an existing oak crop to control epicormic shoots.
Sitka spruce, Norway spruce, western hemlock in mixture with birch	As previously stated, birch is ideal as an overhead screen against spring frost damage for more delicate species during the establishment phase. However, unless already present on the site, the birch needs to be planted well in advance. When it reaches a height of about 6 m, the main species is introduced as an understorey following a heavy thinning of the birch. These plantations must be carefully managed to prevent whipping of the main crop leaders by the birch. Further thinning of the birch, as required, can provide additional relief to the main crop.	The birch in this mixture can be difficult to establish on farmland afforestation sites and mixtures with birch often result from situations where naturally regenerating birch invades restock sites (either before or after restock planting takes place). A good example of planting both Sitka and Norway spruces under an already existing canopy of birch exists in Offaly (experiment CLE 5/00). On this site, both spruces were planted when the birch (naturally regenerated) was already up to 10 m tall. The trial was established in 2000 and now badly needs some of the birch overstory to be removed. The shelter from the birch greatly improved the early growth of both spruce species compared to open grown spruce on this frost prone site. The spruce (Norway and/or Sitka)/birch mixture is also currently found over large areas of the midlands where natural regeneration of birch has invaded clearfelled sites (mostly on Coillte land) on peat either just before or after restocking with the spruce. Although many of these spruce crops were cleared of the birch regeneration for years after planting, many sites now carry crops with a large proportion of birch in the canopy. Given that many of these crops are near facilities which use large quantities of woody biomass, there are possibilities to manage these mixed forests by removing some of the birch for biomass while improving the future growth of the spruce.
Sitka spruce, Norway spruce, western hemlock in mixture with alder	On heavier soils, common alder as an overhead screen can substitute birch. Alder's ability to make direct use of atmospheric nitrogen can be an additional nutritional benefit to the main crop on many sites.	The fate and management of these crops depends on the planting pattern and the health and vigour of the alder. Where the alder dies off at a young age, there must be sufficient stocking of the conifer to produce an economic crop. There are some good demonstration areas on midland sites of where Sitka spruce was planted and has done well under an existing alder canopy.

5.3 Possible additional species for use in mixtures

Although the tables in section 5.2.2 cover most of the possible species and mixture combinations that could be considered within Irish forestry, there are a few additional possibilities that could be considered as part of a strategy of diversifying Irish forests. These species are briefly considered below:

Broadleaved species

Aspen

This fast-growing pioneer species, *Populus tremula,* is one of the few broadleaves whose early height growth could be compatible with that of Sitka spruce. It grows on a range of soil types including the wetter gleyed soils where Sitka is often planted. The timber is often used for pulpwood, particularly when grown on a short rotation. It is widespread in the boreal forests of Scandinavia where it is considered to be a valuable species for enhancing biodiversity, although it can be disadvantaged by browsing pressure from deer. There has been increasing interest in using this species to diversify spruce dominated forests in upland Britain (e.g. Worrell, 1995) but as yet, there are no reported formal trials of such mixtures. The closely related trembling aspen (*Populus tremuloides*) found in North America is now widely grown in mixture with white spruce (*Picea glauca*) in western Canada where two storied mixtures develop as a result of the aspen colonizing clear felled areas that are being restocked with spruce (Kabzems *et al*., 2016).

Nothofagus spp.

The southern beeches from Chile and Argentina are a group of fast-growing species with desirable timber properties that grow on well drained mineral soils. With the exception of Eucalypts, they are probably the fastest growing broadleaved species that have been trialled in Britain and Ireland. The two main species that have been of interest are rauli (*N. alpina*, syn. *N. procera*) and roble (*N. obliqua*) and their fast, early height growth would allow these species to be grown in mixture with conifers such as Douglas fir or larch on suitable soils. Unfortunately, operational trials carried out in the late 1970s and early 1980s in Britain often used provenances that were not fully cold-hardy and the subsequent widespread losses resulted in a decline in interest in these species. However, more recent trials, plus climate warming, suggest that more cold-hardy material can be identified with promising results (Mason *et al*., 2018). In general, the better form and timber quality of rauli would make this the preferred species to be grown. One concern is the apparent vulnerability of these species to attack by *Phytophthora pseudosyringae* which can cause high mortality on heavier or wetter soils.

Conifer species

Silver firs (Abies spp.)

The main group of conifers that appears to be absent from the existing Irish stands and trials recorded in this report are the various silver firs (e.g. Pacific silver fir (*Abies amabilis*), grand fir (*A. grandis*) and noble fir (*A. procera*)) which have been recommended for use in mixture with Sitka spruce in upland Britain (Wilson *et al*., 2016). In addition, there has been renewed interest in the potential role of European silver fir (*A. alba*) in British forests following a re-evaluation of existing provenance trials (Kerr *et al*., 2015). All the species are best grown on freely drained, brown earths or podzolic soils although European silver fir may tolerate heavier gleyed soils, provided no peat is present. Except for noble fir, the shade tolerant habit of these species means that they may be particularly useful for growing in mixed stands with other conifers (e.g. Douglas fir, Sitka spruce) where the intention is to introduce these species into the understorey as part of a continuous cover forestry (CCF) approach. Noble fir is only of intermediate shade tolerance which makes it less suitable for use in CCF, but it is more exposure resistant than other silver firs, which could make it suitable for use in mixture with Sitka spruce on freely drained soils at higher elevations. One additional advantage that these species can confer in mixture is that they are all capable of deep rooting on free draining soils and may therefore provide additional stability.

Coast redwood (Sequoia sempervirens) and Japanese red cedar (Cryptomeria japonica).

The main interest in both these species is that they are potentially highly productive when grown on freely drained mineral soils, but can be very difficult to establish in open ground because of their sensitivity to frost and limited tolerance of weed competition (Wilson *et al*., 2016; Savill, 2015). Therefore, recommended practice is to establish these species in the shelter of an admixed light-demanding species such as birch or Scots pine. Once established, their fast rate of growth and high volume production means that they could be grown in mixture with other yielding species such as Douglas fir.

Section 6 - Future research programmes, knowledge gaps and recommendations

6.1 Future Research Programmes

Recent years have seen a substantial international research effort devoted to mixed species forests with a number of useful reviews provided in the literature (e.g. Table 6 and Pretzsch *et al*., 2017). A common theme from such reviews is the lack of adequate field trials to demonstrate the effects of mixtures upon the provision of ecosystem services from forests. However, given that results from such empirical trials may only be available after several decades, developing a research programme to identify suitable mixtures for use in Irish forestry in the near future should arguably pay greater attention to understanding the dynamics of mixed stands through the use of improved growth models and fundamental studies, supplemented by a set of judiciously selected and carefully managed field trials. Such an approach is likely to prove more cost-effective and provide quantitative guidelines for management of mixtures in Irish forests at an early date (see also Pretzsch and Zenner, 2017).

Some projects on mixtures are already underway, but the research effort needs to be increased and adequately resourced in order to provide the necessary scientific data that are urgently needed to inform policy and practice. Technology transfer is also required to provide advice to forest managers and growers on best practice through advice and demonstration.

Given the immediate need for information on best practice, the research effort (and funding) should initially be focused on the practical aspects of the silviculture of mixtures.

Key elements of the programme should consist of:

Fundamental studies

- Developing and/or adapting growth models that are capable of being used to predict the growth of mixed stands, supported by appropriate sample plots;
- Examination of existing mixtures and carrying out studies of impacts of mixtures upon timber properties, especially for major timber species;
- A re-evaluation of the mycorrhizal effect found in nursing mixtures to try to understand how this changes over time and to see if the effect can be harnessed for use with other mixtures;
- Collaboration in other studies to see if greater use of mixtures can reduce the risk of damaging pests and diseases and/or make stands more resilient to the effects of windthrow.

Field trials

- Developing a long-term maintenance, monitoring and reporting programme for existing trials. Publishing the results from these trials.
- Establishing a series of replicated trials with standard treatments of various mixture types and configurations across the main site types.
- Identification of new mixture types that have potential but have not been planted in this country.

Demonstration areas

- Establishing a network of demonstration plots in key locations illustrating the different management options for mixed crops.
- Provide financial information on the outturn from the mixtures, including vulnerability to browsing, etc.

Extension

- Publishing a series of information notes, videos etc. on best practice regarding the management of specific mixture types.
- Developing a series of demonstration/field days which are held on a regular basis.

Silvicultural research, in many cases, requires decades before meaningful results are obtained. It is imperative, therefore, that careful consideration is given to the planning, location, security and commitment to maintenance before trials are established. Equally, a long-term commitment by funding organisations is required to ensure that resources are spent wisely and in such a way that will ensure the continuity of trials until results are obtained. Proposals for the funding of long-term research have been made and it is appropriate that mixture trials should come under such a programme.

6.2 Knowledge Gaps

TABLE 31: Knowledge gap by topic.

Topic	Current situation	Deficiency	Action required
Policy	Unclear policy as to why we use mixtures. Is it driven by EU pressure to increase broadleaf planting, to mitigate risk, etc?	Lack of a clear vision which will form the basis of a future plan	Develop a National Policy on mixtures.
Silviculture	Relative growth rates of species combination are not known on different sites. This has led to unexpected competition from nurse species.	Knowledge and experience of mixtures performance is limited at present.	As an interim measure, before formal field trials are established, survey the main mixture types, assess crop performance and relate to site and crop characteristics (soil type, fertility, moisture regime, altitude, exposure, spacing, etc.). This will provide objective data to determine mixture performance on a range of sites.
	Only one formal survey of mixtures has been conducted to date (Guest & Huss, 2012.)	Robust data required – whether based on surveys or replicated trials	As above
	Many species mixture combinations have been established without knowledge of their outcome.	Clear guidance is lacking.	
	Provide published guidance.		
	Time and extent of first intervention (thinning) unclear	Linked to growers' issue (see below under Technical Support) as well as thinning being associated with crop age rather than development stage.	Major education programme for educators, owners and managers
	Uncertainty regarding the timing and extent of nurse crop removal and selection and management of final crop trees.	No clear guidelines identifying when and how thinning should take place.	Major education programme for educators, owners and managers.
	Many potential mixture types have not been tested on farmland.	Insufficient data available from replicated field trials and demonstration areas to feed growth models.	Establish field trials to provide required data.
	Timber yields and quality from mixtures unknown.	Major deficiencies in terms of data here (only a small number of operational stands have been harvested).	Establish sufficient field trials/ permanent sample plots to provide data.
	Currently using conventional harvesting/ forwarding equipment.	Knowledge of suitable harvesting systems has yet to be acquired.	Assessment of various pieces of harvesting/forwarding technology in terms of suitability, economics, damage to site and remaining crop, etc.
	Little information exists in relation to possible use of CCF systems in mixed crops.	Guidance on early interventions and subsequent management required.	Establish field trials and demonstration areas
Economics	Financial aspects of mixtures not quantified.	Financial models to aid decision making, considering grant aid, markets and equipment availability.	Models required (data availability is still a major problem in this regard).

TABLE 31: Knowledge gap by topic. Continued.

Topic	Current situation	Deficiency	Action required
Research	Uncertainty regarding the effects of climate change on current species, provenances, etc. and their performance in mixtures.	Suitable species (and provenances?) and new mixture types to mitigate the effects of climate change on forests are not known.	Research linked to existing climate change research.
	The need for improved evidence for the resilience of mixtures to abiotic and biotic hazards.	Knowledge is currently limited.	Monitoring of mixtures performance should be periodically reported by the NFI.
	Certain broadleaves in many mixed crops are damaged by sheep, deer or squirrels.		
	Insufficient knowledge on how to reduce damage to potential valuable final crop trees.	Initially, investigate solutions from countries that have long experience in dealing with the management of mixed forests.	
	Some field trials established on farmland, but most are on poor upland ORS sites and midland cutaway bogs.		
	Focused research on site types which are currently used, or which will be used for mixtures into the future.	Urgent management and assessment of existing trials. New trials on site types where mixtures might be planted into the future are required. New trials also required on existing mixture types (afforestation and restock sites).	
	Research infrastructure for establishing, assessing and maintaining long term field trials has been greatly diminished.	Adequate capacity to establish and maintain long-term field trials is lacking.	Build capacity in an institution to establish, assess and maintain long-term field trials.
	Few silvicultural specialists available to carry out research.		
	In depth knowledge on management of mixtures is yet to be acquired/ developed.	This will only come after researchers are in place for some time.	
Education and Training	Little emphasis in colleges on mixed plantations. Graduates do not have the skills with which to manage mixed plantations.	Lack of skills to teach the management of mixed plantations.	Educate the educators, followed by teaching (lectures and field skills).
	Little training currently given to machine operators on management of mixtures.	Field skills on selecting and caring for final crop trees.	Instigate operator training.
Technical support	Owners and managers are either not managing mixtures or do not know where to go for guidance on how to manage them.		
	Little published guidance e.g. information notes and other media, leading to decisions on thinning being left too late.	Simple, best-guess guidance should be produced for now, until better information becomes available, in time, from a research programme. Build an extension programme to communicate best practice to owners/managers.	
	Few suitable on-the-ground demonstration areas available.	Well located, well documented woodlands required for technology transfer and demonstration.	Identify existing suitable areas and the establishment of new areas.

6.3 Recommendations

Based on the above discussion of Future Research Needs and Knowledge Gaps, the authors recommend the following phased approach to the topic of mixtures over the coming years:

1. Immediate (within 12 months)

- Using the organisational framework of the Society of Irish Foresters, establish a series of regional workshops, bringing together researchers who are working on mixtures and operational foresters who are currently managing mixtures on the ground. The output from these workshops will be an analysis of existing expertise, a state of the art on current knowledge and an identification of where additional knowledge gaps exist.
- Put in place an assessment and maintenance programme for existing field trials and demonstration areas on mixtures.
- Publish a COFORD summary document which updates the recommendations in Tables 5.3 (conifer/conifer), 5.4 (broadleaf/broadleaf) and 5.5 (conifer/broadleaf) of the Guide to Forest Tree Species Selection and Silviculture in Ireland (Horgan *et al*., 2004). Information to help inform this is given in this report (Section 5.2.2).
- Begin a planning and execution programme for a long-term research programme on mixtures in this country. This may initially involve growth models (sufficient data may not exist?) and establishment of additional demonstration areas and long-term experiments, some of which should include species that have not been field tested in mixture trials up to now.
- Work with policy makers to encourage the introduction of novel incentive schemes which encourage land owners and managers to manage mixtures from an early stage and over multiple interventions. This should be carried out within the development of a National policy on the future of mixtures in Irish woodland.

2. Medium term (within 24 months)

- Based on knowledge gleaned from the workshops (above), compile a Decision Support System on management of mixtures and roll it out to practitioners via a technology transfer programme. The COFORD model on woodfuel should be used as a template for this.
- Using the existing COFORD website, establish a users' "go to" portal which would bring together all existing information on management of mixtures. This portal should include up to date information on suitable harvesting/forwarding equipment for use in mixtures.
- Involve teachers of third level colleges in this technology transfer programme to begin to develop expertise in the management of mixtures at third level. Ensure that whatever information is available (acknowledging it will be incomplete) is rolled out to forestry undergraduate programmes at the existing third level colleges.

