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The potential for use of rotational mixtures with Sitka spruce in British upland forests

Technical Report to SFT - November 2014

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Executive summary

This short project sought to collate evidence relevant to the record and potential for operation of upland mixed stands combining Sitka spruce with other conifers of equivalent or greater shade tolerance - "insurance mixtures". Principle companion tree species considered were Norway spruce, Douglas fir, western hemlock, grand fir and noble fir, with less detailed commentary on the red cedars and silver firs. Deployment of mixtures of this kind has the perceived advantage of increasing stand resilience by reducing the likelihood of complete loss of wood production through climate or disease impacts. There are also possible benefits from mutual silvicultural support and facilitation which may enhance combined yields. A number of forestry commentators over the years have highlighted the need to develop our first rotation upland conifer forests towards more self-sustaining mixed-species assemblages emulating those of either the Pacific Northwest (Sitka spruce-Douglas fir-hemlock) or of montane Central Europe (Norway spruce-European silver fir-beech). Hence this is an approach to forest resilience and diversity that can be seen to have a "good pedigree". Set against these potential advantages are a number of challenges, including a lack of silvicultural experience with relevant mixtures in Britain, a need for more frequent thinning interventions, and lower market values for the timber of companion species such as hemlock and *Abies* firs.

Evidence was collated from a variety of sources. These included the very small body of data from previous research trials of spruce-hemlock mixtures, together with field reconnaissance of more numerous standing (non-research) examples of relevant mixtures in upland Britain. A literature review and technical correspondence with relevant experts were combined with a range of desk analyses exploring species site tolerance and mensurational data/ yield models. While the latter models are largely derived from previous comparative studies of pure, even-aged stands of spruce and potential companion species on similar sites, results of analyses can be used as a first approximation to suggest likely performance of species in mixed stands. More detailed mensuration and modelling information, directly from relevant mixed stands, will have to await results from future work, often requiring the establishment of new trials.

The body of evidence collated has indicated that there is considerable potential for upland operation of mixed stands (mosaic, row and intimate) of Sitka spruce with each of Norway spruce, Douglas fir, grand fir, noble fir, western hemlock and western red cedar. Ecological compatibility of these species is generally good, although some revision of ecological site suitability envelopes for pure Sitka spruce is required. For example Douglas fir and noble fir should not be used on wetter sites, while Douglas fir and western red cedar are more drought tolerant. Silvicultural compatibility varies - very good with Douglas fir, grand fir, Pacific silver fir and western red cedar, with some more obvious differences in habit with Norway spruce, western hemlock and noble fir, which tend to show slower height increment. These species may therefore require either favouring by earlier and more careful thinning or, alternatively, by initial stocking at 2:1 or similar where site factors preclude regular thinning. For many of these species combinations there will be a moderate yield penalty arising from slower growth of the companion species and/or reconciliation of optimal rotation lengths. This must be set against the advantages of increased resilience arising from species diversity.

This reports makes recommendations both for cautious operational deployment of mixtures based on current knowledge and for future research work - both of a short term tactical nature and long-term, involving the establishment of new experiments. There is a considerable need for further research in this area, particularly in terms of the optimum silviculture of mixtures (spatial arrangement, thinning, rotation length) and implications for wood properties of both Sitka spruce and the companion species, whose timber currently tends to be less valuable.