3. Long term (beyond 24 months)

- Use the demonstration areas and experiments (both newly established and from previous research programmes) as a strong basis for an ongoing technology transfer programme on mixtures.
- Begin to harvest and publish data from the long-term research programme, established under Phase 1 (above) and refine the growth models developed.
- Strengthen links between researchers, educators and policy makers to ensure new results influence ongoing policy decisions in relation to mixtures.

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Appendix 1

National Forest Inventory - 2012 data for mixed species forests

1. Ownership

Definition
Ownership: Specifies forest ownership **Public:** All state-owned forests **Private (grant aided):** private afforested land in receipt of either grant and or premium since 1980. **Private (other):** private non-grant aided plantations or naturally regenerated forests.
Mixture type **Conifer pure:** More than 80% of coniferous tree species **Conifer/conifer mix:** More than 80% of mixed coniferous tree species **Broadleaf pure:** More than 80% of broadleaf tree species **Broadleaf/broadleaf mix:** More than 80% of mixed broadleaf tree species **Conifer/broadleaf mix:** A forest composed of broadleaved and conifer species, the minor category making up at least 20% of the canopy.

TABLE 32: Stocked forest area by Forest sub-type and ownership.

Forest sub-type	Ownership/Area (ha)		Total (ha (%))
	Public (ha (%))	Private (ha (%))	
Pure	212,834 (62)	124,436 (42)	337,270 (53)
Mixed	128,856 (38)	171,008 (58)	299,864 (47)
Total	**341,690 (100)**	**295,444 (100)**	**637,134 (100)**

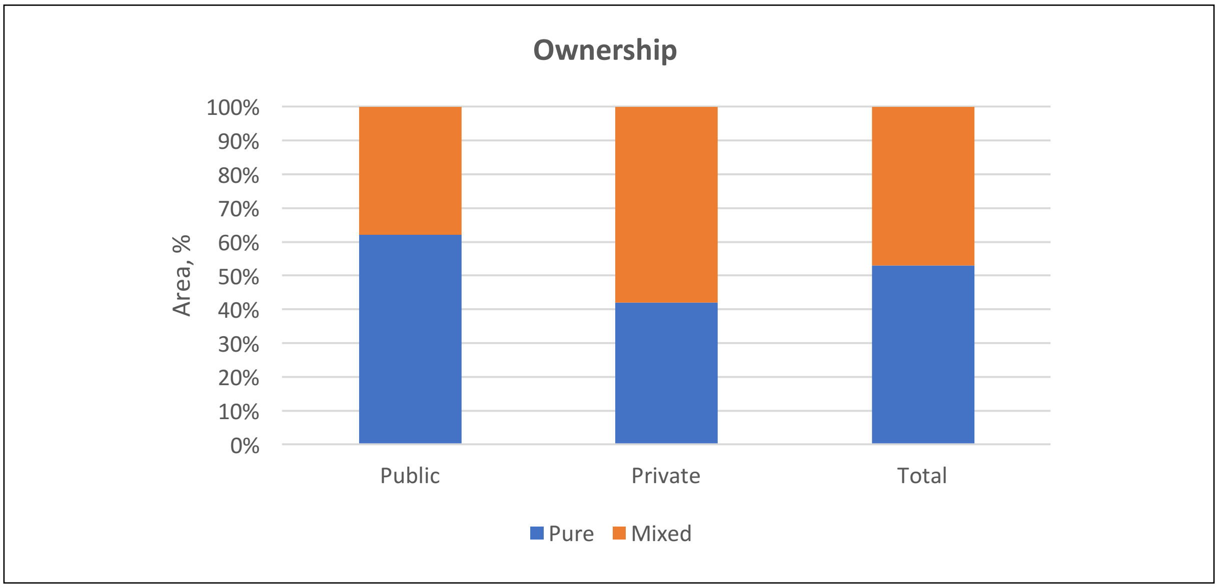
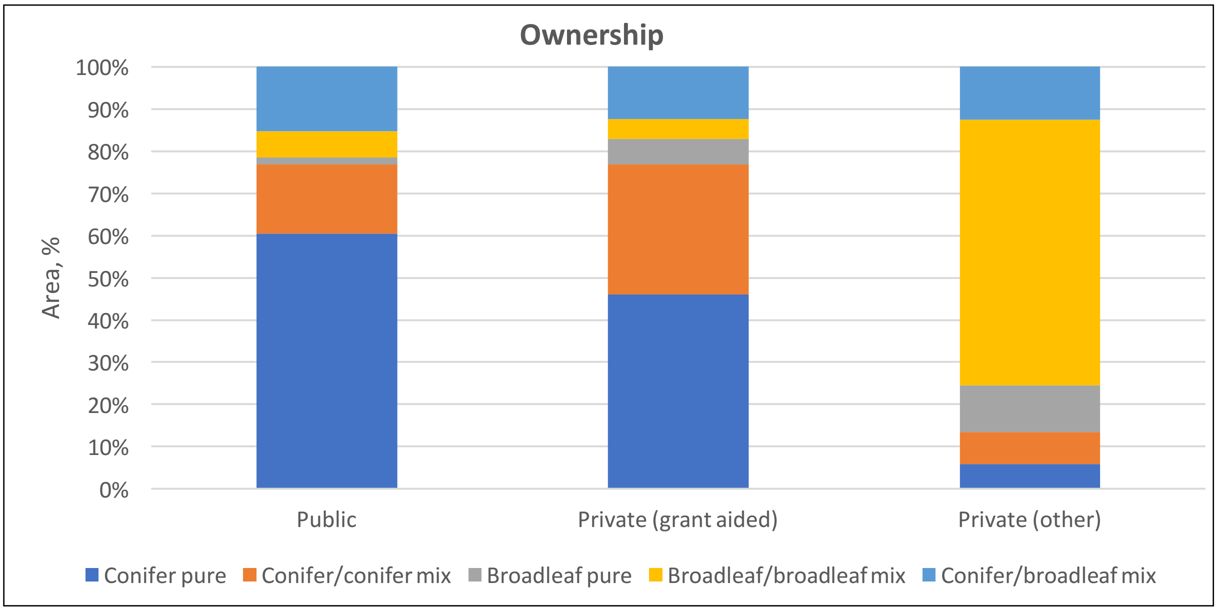


TABLE 33: Stocked forest area by species mixture type and ownership.

Species Mixture Type	Ownership/Area			
	Public	Private (grant aided)	Private (other)	Total
	ha (%)	ha (%)	ha (%)	ha (%)
Conifer pure	206,815 (61)	97,630 (46)	4,809 (6)	309,253 (49)
Conifer/conifer mix	55,632 (16)	65,687 (31)	6,412 (8)	127,731 (20)
Broadleaf pure	6,019 (2)	12,795 (6)	9,202 (11)	28,015 (4)
Broadleaf/broadleaf mix	21,211 (6)	10,012 (5)	52,102 (63)	83,326 (13)
Conifer/broadleaf mix	52,013 (15)	26,401 (12)	10,394 (13)	88,807 (14)
Total	**341,690 (100)**	**212,524 (100)**	**82,918 (100)**	**637,133 (100)**

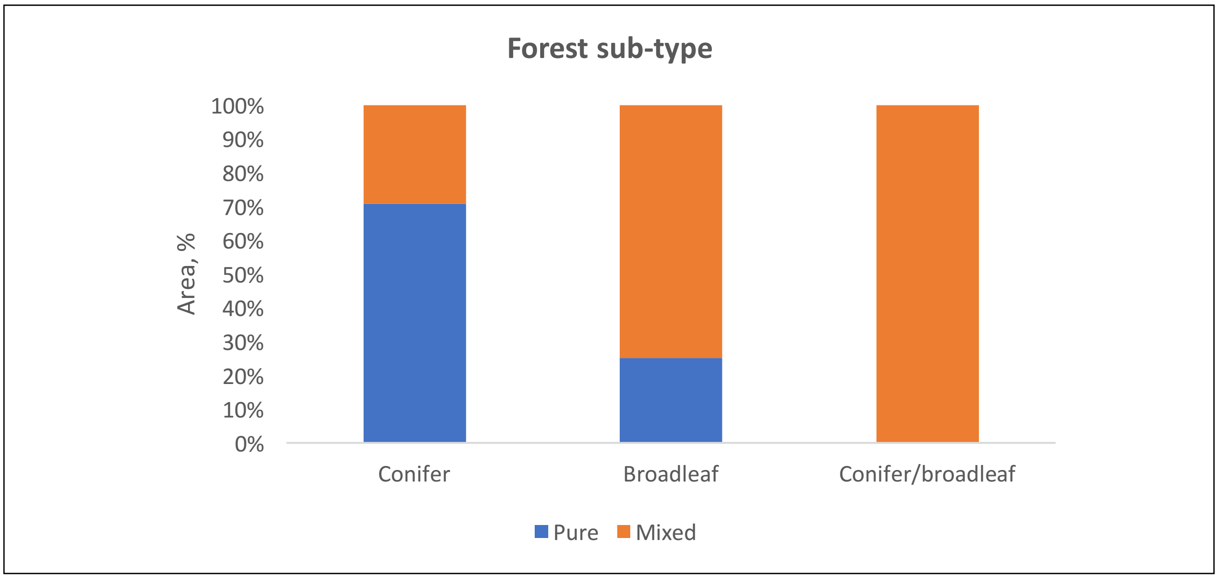


2. Forest type and Sub-type

Definition
European Forest Type (EFT): Broad forest type classification system based on species composition.
Conifer: More than 80% of coniferous tree species
Broadleaf: More than 80% of broadleaf tree species
Mixed: A forest composed of broadleaved and conifer species, the minor category making up at least 20% of the canopy.

TABLE 34: Stocked forest area by European forest type and sub-type.

Forest subtype	EFT/Area			
	Conifer	Broadleaf	Conifer/ broadleaf	Total
	ha (%)	ha (%)	ha (%a)	ha (%)
Pure	309,253 (71)	28,015 (25)	N/A	337,269 (53)
Mixed	127,731 (29)	83,326 (75)	88,807 (100)	299,864 (47)
Total	**436,984 (100)**	**111,341 (100)**	**88,807 (100)**	**637,133 (100)**

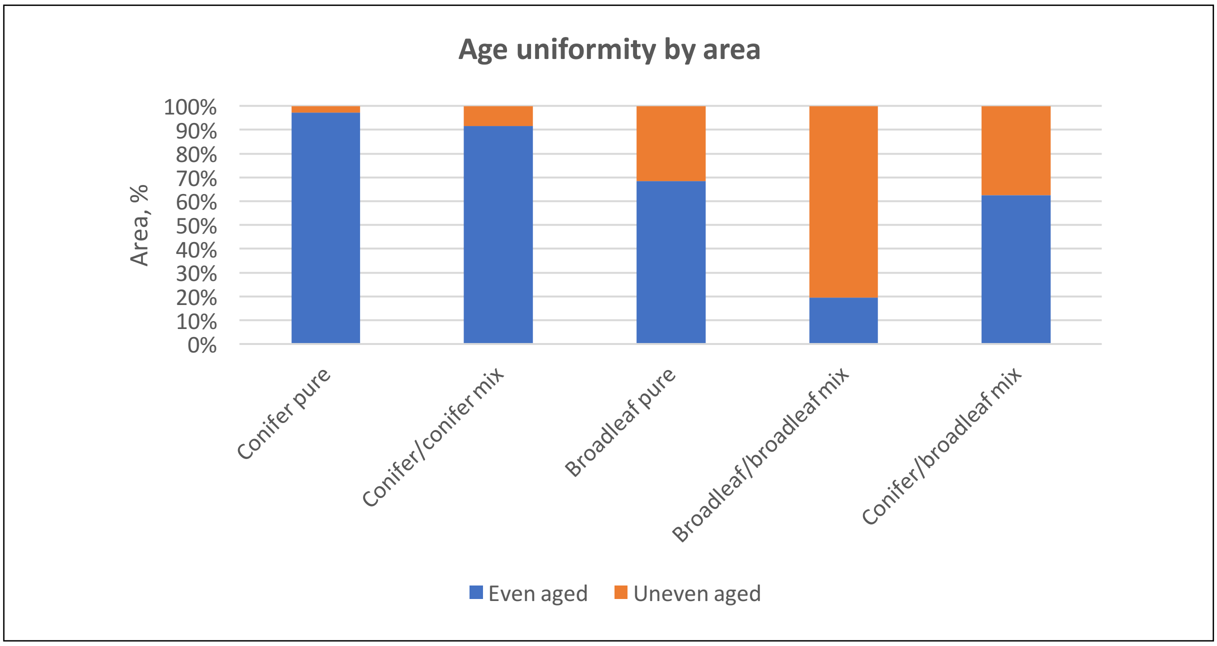


3. Age Uniformity

Definition
Even/unevenaged: Uniformity of the age of the tree species in a forest. **Evenaged:** Greater than 80% of the canopy is made up of trees that have an age difference of 4 years or less. **Unevenaged:** Between 20-80% of the canopy is made up of threes that have an age difference of 5 years or more.

TABLE 35: Stocked forest area by even/uneven aged and species mixture type.

Even/ uneven aged	Species mixture type/Area											
	Conifer pure		Conifer/ conifer mix		Broadleaf pure		Broadleaf/ broadleaf mix		Conifer/ broadleaf mix		Total	
	ha	(%)	ha	(%)	ha	(%)	ha	(%)	ha	(%)	ha	(%)
Even aged	300,432	(97)	116,889	(91)	19,209	(69)	16,436	(20)	55,581	(63)	508,547	(80)
Uneven aged	8,822	(3)	10,841	(9)	8,806	(31)	66,890	(80)	33,227	(37)	128,586	(20)
Total	**309,253**	**(100)**	**127,731**	**(100)**	**28,015**	**(100)**	**83,326**	**(100)**	**88,807**	**(100)**	**637,133**	**(100)**

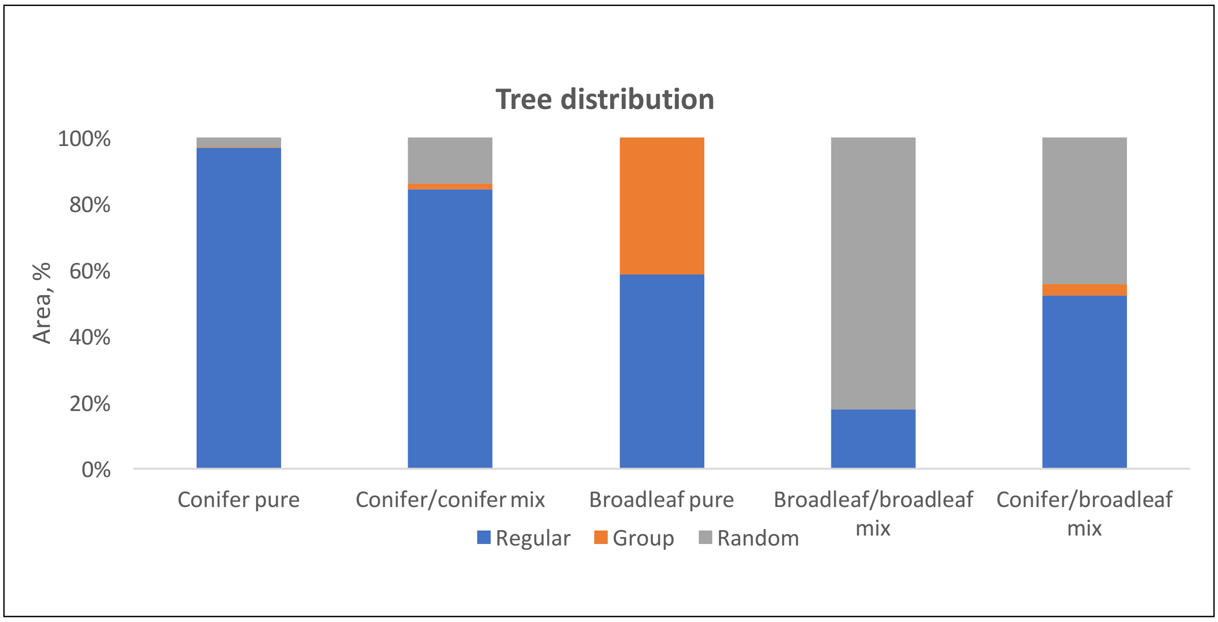


4. Tree Distribution

Definition
Tree distribution: The distribution of threes in terms of their special arrangement.
Regular: The trees are distributed uniformly, e.g. 2 m x 2 m square spacing.
Group: The trees are distributed in groups.
Random: The trees are distributed randomly with no particular pattern.

TABLE 36: Stocked forest area by species mixture type and tree distribution.

Tree distribution	Species mixture type/Area					
	Conifer pure	Conifer/ conifer mix	Broadleaf pure	Broadleaf/ broadleaf mix	Conifer/ broadleaf mix	Total
	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)
Regular	300,030 (97)	107,694 (84)	16,404 (59)	14,828 (18)	46,380 (52)	485,336 (76)
Group		2,405 (2)	11,611 (41)		3,206 (4)	6,016 (1)
Random	8,818 (3)	17,632 (14)		68,498 (82)	39,221 (44)	145,780 (23)
Total	**309,253 (100)**	**127,731 (100)**	**28,015 (100)**	**83,326 (100)**	**88,807 (100)**	**637,133 (100)**

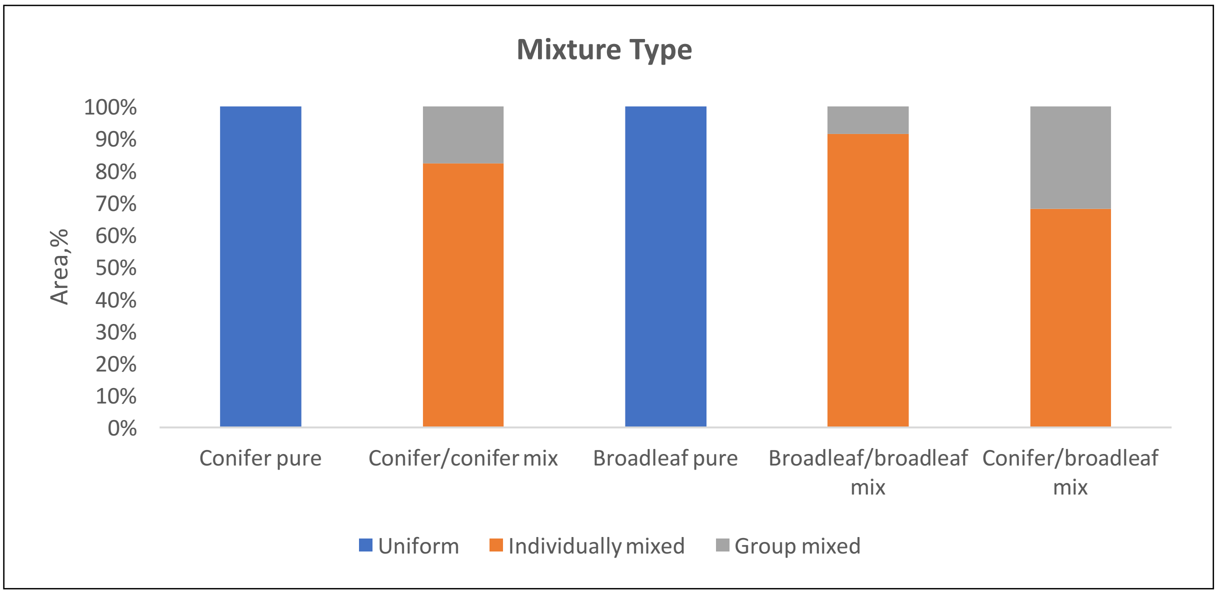


5. Mixture Type

Definition
Species structure
Mixture type describes the species distribution of trees. If there is more than one species present the plant distribution may follow a predefined structure e.g. planting in groups. **Uniform:** Only one tree species is present. **Individually mixed:** More than one species present, with species mixture occurring in a random manner. **Group mixed:** The structure is based on groups of trees of each species. Line mixtures are included in this category.

TABLE 37: Stocked forest area by species mixture and mixture type.

Mixture	Species mixture type/Area					
	Conifer pure	Conifer/ conifer mix	Broadleaf pure	Broadleaf/ broadleaf mix	Conifer/ broadleaf mix	Total
	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)
Uniform	309,253 (100)	104,465 (82)	28,015 (100)	76,101 (91)	60,412 (68)	337,674 (53)
Individually mixed		22,861 (18)		7,225 (9)	28,395 (32)	240,978 (38)
Group mixed						58,481 (9)
Total	**309,253 (100)**	**127,731 (100)**	**28,015 (100)**	**83,326 (100)**	**88,807 (100)**	**637,133 (100)**

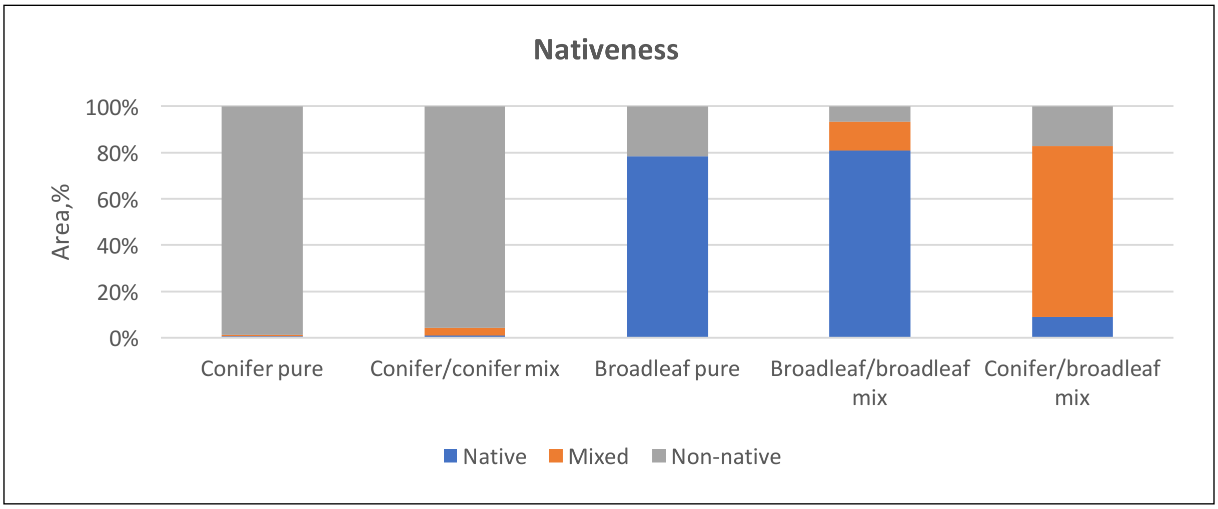


6. Nativeness

Definition
Nativeness describes the origin of species **Native:** More than 80% of the canopy comprises native species **Mixed:** Between 20-80% of the canopy comprises native species **Non-native:** More than 80% of the canopy comprises exotic species.

TABLE 38: Stocked forest area by species mixture type and nativeness.

Nativeness	Species mixture type/area					
	Conifer pure	Conifer /conifer mix	Broadleaf pure	Broadleaf/ broadleaf mix	Conifer/ broadleaf mix	Total
	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)
Native (>80%)	1,996 (1)	1,202 (1)	22,005 (79)	67,303 (81)	8,001 (9)	100,507 (16)
Mixed (20-80%)	1,599 (1)	4,402 (3)	6,011 (21)	10,427 (12)	65,585 (74)	82,013 (13)
Non-native (20%)	305,658 (98)	122,127 (96)		5,596 (7)	15,221 (17)	454,613 (71)
Total	**309,253 (100)**	**127,731 (100)**	**28,015 (100)**	**83,326 (100)**	**88,807 (100)**	**637,133 (100)**

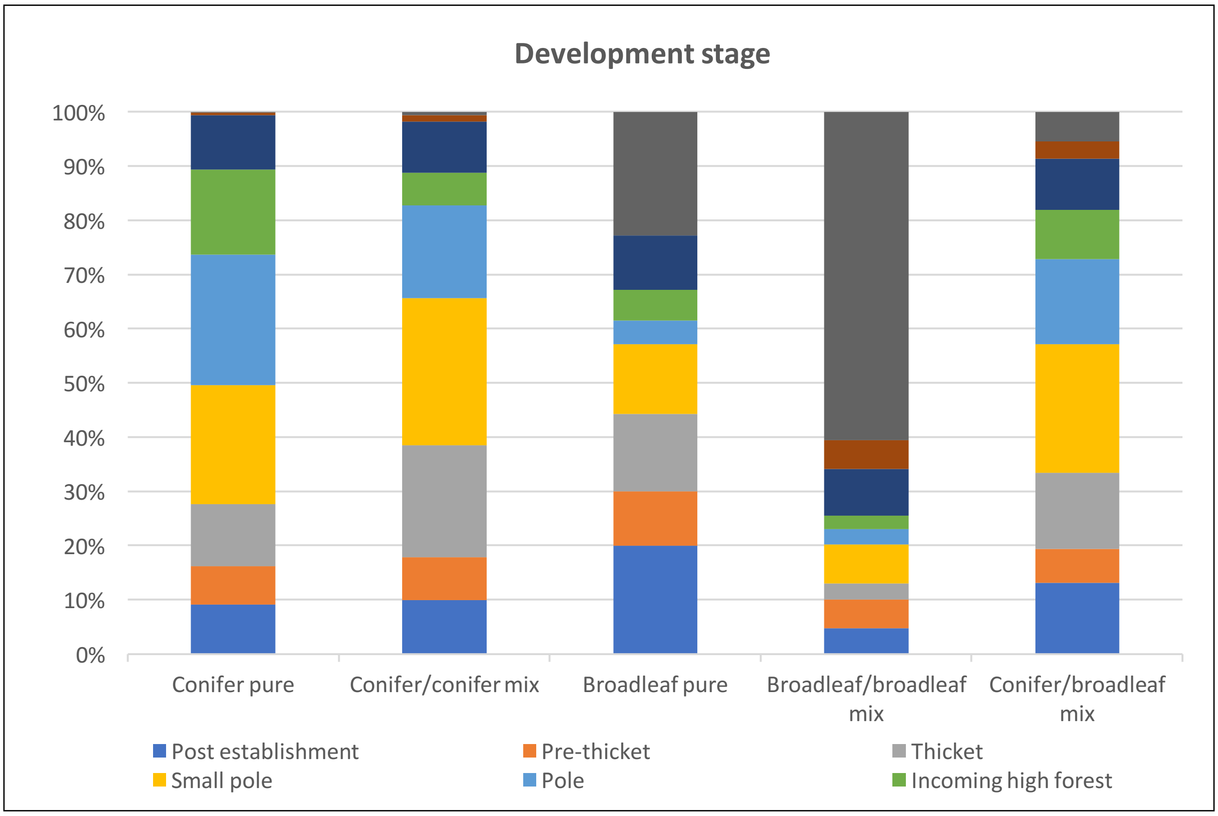


7. Development Stage

Definition
Development stage: Describes the development stage of the forest
Post establishment: An established storey up to and including 4 years of age.
Pre-thicket: This covers the storeys where the green branches are not yet touching, where the trees are older than 4 years of age.
Thicket: This covers storeys where the canopy is closed but the lower branches are mainly green.
Small pole: This covers storeys where the canopy has fully closed and the lower branches are dead. It may be unthinned.
Pole: This covers storeys where it could be thinned or in the early stages of thinning.
Incoming high forest:
High forest: These storeys may be thinned or unthinned and have a high proportion of sawlog approaching or at normal rotation length.
Overmature: Forest retained beyond normal rotation length, resulting in the presence of large trees.
Multi-storied: Forest with trees present at various stages of development, i.e. height.

TABLE 39: Stocked forest area by species mixture type and growth stage.

Development stage	Species mixture type/Area											
	Conifer pure		Conifer/ conifer mix		Broadleaf pure		Broadleaf/ broadleaf mix		Conifer/ broadleaf mix		Total	
	ha	(%)	ha	(%)	ha	(%)	ha	(%)	ha	(%)	ha	(%)
Post establishment	28,009	(9)	12,819	(10)	5,604	(20)	4,003	(5)	11,601	(13)	62,037	(10)
Pre-thicket	22,068	(7)	10,005	(8)	2,793	(10)	4,405	(5)	5,572	(6)	44,844	(7)
Thicket	35,636	(12)	26,458	(21)	4,007	(14)	2,413	(3)	12,416	(14)	80,930	(13)
Small pole stage	67,711	(22)	34,426	(27)	3,601	(13)	5,997	(7)	21,227	(24)	132,962	(21)
Pole stage	74,489	(24)	21,986	(17)	1,201	(4)	2,402	(3)	13,986	(16)	114,064	(18)
Incoming high forest	48,489	(16)	7,636	(6)	1,600	(6)	2,011	(2)	7,979	(9)	67,715	(11)
High forest	30,848	(10)	12,002	(9)	2,813	(10)	7,203	(9)	8,405	(10)	61,270	(10)
Overmature			1,595	(1)	6,396	(23)	4,417	(5)	2,808	(3)	10,425	(2)
Multi-storied			801	(1)	6,396	(23)	50,475	(61)	4,814	(5)	62,885	(10)
Total	**309,253**	**(100)**	**127,731**	**(100)**	**28,015**	**(100)**	**83,326**	**(100)**	**88,807**	**(100)**	**637,133**	**(100)**



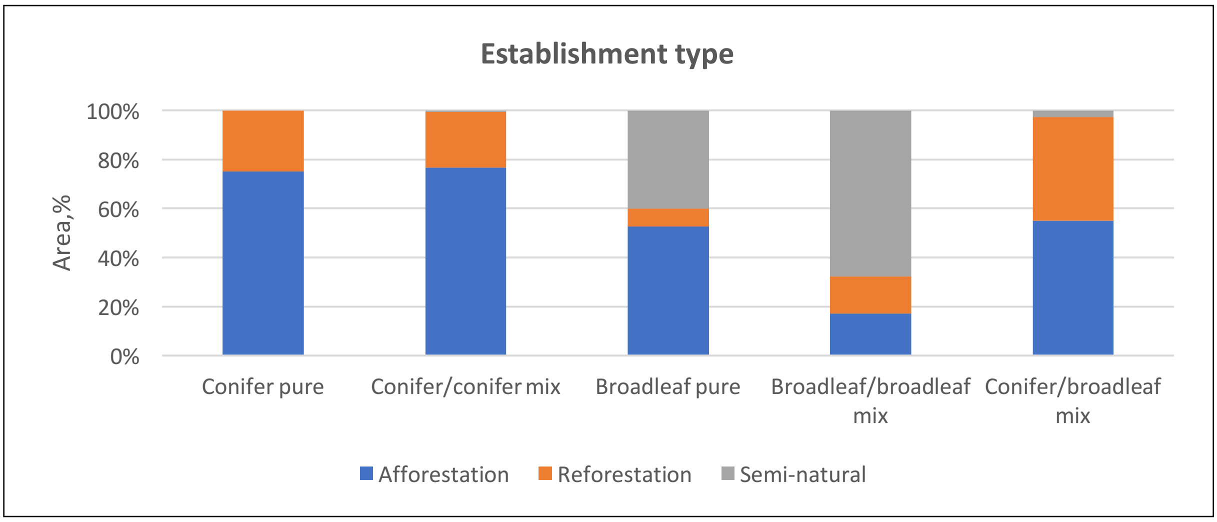
Development stage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Conifer pure
Conifer/conifer mix
Broadleaf pure
Broadleaf/broadleaf mix
Conifer/broadleaf mix
Post establishment
Pre-thicket
Thicket
Small pole
Pole
Incoming high forest

8. Forest Establishment Type

Definition
Forest establishment type: Describes the land type on which the forest has been established and how the storey was established) i.e. artificially or naturally). **Afforestation:** The man-made establishment of new forests on treeless lands which did not carry forest in contemporary history. Implies transformation from Non-Forest to Forest. **Reforestation:** The man-made establishment of trees on lands that have been cleared of forest within the relatively recent past. **Semi-natural:** Forest land where greater than 80% of the tree species regenerated naturally. Native and non-native tree species are included.