Context and objectives

This was a short exploratory study examining the previous record, and potential for future development, of a specific class of forestry mixtures for British upland conditions - those combining Sitka spruce with alternative productive conifer species of equivalent or greater shade tolerance. The main "companion species" being considered here are Norway spruce, Douglas fir, western hemlock, grand fir and noble fir, but other options such as European and Pacific silver firs, western and Japanese red cedars and Lawson cypress are commented upon. The potential advantage of "rotational" or "insurance" mixtures of this kind is that either or both species could be allowed to complete the rotation, depending on appropriate silviculture. This differs in principle from the established concept of nursing mixtures such as SS/LP and SS/JL, where the nurse is not intended to complete the rotation or to contribute significantly to economic returns. There is also a potential to create productive mixed coniferous forests which are an ecological analogue of those found in the Pacific Northwest, primarily of the Olympic and Cascade "spruce-hemlock-fir" types. The potential advantages of that approach in terms of forest perpetuation and site relations have been highlighted over the years by M.L. Anderson, R.F.Wood, Phil Ratcliffe and others. The timbers of several of the conifer species involved are used for equivalent purposes to Sitka spruce in the Pacific Northwest and could be here, following appropriate research and market development effort. The challenge in this area of work is that there has been very little consistent record of silvicultural research and implementation in Britain, using these mixed-species combinations, and hence a scarcity of examples available for study, away from the better quality of sites, commonly used for CCF working. There were two distinct previous episodes of interest in this kind of upland mixed-coniferous forestry - the period 1890-1940 and again during the period 1955-1965 - otherwise this has tended to be seen as a "Cinderella" strand of thinking in British forestry practice. This study aimed to draw together the rather disparate and incomplete evidence that we do have in this area, and to use that as a basis to chart a future course for research and technical development, allowing growers an opportunity to evaluate this option for their circumstances. This project may be seen as an adjunct to the larger studies that the Contractor has recently undertaken on the adoption of alternative conifer species and alternative silvicultural systems.

Existing choices of productive tree species for upland plantation forestry are currently under serious challenge. Lodgepole pine and Scots pine are susceptible to *Dothistroma septosporum* infection while Japanese/ hybrid larch is susceptible to *Phytophthora ramorum* infection. The former pathogen has caused major pine crop damage in the Northern Highlands, while the latter has caused significant damage to larch crops in South West Scotland, Wales and South West England. The preferred replacement species in many instances might be Sitka spruce, but there is concern over the potential drought susceptibility of that species in eastern areas such as Grampian, the Borders and the North York Moors, especially given ESC/UKCP-based climatic predictions for the next rotation to 2050 and 2080. Even where Sitka spruce remains climatically suitable, there are serious questions raised over increasing dependence on any single species given the diversification requirements of UKFS/ UKWAS protocols and the latent risk of introduction of a damaging pest or pathogen affecting spruce species from Continental Europe or North America. Given that Sitka spruce represents 60-70% of the upland plantation resource, the potentially disruptive consequences for the forest management and industrial timber processing sectors cannot be ignored in forest planning. However the specialisation of the industrial timber processing sector in Great Britain along "Scandinavian lines" implies a very strong preference in commercial forestry for "European whitewood" or "spruce equivalent" conifer species in comparison to other relevant options such as pines or native hardwoods. At present Sitka spruce and Norway spruce are the main species that meet this criteria in Britain, and consequently these are preferred in upland restocking. However it must be recognised that admixture of Norway spruce, while it may offer some buffering against drought in the east, offers little real resilience to pest or disease, as most "likely candidates" as damaging agents could affect both spruce species comparably.

Douglas fir is generally a favoured timber if well grown on better quality sites, but tends to be viewed as a distinct resource from spruce whitewood, especially the heartwood of older trees. Younger Douglas fir grown on upland spruce-type sites is often seen as an inferior resource. European silver fir is widely accepted as "spruce equivalent" in central Europe and is actually included as a minor proportion of many imported "European whitewood" timber packs. However there has been no real record of growing this species productively in Britain since the early 1900's, due to perceptions (recently seriously challenged) of *Adelgid* susceptibility. In the Pacific Northwest, western hemlock, Pacific silver fir, grand fir and noble fir timbers are accepted as elements of the "spruce-hem-fir" general purpose lumber classification and, while not as strong as pure structural spruce, are widely traded as joinery timbers. However the timbers of these species are not currently favoured in Britain, due to perceptions of poor timber quality and a propensity to defects such as stem fluting and drought cracking. There is some level of interest in exploring these species further at present, given their latent potential to produce higher volumes of industrial softwood, based on overseas evidence. A fresh programme of research and development work including provenance selection, tree breeding and silvicultural trials is likely to be an appropriate way forward for these species.