TABLE 40: Stocked forest area by species mixture and establishment type.

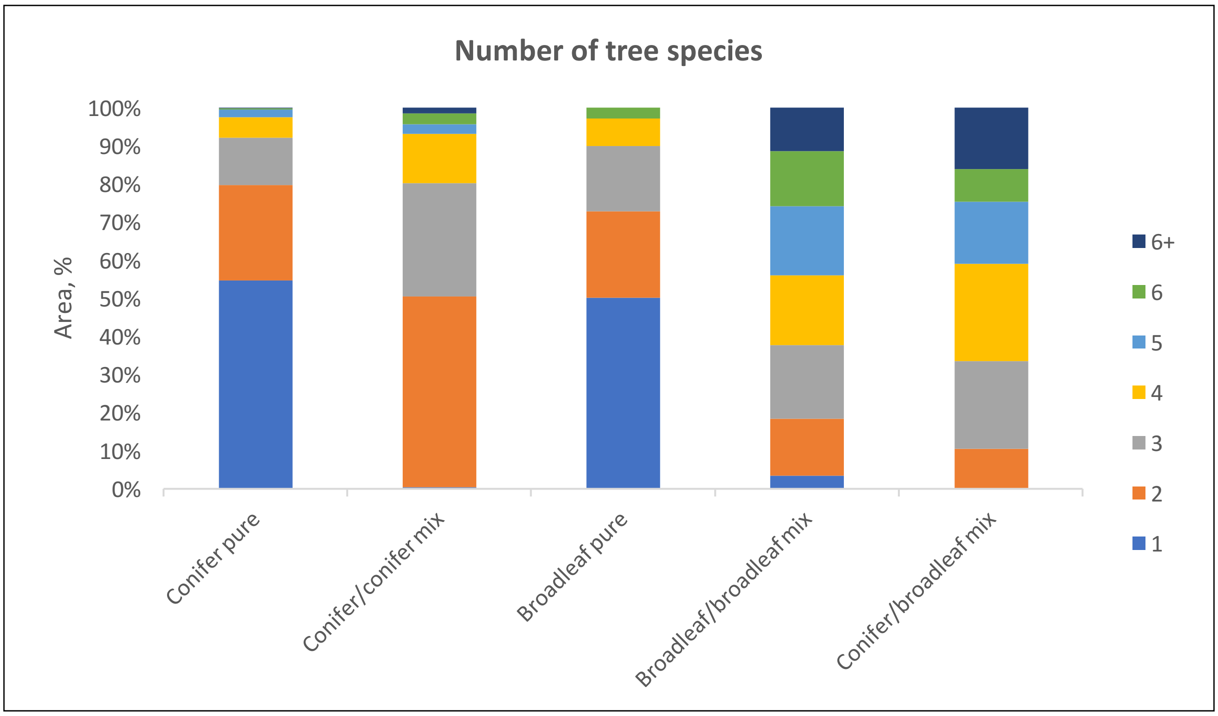
Establishment type	Species mixture type/Area					
	Conifer pure	Conifer/ conifer mix	Broadleaf pure	Broadleaf/ broadleaf mix	Conifer/ broadleaf mix	Total
	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)
Afforestation	232,704 (75)	98,096 (76)	14,807 (53)	14,436 (17)	48,816 (55)	408,859 (64)
Reforestation	76,549 (25)	28,828 (23)	2,009 (7)	12,405 (15)	37,590 (42)	157,382 (25)
Semi-natural		806 (1)	11,200 (40)	56,485 (68)	2,401 (3)	70,892 (11)
Total	**309,253 (100)**	**127,730 (100)**	**28,015 (100)**	**83,326 (100)**	**88,807 (100)**	**637,133 (100)**



9. Number of Tree Species

TABLE 41: Stocked forest area by species mixture type by number of tree species.

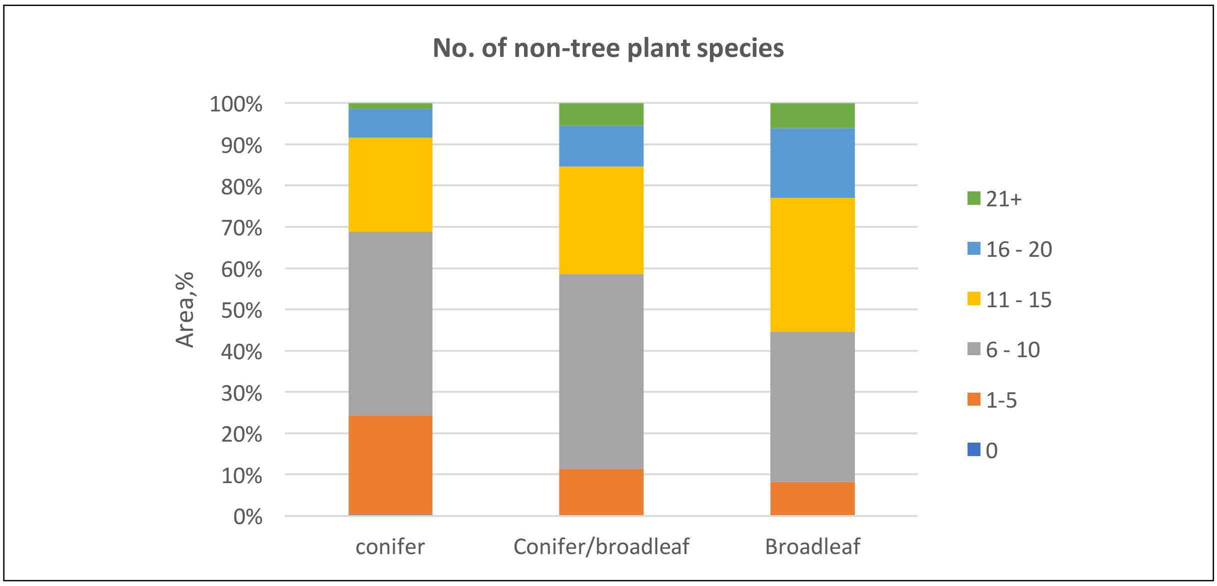
No of Tree species	Species mixture type/Area					
	Conifer pure	Conifer/ conifer mix	Broadleaf pure	Broadleaf/ broadleaf mix	Conifer/ broadleaf mix	Total
	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)	ha (%)
1	168,344 (55)		14,011 (50)	2,808 (3)		185,566 (29)
2	77,674 (25)	64,074 (50)	6,389 (23)	12,435 (15)	9,198 (10)	169,769 (27)
3	38,807 (12)	38,046 (30)	4,803 (17)	16,011 (19)	20,412 (23)	118,078 (18)
4	16,810 (5)	16,428 (13)	2,009 (7)	15,231 (18)	22,801 (26)	73,280 (12)
5	6,020 (2)	3,196 (2)		15,180 (18)	14,380 (16)	38,776 (6)
6		3,594 (3)	804 (3)	12,038 (14)	7,606 (9)	24,845 (4)
6+		1,992 (2)		9,621 (11)	14,410 (16)	26,817 (4)
Total	**309,253 (100)**	**127,731 (100)**	**28,015 (100)**	**83,326 (100)**	**88,807 (100)**	**637,133 (100)**



10. Non-tree Plant Species

TABLE 42 Stocked forest area by total number of non-tree plant species and EFT.

No. of plant species	EFT/Area							
	Conifer		Broadleaf		Conifer/broadleaf		Total	
	000'ha (%)		000'ha (%)		000'ha (%)		000' ha (%)	
0								
1-5	104.90	(24)	9.23	(8)	10.01	(11)	124.14	(20)
6 -10	195.35	(45)	40.46	(36)	41.99	(47)	277.53	(44)
11 -15	99.35	(23)	36.04	(32)	23.20	(26)	158.59	(25)
16 – 20	30.44	(7)	18.80	(17)	8.80	(10)	58.04	(9)
21+	6.01	(1)	6.82	(6)	4.80	(5)	17.64	(3)
Total	**436,984**	**(100)**	**111,341**	**(100)**	**88,807**	**(100)**	**637,133**	**(100)**

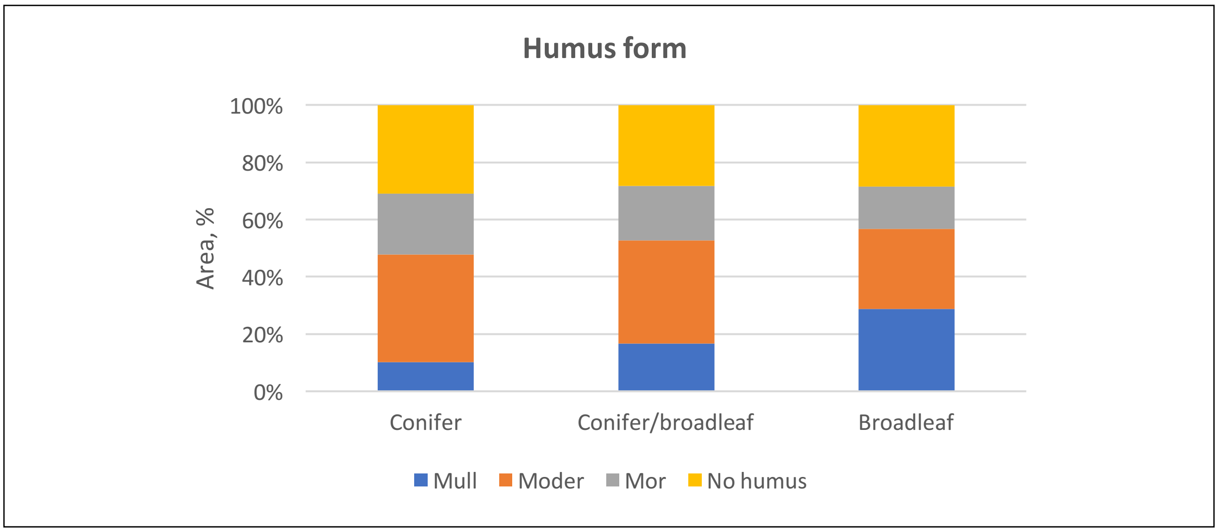


11. Humus Form

Definition
Humus: Organic layers at the soil surface, where leaf litter and other organic matter are decomposing and being incorporated into the upper mineral soil. Humus forms: **Mull humus:** This is the humus-rich layer of forest soils consisting of mixed organic and mineral matter. The humus is being incorporated into the soil. **Moder humus:** The current litter layer overlies partly decomposed material, which is not as matted as mor. **Mor humus:** This is raw humus, composed of unincorporated organic material, usually distinct from the mineral soil. It comprises the current litter layer overlying a matted layer of partly decomposed material. **No humus:** No humus development. The litter layer may not have formed yet or could be removed due to surface runoff or flooding.

TABLE 43 Stocked forest area by humus form and EFT type

Humus form	EFT/Area							
	Conifer		Broadleaf		Conifer/broadleaf		Total	
	000' ha (%)		000' ha (%)		000' ha (%)		000' ha (%)	
Mull	44.95	(10)	32	(29)	14.82	(17)	9	(14)
Moder	164.65	(38)	31.26	(28)	32.03	(36)	227.95	(36)
Mor	92.49	(21)	16.45	(15)	16.78	(19)	125.73	(20)
No humus developed	134.88	(31)	31.62	(28)	25.17	(28)	191.67	(30)
Total	**436,984**	**(100)**	**111,341**	**(100)**	**88,807**	**(100)**	**637,133**	**(100)**



Appendix 2

Area of main species in mixture with others

Additional information from IFORIS on mixtures under the different Grant and Premium Categories (GPCs)

Five conifer and five broadleaves which represent the main species occurring in the parcels were selected to show the area of other species growing with them. The ones which had the largest areas were then graphed to show the percentage of the main species in the mixture. Information for Sitka spruce is shown earlier in the main body of the report (Section 3.1.3). The information for the remaining nine species is shown in the following pages.

Japanese larch

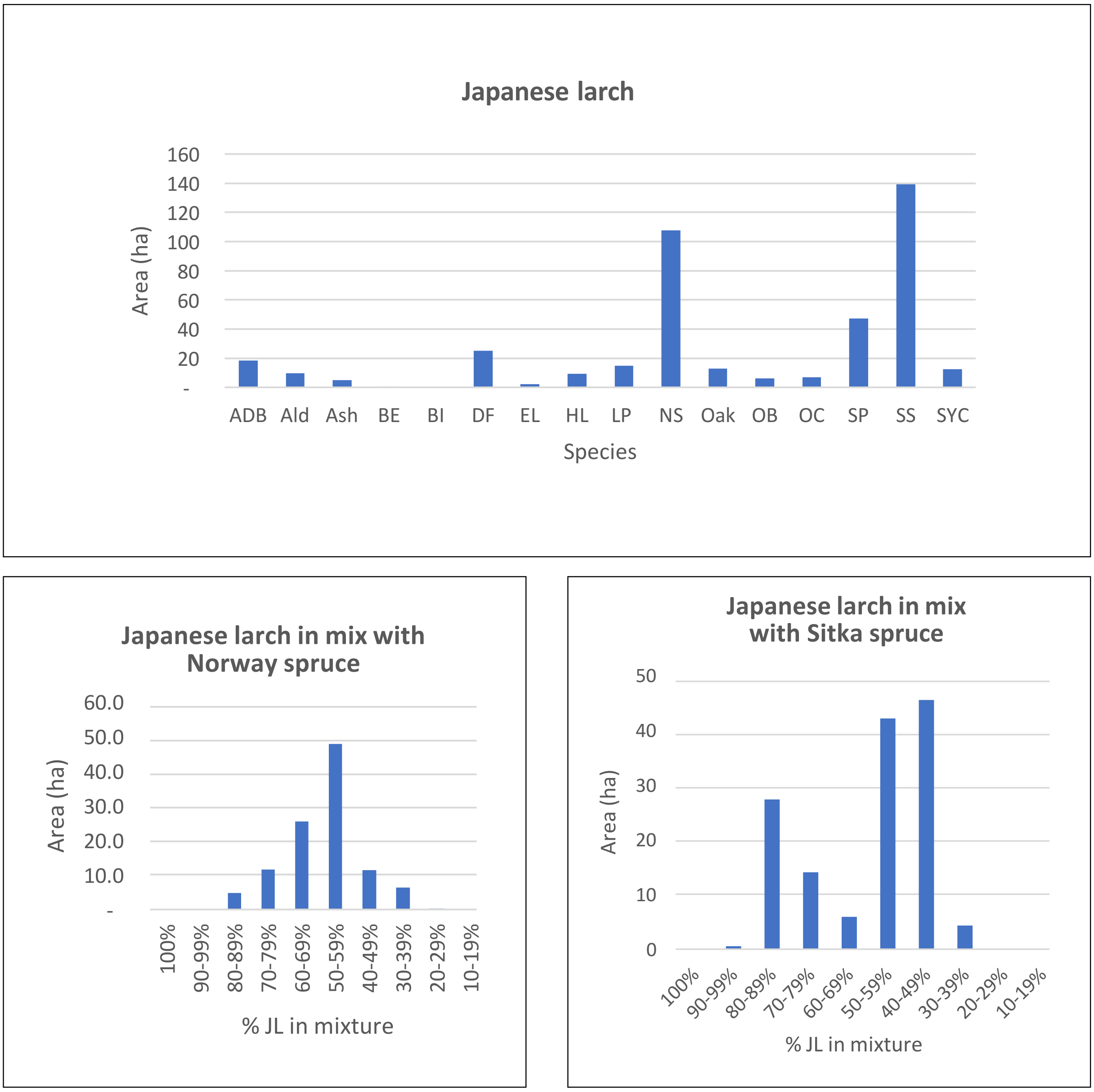


FIGURE 10: The breakdown of Japanese larch in mixture with other species (three graphs).

Norway spruce

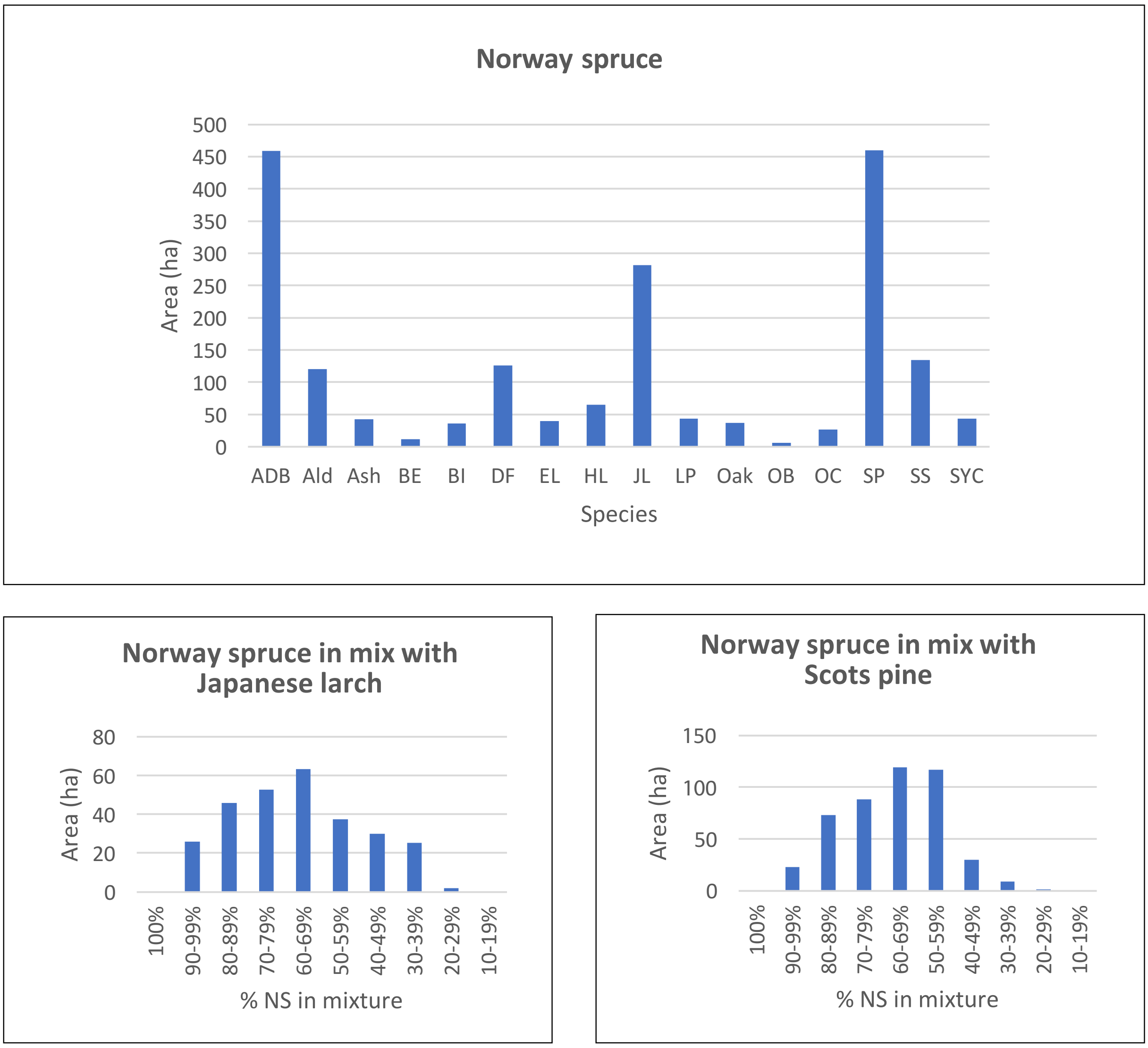


FIGURE 11: The breakdown of Norway spruce in mixture with other species (three graphs).

Scots pine

The areas of accompanying species in mixture with Scots pine are so small that graphs of these provide little information and are therefore omitted.

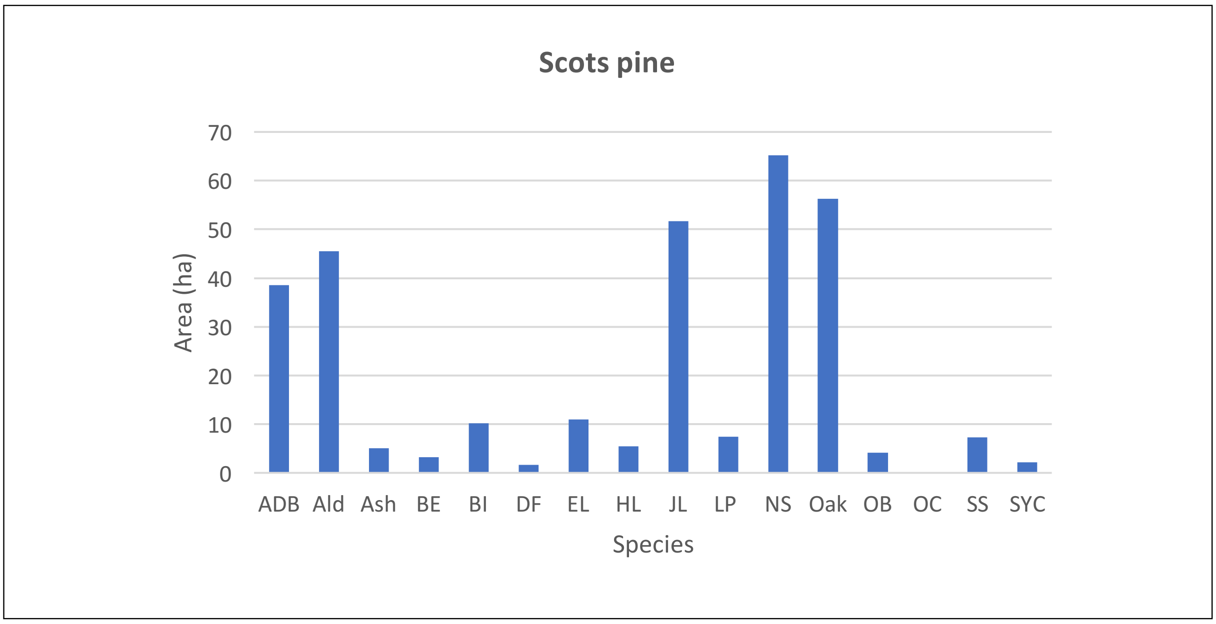


FIGURE 12: The breakdown of Scots pine in mixture with other species.

Douglas fir

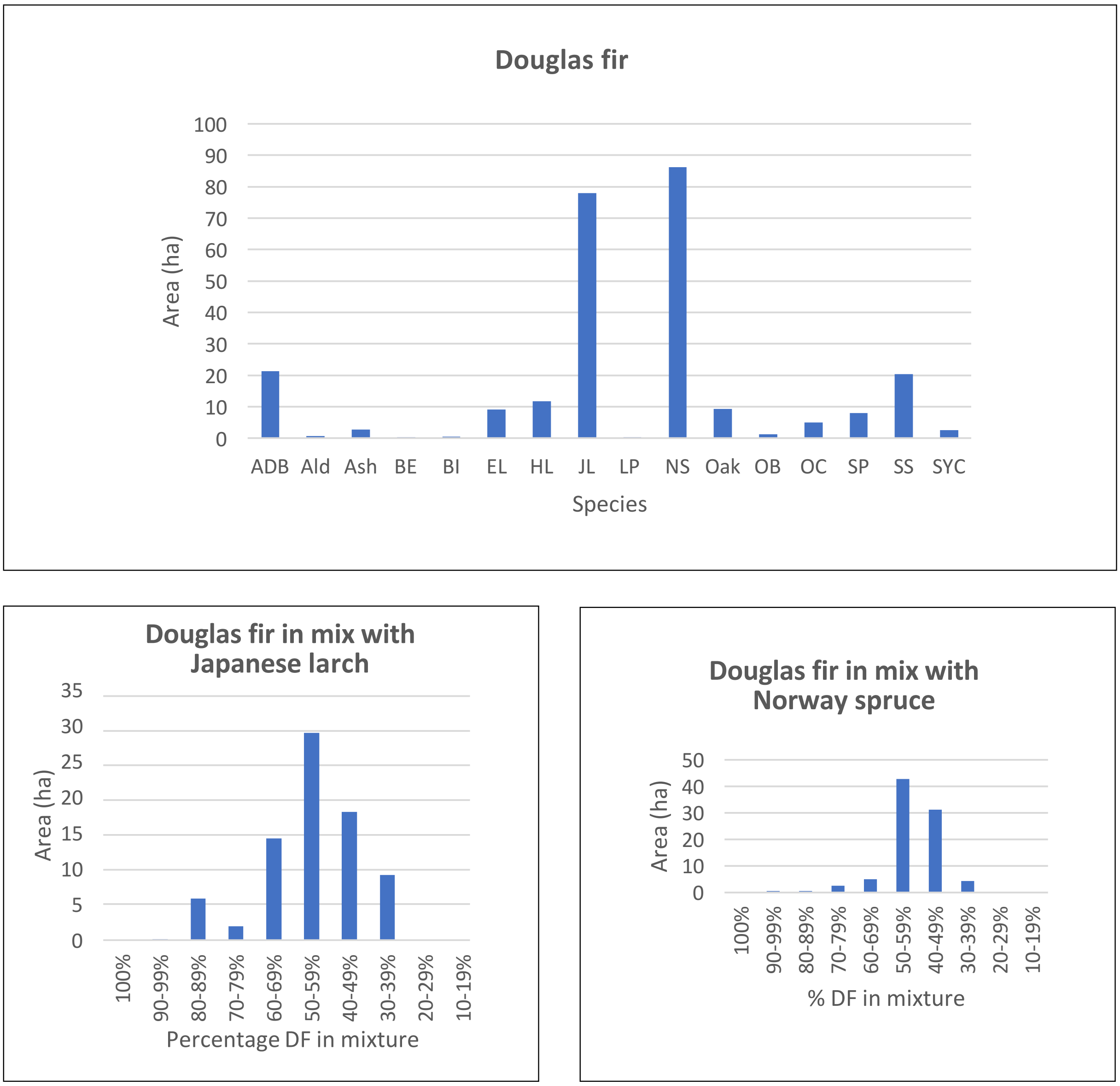
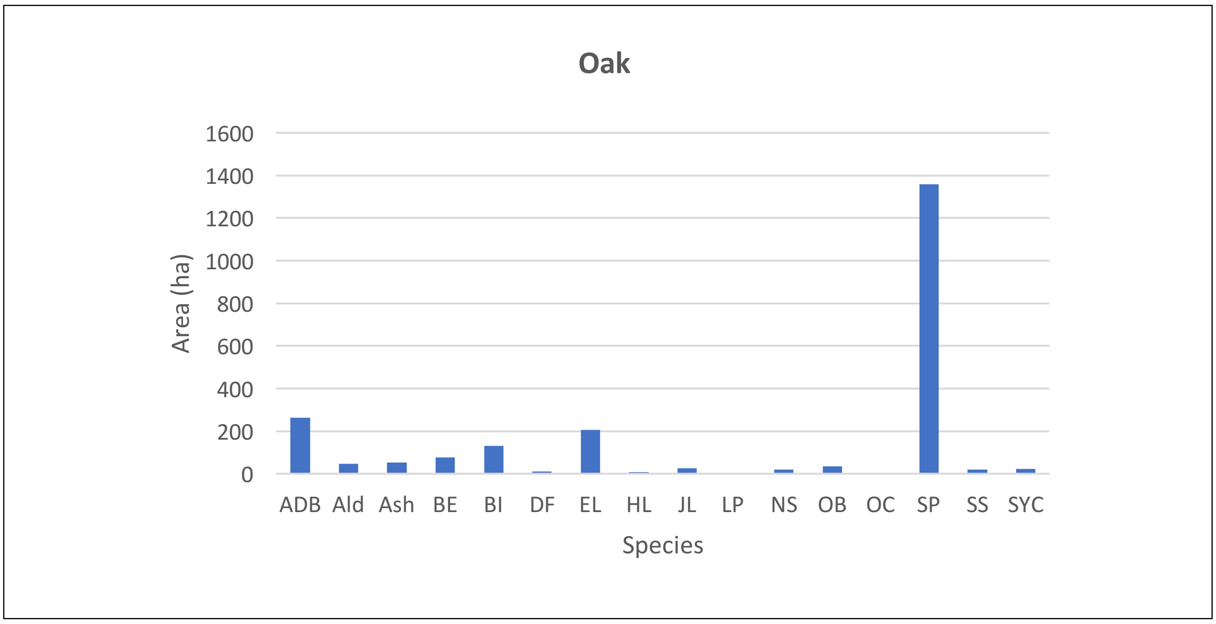


FIGURE 13: The breakdown of Douglas fir in mixture with other species (three graphs).