With many commercial foresters responding to the priorities of investment forestry owners, there is a very strong reluctance to restock productive sites other than with spruce at present. However there is a latent opportunity to exploit the observation that, especially in thinned stands, only a proportion of the initial stocking is required to complete the rotation, with the remainder of volume removed as thinnings, serving particle, pulp and biomass markets. In theory, up to one-half of the rotational volume production can be taken as thinnings. In un-thinned stands, given the medium-tolerance of Sitka spruce, density-dependent mortality can be significant according to Yoda's law. Were Sitka spruce to be initially combined in even-aged mixtures (*sensu lato*) with other shade tolerant conifers, capable of completing the rotation and serving equivalent industrial markets, the option would remain to thin out the complementary species for small roundwood applications, leaving a fully-stocked final crop stand of Sitka spruce. However if drought, pest or disease were to affect the spruce during the first half of the rotation, the "insurance policy" of the mixture could then be "cashed in" for a fully-stocked crop of the other species. Even if the timber of that species were less valuable than spruce, the potential total loss would at least be significantly reduced to a partial loss. The option of taking the mixture through to a final crop (thinned or unthinned) also exists. Especially (but not exclusively) in the latter case, the option of perpetuation using natural regeneration under alternative silvicultural systems would be open to growers on some sites. That approach has recently been widely promoted to enhance resilience in Welsh forests. Even-aged mixtures of the relevant types (mosaic, row or intimate) can be formed either by simultaneous planting/ restocking or by natural regeneration from mature stands nearby. The latter mechanism is increasingly common in second and third rotation plantations, with extensive areas of informal spruce-hemlock-fir mixtures forming in areas such as Argyll. Diversification under-planting with shade tolerant conifers is also a relevant mechanism, applied in stands of pine, larch and spruce species in some parts of England and Wales.

However, widespread adoption of the rotational or "insurance" mixtures option is impeded primarily by unfamiliarity and limited confidence in their application, occasioned by the lack of an established record of research and development. This is even more acute than in the case of adoption of alternative silvicultural systems, where there has been an established record of upland trial and demonstration sites across the country over the past 60 years (e.g. Glentress, Clocaenog, Fernworthy, Cwm Berwyn). One aim of the present work was to collate and evaluate the information that we do have and lay that before “early adopters”. However it is fully recognised that the restricted body of available evidence is likely to prove an inadequate basis from which to promote the model to the more conventional growers, and hence a second aim of the present work is to scope the requirements for future research and development work on this model in Britain, and to encourage support for that to be pursued.

Methods

This study sought to collate information relevant to the subject of enquiry from a wide variety of sources, given the relatively sparse field evidence. The main lines of investigation were:-

1. **Literature review**, primarily of the previous British and Pacific Northwest published literature, relevant to silvicultural operation record of mixtures of the relevant tree species. Ireland and Denmark are also relevant as the other major Sitka spruce plantation countries. The review used conventional library resources and internet citation search facilities at the Universities of Aberdeen and Edinburgh and at Harper Adams University. Forestry Commission Bulletins 25, 30 and 49 were key references.

2. **Technical discussions** with forestry researchers and practitioners considered to be knowledgeable on the previous record of relevant mixtures in British forestry. This to supplement the literature review output and to obtain notifications of potential examples to visit in the field. An informal collaboration was established with Dr. Andrew Cameron in the Department of Forestry at the University of Aberdeen, who is a member of the EU EUMIXFOR research consortium active in this area. Bill Mason, Gary Kerr and Victoria Stokes of Forest Research provided advice on the use of the NOLTFOX database to identify relevant long-term research experiments in Britain. Information on the relative timber properties of British grown crops of the relevant conifer species have now become available from Forest Research/ Edinburgh Napier University, although this is based on comparison of samples from pure stands. Some information is available on the timber quality impacts of growing spruce in stands of irregular structure or with pine and larch nurses, but little or no specific information relevant to rotational insurance mixtures with the more shade tolerant conifers.