Oak



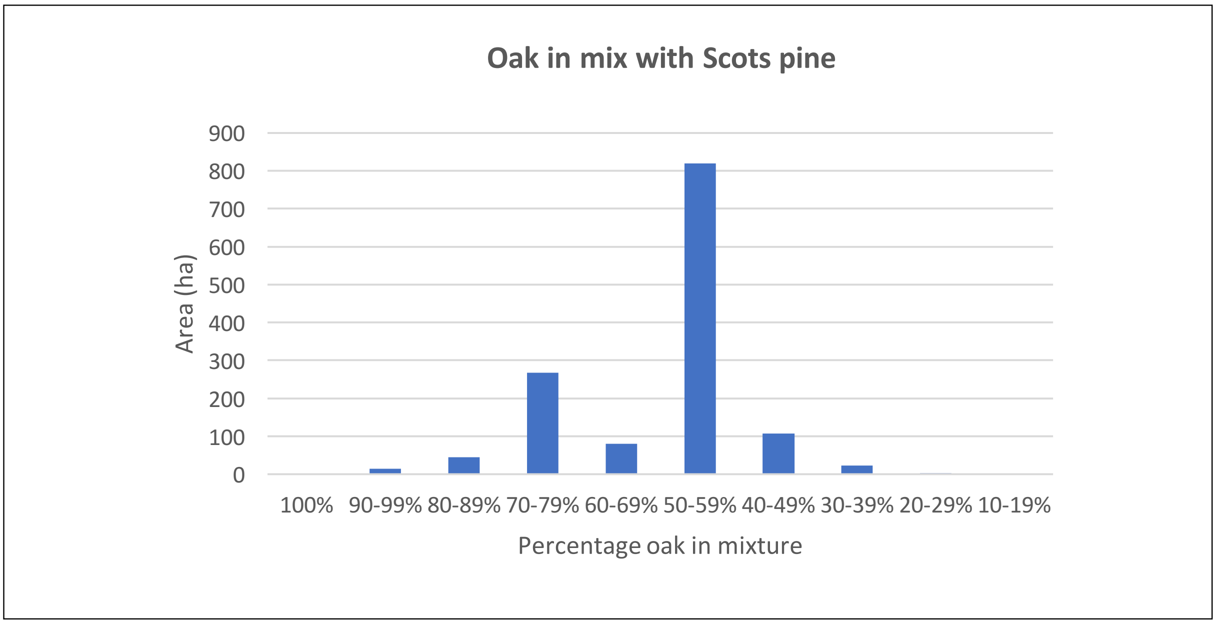
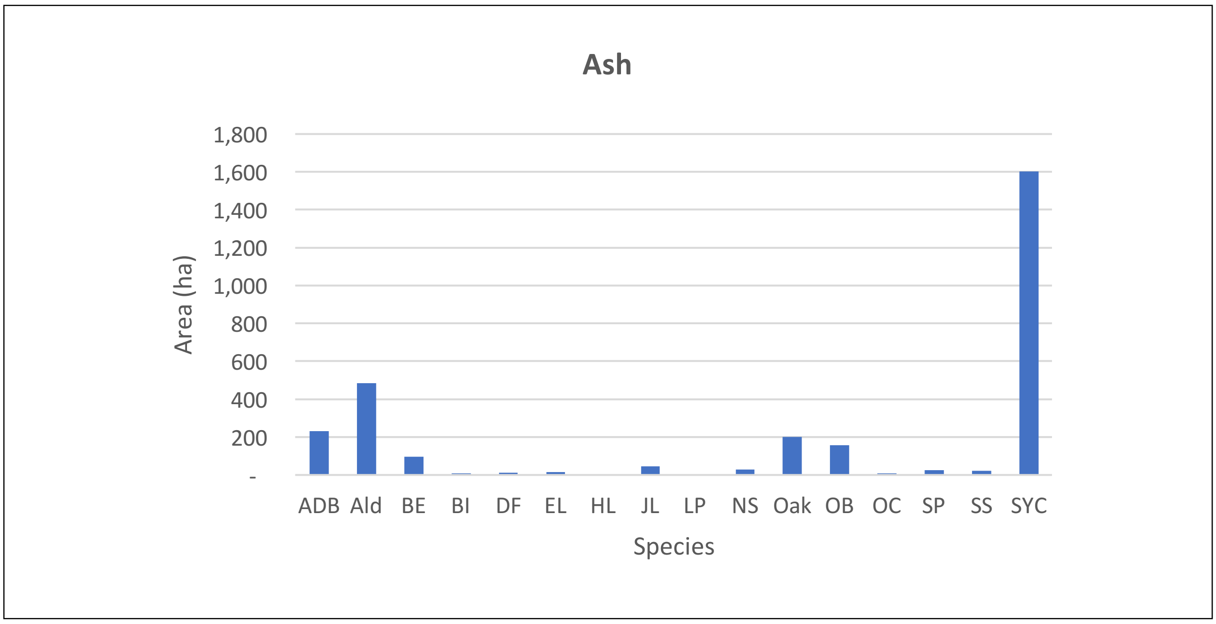


FIGURE 14: The breakdown of oak in mixture with other species (two graphs).

Ash



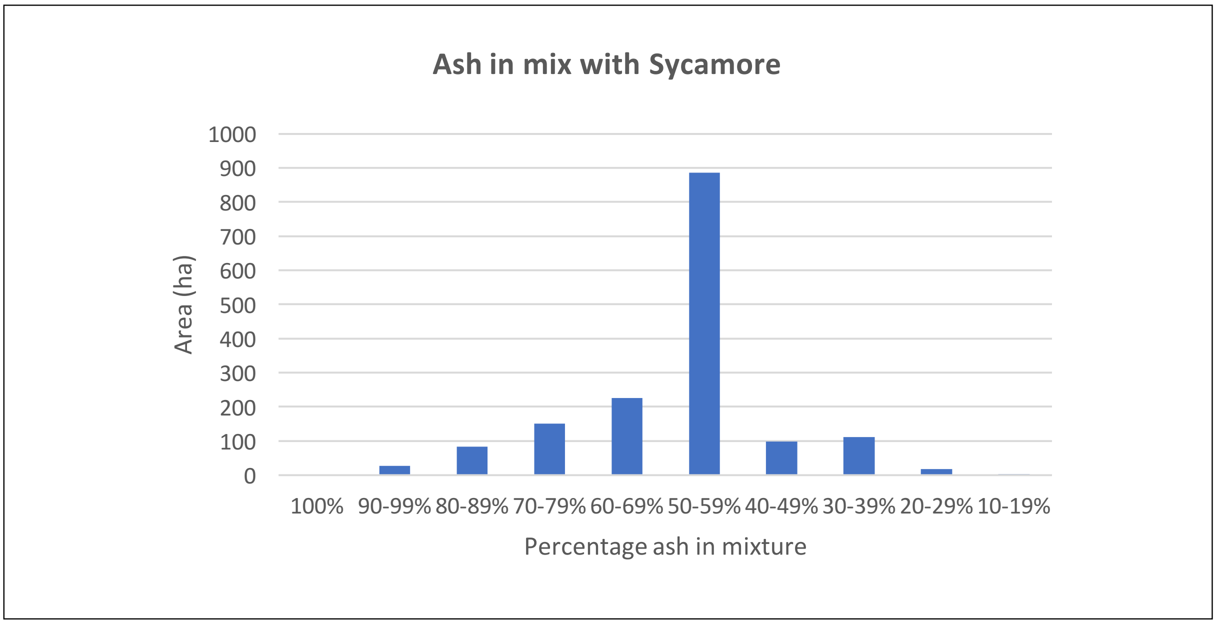
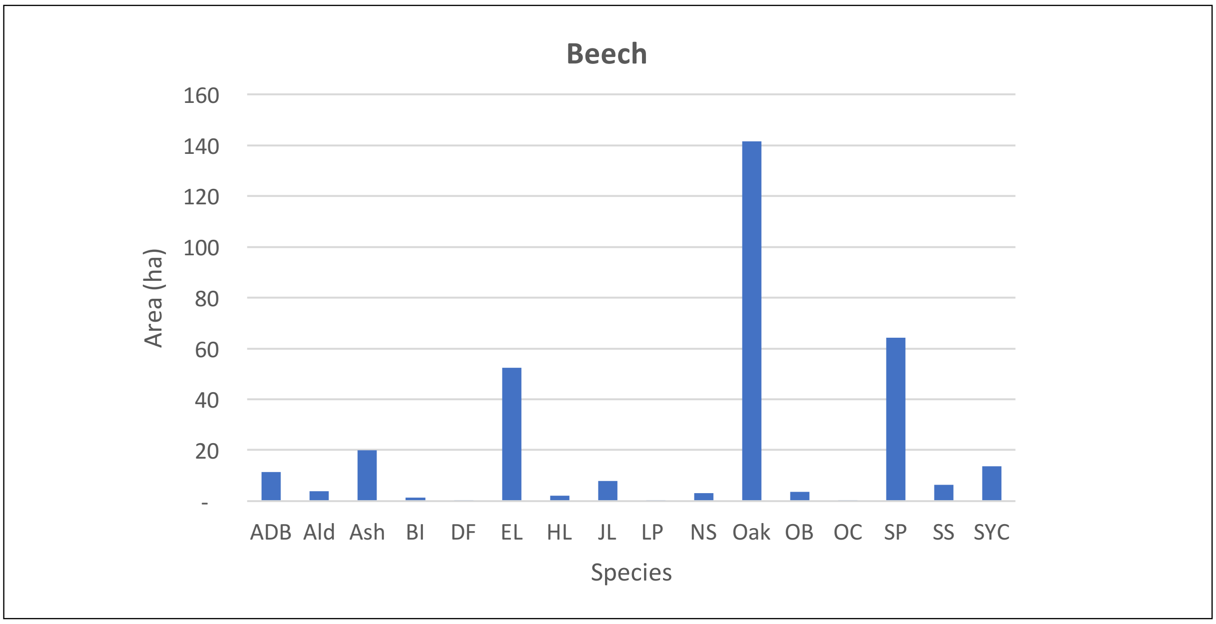


FIGURE 15: The breakdown of ash in mixture with other species (two graphs).

Beech



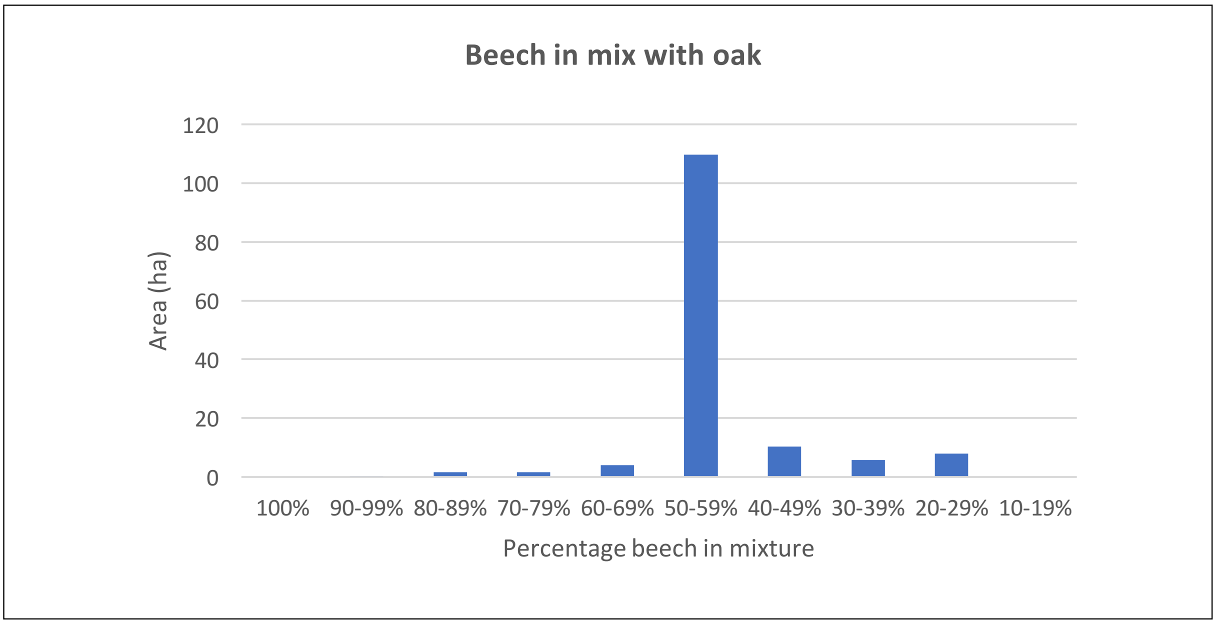
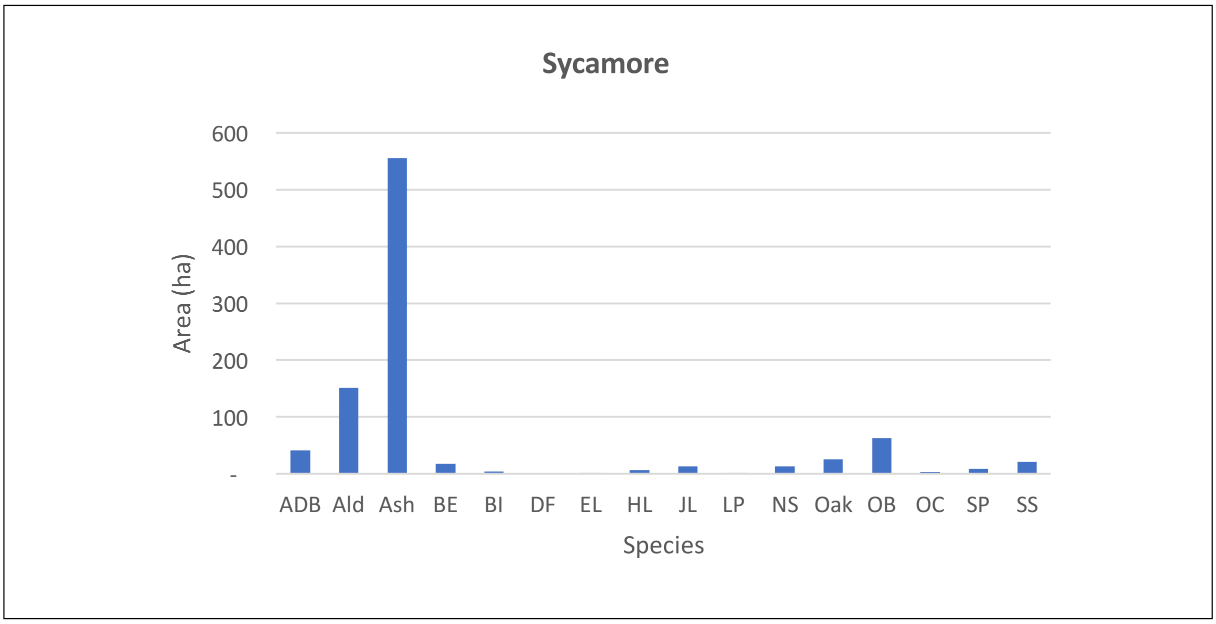


FIGURE 16: The breakdown of beech in mixture with other species (two graphs).

Sycamore



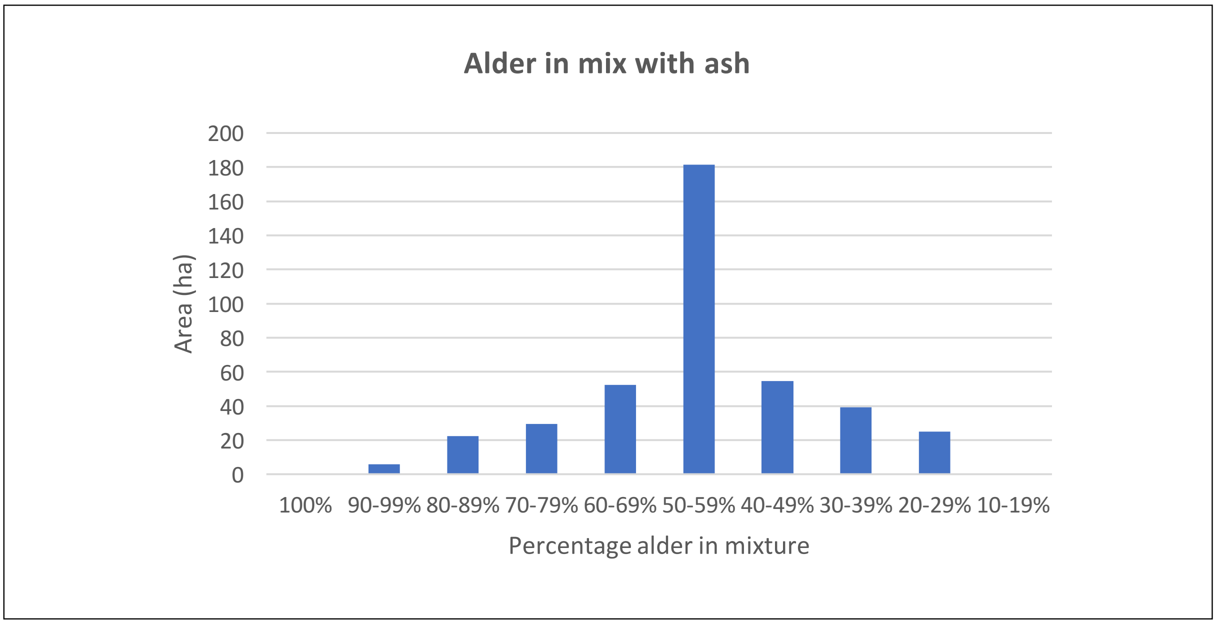
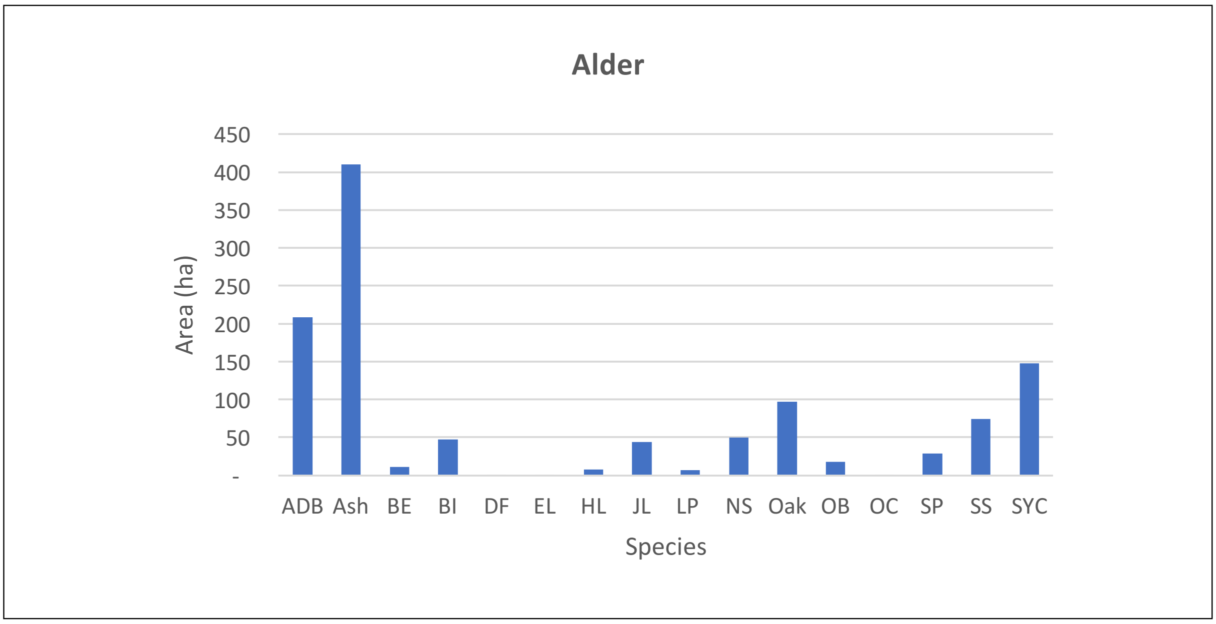


FIGURE 17: The breakdown of sycamore in mixture with other species (two graphs).

Alder



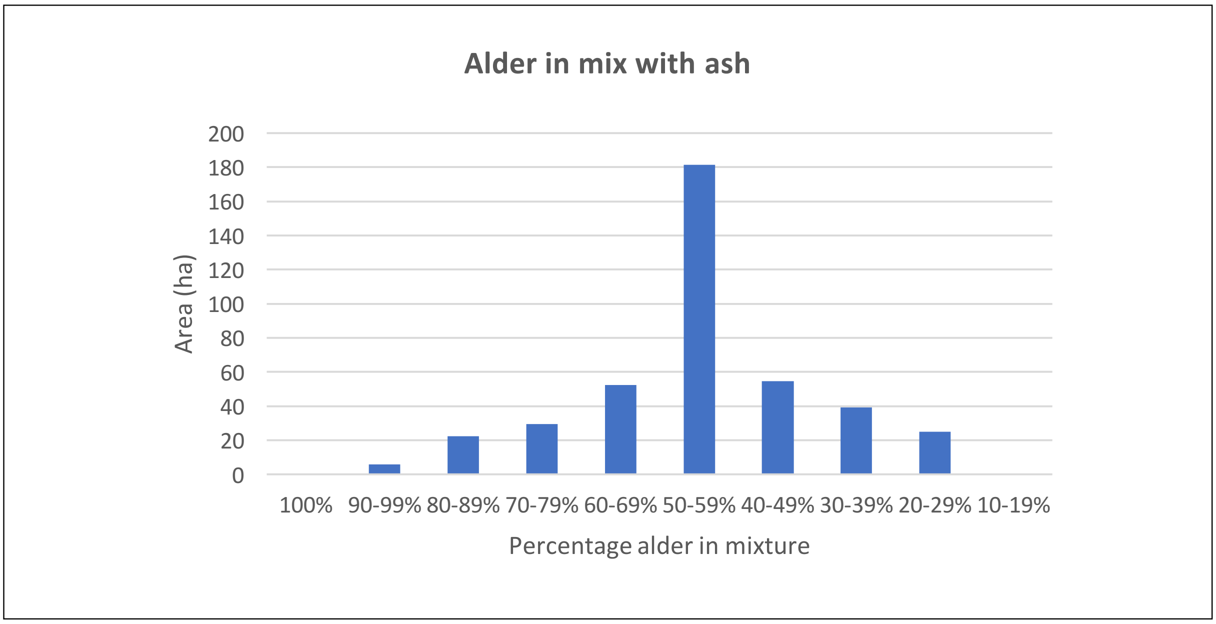


FIGURE 18: The breakdown of alder in mixture with other species (two graphs).

Appendix 3.

Respondents' individual comments from the Survey of Practitioners

QUESTION 10: For the mixture type you ranked as most difficult in Q9, why is it difficult to manage?

Although most respondents nominated crops as being difficult to manage, fewer of them gave information as to why they found specific mixtures difficult. For the main difficult mixtures (from Question 9), some of the main reasons are given below 3 as direct quotes from the respondents themselves:

Scots pine/oak

"The Oak/SP mixtures planted at a stocking rate of 6,600/ha have been more difficult to manage due to density of trees planted and small material, trees stunted, often left unmanaged for too long, often unsure what to do with them."

"The short window in which thinning intervention should be carried out, if done too late disastrous effect on main crop."

"The SP is difficult to harvest/remove from the oak without causing damage. It depends on when you have been asked to manage the crop on time. The Pine is usually only firewood. Most cases the Oak is so poor you wonder should you leave the Pine to be the final crop. If the oak is good how early and often do you thin?"

"Too costly to take the Scots pine out"

"A lot of owners leave it too late to take out the Scots pine which is used as a nurse species for the oak. In most cases the Scots pine has smothered out the oak and realistically the oak should be taken out and the Scots pine should be left as the main crop, but due to schemes this cannot be the case."

Sitka spruce/Japanese larch

"JL outgrows the SS by Year 10 and seriously impacts on SS crop"

"The mandatory mixing of either Jap larch or Alder through Sitka spruce has been a disaster. It has a significantly negative impact on the economic return from the crop. Also, as both species have vigorous growth they suppress the growth of the spruce. It is not unusual to see two or three Sitka either dead or significantly suppressed by 16 or 17 years of age. This reduces the stocking on the site meaning even on the best of site you will only get two thinnings. Also, the larch only produces pulp wood due to its very crooked form."

"JL when grown in groups with SS can be very twisted and suffers from basal sweep. This causes the JL to be useless as a commercial crop and needs to be removed on first thinning, this however is not a problem when planted as an intimate mixture but when planted in groups will leave open pockets in the crop which then have to be under-planted with a shade bearing species such as BE."

"At thinning stage the Larch accounts for a very large percentage of pulp. In some sites its removal can increase the risk of windblow."

"The incompatibility of JL planted in intimate mixture with SS. JL tends to be poorly formed and more dominant, leading to killing off of SS if not removed early. However, removing early has to be done at an economic loss to the owner."

"Removal of larch is difficult due to its growth rates over and above the SS, can lead to destabilise crop if left too late and creates big gaps in canopy during thinning"

"Sitka and Larch on gley soils On such soils Japanese larch serves no financial return to grower. Grows too fast and produces high pulp with poor stumpage. On gley soils Planting non-intimate blocks of larch causes financial

constraints to overall crop. You can't remove all the larch in the thinning's and you are left with a poor quality crop of larch at clearfell. Larch on dry mineral soils only."

Larch/oak

"Damage to remaining trees when extracting if not dealt with on time plus oak dying as a result of being shaded out"

"The 'difficulty' is not silvicultural but in the timing and the cost of operations. The owner must be aware of the necessity to carry out the work and must be prepared to engage in the grant application process. Often owners have no interest and/or are unwilling to get involved (even to engage someone else). The grant incentives are often insufficient to cover the costs of operations (partic in relatively small stands). The Forest Service continue to pay annual premiums on stands which clearly require respacing intervention. I am aware of many examples of such stands, established at high cost but which are unthinned and as a result the intended main crop tree, the light demanding oak, is being suppressed and killed by the 'nurse'"

"Growing quicker than initially expected and because it is only fit for pulp cost more to remove it than it is worth, thus difficult to get anyone to do this work."

"OAK/EL - Larch grows too fast and if let, completes shades out the oak. On the plus side at least some of the EL is of commercial size to sell. Alternate lines means damage to a lot of the oak as the El is being felled."

"Larch and Oak have completely different growth rates. No nursing effect to Oak larch smothers Oak within ten years. Uneconomic to thin out larch early enough to save the oak."

"The larch by year 12 far outstrips the Oak and if left until time to clean the oak will have become unstable and begin to fall on top of the oak. To intervene early s the solution but this expensive and many owners unaware of what is happening"

Other conifer/beech

"Poor response from beech once thinned and the timing of thinnings"

"European Larch becomes dominant in the lines, beech struggling, do you take out the larch and possibly be left with a poor crop of beech or do you leave and thin both crops.

Sitka spruce/lodgepole pine

"These are usually planted on sites deficient in phosphorus and nitrogen. Striking a balance between the growth of the pine and the nutrient requirement of the spruce is very difficult and rarely achieved."

Spruce/birch

"Managing any site from thinning stage on wards requires a harvesting infrastructure on the site - it is hard to envisage harvester and forwarder machinery being suitable for these midland cutaway bogs therefore limiting management options."

"Depending on level of invasion trying to decide the most appropriate sociocultural regime is difficult, especially when trying to incorporate economic factors into your decision making process"

"This has happened due to resource to manage the conifer crop with particular reference to reforestation - and where guideline or help is needed to salvage a large part of the forest estate. We need a solution to this problem."

"Generally, this occurs on the poorer soil types where a more demanding species has been selected for replant. Often pushed by the owner wanting a commercial species. However after this the invading Birch takes over and it becomes difficult to backtrack a number of years later to change and downgrade the Conifer species to LPS. The result is that the SS or NS keeps growing slowly and the Birch takes over further. At the finish the Forester ends up respacing the site to favour some better spruce stems but ultimately the forest ends up as 70/30 Spruce /Birch mix. Needed is 1. Better initial understanding and species choice is required. 2. Replanting sites closer to the post felling period "

"Damage to planted Sitka from naturally occurring and over plentiful Birch"

"Often the preferred species Norway spruce has very low stocking, having been invaded by birch. When is it economic to do a thinning to remove the birch, is there a market for small diameter birch? Will you get a contractor in to thin such a stand?"

QUESTION 12: For the mixture type you ranked as easiest in Q11, why is it easy to manage?

Responses here were fewer and shorter than those given in Question 10. Again however, some of the main reasons are given below as direct quotes from the respondents themselves on why they found certain crops relatively easy to deal with:

Scots pine/oak

"In many cases that I have encountered the Pine will outgrow the Oak slightly. The line thinning allows a significant amount of the Pine to be removed, leaving some good quality Pine on site to keep the site as a mixed woodland. The close initial spacing allows for more choice when thinning the stand. Faster growing larch species have been shown to outgrow the Oak or Beech far to quickly causing excessive shading and will often have to be felled very early."

"This mixture was planted from about 2000 up to 2012. Both species have a similar growth rates. It is not unusual to the oak suppressing the pine. Even in situation where there is no management is undertaken this mixture will produce a very nice mixed forest."

"Similar growth rates, removal of every other line."

"Scots pine never gets too far ahead of the oak, no coppice regrowth when its cut. Grant will cover most of the cost."

"In my experience growth rates match even on fertile sites and Scots is particularly useful from an aesthetic point of view."

"Nurse grows slower and more adaptable to oak, especially on some of the sites that came into private forestry - the necessity to intervene as early is not as important as with larch species"

Sitka spruce/Japanese larch

"For non-intimate crop - Can be thinned at the same rotation/time/intensity • markets available • financially viable • can be clear felled together at the same time"

"It is easy to remove the JL during thinning operations, it doesn't affect the management too much, intimate mix of JL overall not only looks best in the landscape but also is the easiest to manage as opposed to every 5th line or groups of JL making up the 20% diversity".

"GPC 3 SS JL Mix once you remove all the JL at 1st thing stage"

"Survival of the strongest - SS will naturally outgrow JL but will benefit from the mixture"

"larch is good nurse & then be taken out in thinning."

"Plant the larch in groups for landscaping and remove some of them for pulp in the first thinning."

"This can be removed at first thinning if it is poor quality and taking over a number of potential future SS. Easy to give this direction to machine operator and to manage from machine cab. "

"Often similar growth rates of the two species so one species is not dominated by the other, therefore you do not need to be as careful with timing of interventions. Both species are relatively easy to sell"

Other conifer/beech

"Beech is shade bearing and more accommodating of delays in thinning larch."

"Beech is so shade tolerant that it can take all kinds of abuse. I've worked with 1 metre tall beech that turned out to be 60 years old. when an appropriate coupe was created, it developed really nicely."

Sitka spruce/lodgepole pine

"I found it (SS/north coastal LP) behaved as it should in theory and no intervention was necessary"

"It works with the SS ultimately dominating"

"Allows for good Spruce crop through removal of LPN through thinning."

"SS/LP can be easy to manage when it is agreed at the outset that it will be a no thin stand and once established, left to its own devices. no management intervention is required."

"Due to the fact it is pretty much self thinning"

"Good evidence base, reasonable expectation that SS will success over LP. Thinning is relatively easy to manage."

"On the right site the SS will autothin the LP - or alternatively it can be removed at first thin. On the wrong site the SS should never have been considered."

Ash/sycamore

"Same growth rates"

"Very similar growth rates and form"

"It is easiest because the two trees grow roughly at the same rate and offers a hedging if one tree species is underperforming the tree that is doing better can be favoured"

"Ash/Sycamore mixtures are quite compatible growing at a similar rate and all thinning operations benefit as a result."

Sitka spruce/Douglas fir

"Same growth rates"

"The species grew well together, the SS drawing up the DF."

"We have found DF very difficult to establish pure due to instability in the first 15 years and in a mixture with SS to provide stability. To manage after the growth pattern of both species is very similar and the SS provides shelter for DF. From a thinning point of view we have found no difficulty."

"Produces a good quality plantation, in this scenario the mixture blocks must be non intimate."

Other mixtures were also nominated as being relatively easy to manage and include:

- Norway spruce/Sitka spruce
- Sitka spruce/alder
- Norway spruce/oak – alternate lines

Appendix 4A.

Crop details of operational sites visited by the Team

1. Kildalkey (Meath)

Site no.	1	**County**	Meath	**Nearest town**	Kildalkey
Planting year	2000	**Original species mix**	SP/oak	**Pattern**	Alternate lines
Thinned?	Yes	**Age at first thinning**	12	**Thinning type**	Almost all of SP felled at age 12 (when SP was 2 m taller than oak)
Harvested material removed?	Partly – for firewood	**Quality of remaining crop**	Very good (original origin of oak was Netherlands)	**Future plans?**	Best 100 trees/ha already marked and these will be halo thinned
Other comments	Difficult to engage owners of similar crops to carry out necessary thinning				

PLATES 1 and 2: Kildalkey site showing oak where Scots pine was harvested and removed (left) and harvested and left in situ (right).

2. Drumconrath (Meath)

Site no.	2	**County**	Meath	**Nearest town**	Drumconrath
Planting year	2005	**Original species mix**	SS/JL	**Pattern**	Approximately 6/1 SS/JL, planted intimately
Thinned?	Yes (June 2017)	**Age at first thinning**	12	**Thinning type**	Line removed (spruce and larch) and selection between rows concentrated mainly on removal of the larch
Harvested material removed?	Yes, site had been roaded	**Quality of remaining crop**	Some crooked larch remaining and spruce is very vigorous (YC 34)	**Future plans?**	All JL to be removed in 2nd thinning. Continue to thin this very vigorous crop and possibly clearfell before year 30.
Other comments	Crop was recently FSC certified				

PLATES 3 and 4: Drumconrath crop (SS/JL) showing crooked stems and blow in larch (image taken almost one year after first thinning)

3. Tulla (Offaly)

Site no.	3	County	Offaly	Nearest town	Kinnitty
Planting year	1999	Original species mix	SS/DF	Pattern	Approximately 8/1 SS/DF, planted intimately
Thinned?	Yes, twice (2015 and 2018	Age at first thinning	16	Thinning type	Line removed (spruce and DF) and selection between rows.
Harvested material removed?	Yes, site had been roaded	Quality of remaining crop	Spruce is impressive and is mostly dominating the remaining DF	Future plans?	Depends on whether the owner wants to retain DF as part of the final crop
Other comments	Most of the remaining DF is spindly but may recover if opened up. Spruce is good.				

PLATES 5 and 6: Tulla crop (SS/DF) showing variability in DF stem quality among good spruce stems

4. Tumduff (Offaly)

Site no.	4	**County**	Offaly	**Nearest town**	Kilcormac
Owner	Coillte	**Manager**	Coillte	**Planted under GPC**	Not applicable. The area was planted under the BOGFOR research Programme.
Planting year	1996	**Original species mix**	JL/Syc	**Pattern**	Alternate two row strips of JL and sycamore (50/50), each species planted at 2 m x 2 m
Thinned?	No	**Age at first thinning**	Not thinned	**Thinning type**	Not applicable
Harvested material removed?	Not applicable Sycamore is generally poor but larch is good Crop should be thinned to the best stems – mostly larch				
Other comments	This area is part of a larger species trial on a cutaway bog site. Some other mixtures are included in these trials. Further details available in Renou-Wilson *et al.* (2008).				

PLATES 7 and 8: Tumduff crop (JL/sycamore) showing the effects of delaying removal of nurse trees

5. Blue Ball (Offaly)

Site no.	5	County	Offaly	Nearest town	Tullamore
Planting year	2008	Original species mix	EL/beech and SP/oak (two crops visited)	Pattern	EL/beech – 1 line /2 lines SP/oak – alternate single lines
Thinned?	no	Age at first thinning	8 – EL/beech to be thinned this year	Thinning type	Every third line of EL to be removed with selection in between
Harvested material removed?	Not yet	Quality of remaining crop	EL is very vigorous and needs thinning. Beech growing well.	Future plans?	SP/oak is not yet ready for thinning
Other comments					

PLATES 9 and 10: Blue Ball crops showing EL/beech (left) and SP/oak (right), both crops eight years old

6. Tibradden (Dublin)

Site no.	6	County	Dublin	Nearest town	Tallaght
Planting year	2007	Original species mix	Various mixes of EL and SP with oak and beech	Pattern	EL/oak/SP/oak pattern in one field. Two rows of beech alternating with individual lines of SP and EL in another area
Thinned?	Partly – starting with the EL	Age at first thinning	9 (in 2016) – larch is 12 m while oak is 5-6 m	Thinning type	All the larch is to be removed
Harvested material removed?	Not in 2016. Maybe markets for material currently being felled	Quality of remaining crop	EL needs to be removed. Unsure how the remaining oak will respond.	Future plans?	Remove all the larch firstly and then look at removing SP where interfering with oak.
Other comments	Huge briar problem on much of the site				

PLATES 11 and 12: Tibradden crop, showing larch removal from EL/oak mixture at age 9 (left) and 11 (right)

7. Grangecon (Wicklow)

Site no.	7	County	Wicklow	Nearest town	Grangecon
Planting year	1999	Original species mix	EL/oak and SP/oak	Pattern	Alternate lines of oak and the conifer species
Thinned?	Yes, mechanically thinned with harvester travelling down every second row	Age at first thinning	EL/oak thinned in 2014 and SP/ oak thinned in 2017	Thinning type	Most of the conifer removed in each thinning
Harvested material removed?	Yes	Quality of remaining crop	High levels of squirrel damage in the remaining oak	Future plans?	Some areas have just been underplanted with beech.
Other comments	In the areas where the EL/oak was originally planted, many of the oak have blown over in storm Darwin (12th February 2014)				

PLATES 13 and 14: Grangecon crop, showing relative height of EL and oak (four years after thinning) and blown oak following Storm Darwin.

8. Enniscorthy (Wexford)

Site no.	8	**County**	Wexford	**Nearest town**	Enniscorthy
Planting year	??	**Original species mix**	SP/oak	**Pattern**	Four lines of oak to one line of SP
Thinned?	Yes	**Age at first thinning**	Most of SP removed 6-7 years ago	**Thinning type**	Most of the conifer removed but individual good quality pine left in situ. Oak also thinned .
Harvested material removed?	Yes	**Quality of remaining crop**	Some squirrel damage but crop (currently 95/5 of oak/SP) is generally good	**Future plans?**	Mark potential final crop trees and thin to them.
Other comments	Approximately 800-900 oak/ha currently.				

PLATES 15 and 16: Enniscorthy site, showing good quality remaining oak crop with individual SP dotted through the stand.

9. Mallow (Cork)

Site no.	9	**County**	Cork	**Nearest town**	Mallow
Planting year	1998	**Original species mix**	SP/oak	**Pattern**	Alternate SP/oak lines
Thinned?	Yes	**Age at first thinning**	2014	**Thinning type**	Every second SP line removed and every second pine in the remaining line
Harvested material removed?	Yes	**Quality of remaining crop**	Oak crop is generally good and should look better once the remaining SP are removed	**Future plans?**	Remaining SP to be removed either this year or next. Mark potential final crop oak and thin to them.
Other comments	Very fertile site beside the Blackwater river.				

PLATES 17 and 18: Mallow crop, showing remaining oak and SP crop. Remaining pine to be removed shortly.

10. Kildorrery (Cork)

Site no.	10	**County**	Cork	**Nearest town**	Kildorrery
Planting year	2006	**Original species mix**	EL/oak	**Pattern**	Alternate EL/oak lines
Thinned?	Yes	**Age at first thinning**	October 2017, just before Storm Ophelia	**Thinning type**	Harvester removed and travelled every second larch line and pulled material in from the adjoining larch line
Harvested material removed?	Yes, 850 t of larch removed (over 13ha)	**Quality of remaining crop**	Oak crop is badly affected by windblow, following the high winds of Storm Ophelia	**Future plans?**	Owner now unsure as to what to do next. The oak crop is badly blown.
Other comments	Some oak damaged as harvester pulled in larch from adjoining lines. Italian alder planted on site was not affected by the winds.				

PLATES 19 and 20: Kildorrery crop, showing windblow in oak following removal of lines of large European larch.

11. Moanmore (Kilkenny)

Site no.	11	County	Kilkenny	Nearest town	Knocktopher
Planting year	1992	Original species mix	NS/oak	Pattern	Alternate bands of three lines each of NS and oak (oak planted at 2 m x 1 m)
Thinned?	Yes	Age at first thinning	?	Thinning type	It looks as if the outer two lines of spruce were removed and then the middle line blew and was then removed
Harvested material removed?	Yes.	Quality of remaining crop	Outside oak rows are now 8 m apart so the nursing effect of the spruce is now gone	Future plans?	Unknown.
Other comments	This crop had good potential as the planting pattern was robust. With all the spruce now removed, the future for the quality of the oak is uncertain.				

PLATES 21 and 22: Moanmore crop, showing large (8 m) spacing between remaining oak lines and overall oak quality

Appendix 4.B.

Crop details of experimental sites visited by the Team

The reader is referred to the COFORD NATFOREX database www.natforex.ie (in addition to Table 18 in the main text of this report) for further details on the experiments listed in the following pages. Ted Horgan (ex. Coillte and NATFOREX Research Forester) led the visits and over ten experimental sites were visited by the Group in just two days. Brief update notes only are given.

ADH0588 (Avondhu, Ballyhooley, Cork)

The original objectives of the trial were:
1. To determine the appropriate lodgepole pine provenance for use in mixture with Sitka spruce.
2. To determine the optimum ratio of nurse to main species in lodgepole pine/Sitka spruce mixtures.
3. To examine the interactions between species that may arise over three different site types.

PLATES 23 and 24: ADH1690 showing relative growth rates of two of the SS/LP mixtures

The experiment is now 28 years old and still of enormous value. The relative growth rates of the SS and LP depend hugely on the provenance of the pine. Pure SS plots (already thinned) are included in the trial for comparison.

ADH2493 (Avondhu, Ballyhooley, Cork)

The original objectives of the trial were:
1. To compare the effects of manual and chemical vegetation control methods on tree growth and form of two conifer and two broadleaf species.
2. To examine the merits of a conifer/broadleaf mixture design, which, although introduced into Ireland in 1964, no known record of its application exists.

PLATES 25 and 26: ADH2493 showing current oak groups within a conifer matrix

The experiment is now 25 years old and was established originally on an exposed, gleyed sandstone afforestation site. The current value lies in the on the ground evidence of oak growing within bands of either Norway spruce or western red cedar. Some of the conifers have being selectively killed by herbicide to reduce competition with the oak.

BTR2594 (Banteer, Mallow, Cork)

The original objective of the trial was:

1. To enhance the knowledge base on the comparative development of various species (both as pure crops and mixed species plantations) on a moderately fertile, Old Red Sandstone (ORS) restock site.

PLATES 27 and 28: BTR2594 showing WH/DF (left) and SS/DF (right). Hemlock and spruce are now dominating the fir in both mixtures.

The experiment is now 24 years old (previous crop was lodgepole pine) and contains a wide range of conifer/conifer and conifer/broadleaf mixtures. In addition to the various mixture plots, the experiment also contains good crops of Monterey pine, hybrid larch, western red cedar and Spanish chestnut.

CQN1708 (Cappoquin, Waterford)

The original objectives of the trial were:

1. To investigate the effects on form of early selection and repeated shaping of potential crop trees in an oak crop of very poor quality.
2. To explore the benefits/feasibility of establishing groups consisting of beech, cherry and walnut in gaps within the existing oak crop

PLATE 29: CQN1708 showing area where some of the original pure oak plots had been replaced by groups of cherry.

The experiment was established in 2008 within oak plots of an original farmland species trial which had been established twelve years previously (CQN1796). Species planted in 2008 included beech, cherry and walnut (including walnut crosses).

MDT0202 (Midleton, Cork)

The original objectives of the trial were:
1. To study the performances of twelve conifer and eight broadleaf species, planted both pure and in mixtures.
2. To compare the effects of applying no phosphorous with rates of 250 and 350 kg/ha of rock phosphate.


PLATES 30 and 31: MDT0202 showing western hemlock/hybrid larch (left) and Lawson cypress/hybrid larch (right).

The large (12 ha) experiment was established in 2002 on a restock site. Broadleaves are not growing well but some interesting mixtures currently are Lawson cypress/hybrid larch (to be managed towards a pure larch crop), Japanese larch (one line)/Sitka spruce (two lines) (both species keeping pace), western red cedar/hybrid larch (cedar suffering from shot hole disease and Douglas fir/Sitka spruce (DF very poor, especially in low P plots). Other pure crops include Sitka spruce (doing well at all P levels), hybrid larch (much superior form to Japanese larch), western hemlock (much of the crop is forked) and Corsican pine (currently poor after a good start).

NMT8104 (Newmarket, Cork)

The original objective of the trial was:

1. To explore the beneficial effects of providing immediate shelter from the more adverse effects of climatic conditions to sensitive broadleaf species on an exposed lowland site.

PLATES 32 and 33: NMT8104 showing cedar/oak mixture (left) and oak groups within a conifer matrix (right).

This trial was planned as a follow on from an earlier trial established in Avondhu forest in 1997. This older trial showed the benefits of growing broadleaves within gaps created in an already established conifer crop. The original crop of western red cedar and Norway spruce was planted on the current site in 1998 and the oak was subsequently planted in gaps within the conifers six years later. Hornbeam was planted one year after the oak. Some of the hornbeam have had to be cut back so as not to overtop the oak.

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