3. **Evaluation of relevant British field examples**, using a combination of desk review and selective field visiting. Three main categories of field examples were considered - these being (a) pre-1940 mixed stands of Sitka spruce with relevant conifers, (b) "deliberate mixture" stands of Sitka spruce and relevant conifers from the period 1950-1980 and (c) younger examples arising from replanting or natural regeneration. In the case of category (a) the Contractor was already aware of, and had visited, very many of the surviving examples as these are highly coincident with CCF application. Some further fieldwork was undertaken to review upland SS/NS mixture examples. Category (b) above was the major focus of the fresh example search and field visiting undertaken within the present project. Relevant surviving examples were pre-identified from a circular enquiry to private sector/ estate growers and from detailed spatial searches of the Forestry Commission sub-compartment database GIS layers. One relevant previous series of research experiments on SS/WH row mixtures (p1955) was indentified from a combination of review of Forest Research Annual reports since 1950 and the NOLTFOX database of long-term forestry experiments. Of the five replicates originally established, two survive in South Wales, with examples in Mid Wales, North Wales and Scotland having been destroyed in the past. Results of mensuration from these trials are available, and the surviving stands were visited. Non-research examples within category (b) were selected for field visits using a combination of sub-compartment data review, aerial photographs and consultation with district management and estate staff. Row and intimate mixtures were sought out. Some younger examples in category (c) above were visited in passing to (b)

examples. The field visiting campaign conducted within the present project was non-exhaustive and there may be additional benefit to be obtained from further effort in future. In particular, the present work only sought to identify and photo-record location, composition, condition and silvicultural relevance. Future detailed work might encompass mensuration. The nature and location of upland examples renders them vulnerable to continued attrition by rotational clear-felling, windthrow and windfarm operations, and hence the opportunities to pursue such work are declining.

4. **Desk analysis - ecological site compatibility**. This analysis attempts to define the climatic and edaphic requirements/ suitability of each relevant species composition, using the methods of the Forestry Commission Ecological Site Classification (ESC) as set out in FC Bulletin 124 and subsequent computerised versions. A "weakest link in the chain" approach was adopted - i.e. both species very suitable (green), both species at least suitable (amber) and one or both species unsuitable (red). Key species combinations examined were SS/NS, SS/DF, SS/GF, SS/NF, SS/PSF, SS/WH, SS/RC. This information aims to inform growers as to where they might try mixtures.

5. **Desk analysis - relative height growth comparison**. This analysis attempts to shed light on the silvicultural compatibility of relevant species combinations in terms of predicted differential relative height growth in close mixtures. This employed a combination of observational evidence from field reports with systematic curve family analysis based on the even-aged yield models from Permanent Sample Plots as previously published in FC Booklet 48 (soon to be updated by release of a digital version from Forest Research). The aim of this analysis was to provide information relevant to the optimisation of mixture ratios (1:1, 2:1, 3:1) and spatial arrangements (mosaic, line-row, intimate). Specification may vary with companion species and thinning regime. It is recognised that such analyses do not consider explicitly the potential for differential performance in close mixtures based on criteria other than early height growth, for examples mutual fraying and mechanical branch abscission. Neither is any account taken of the potential for mutually beneficial interactions. Also, the Booklet 48 curves tend only to begin from 8 to 10 years of growth, whereas differential height growth and competition may begin earlier in some stands. Small amounts of past research data available from SS/WH trials were also adduced here. Further insights in this area would have to await results from fresh mixtures trials.

6. **Desk analysis - site yield comparison**. This analysis attempts to explore the likely GYC yield performance of relevant mixtures as compared with pure crops of Sitka spruce on the same sites. Evidence came from two main sources (a) review of the information presented for SS, GF, NF, WH, RC in FC Bulletin 49 (Aldhous and Low, 1974) and automated comparison of predicted GYC for the mixture components in relevant sub-compartments on the current FC GIS database. Work leading to Bulletin 49 compared pure stands (rather than mixtures) of relevant tree species growing on known similar soil types within the same forestry blocks. However by virtue of the time it was undertaken, there were a greater number of relevant examples surviving from p1920's and p1930's plantings than is so today. For the GIS analyses, "blocky mixtures" were included alongside mosaic, line-row and intimate mixtures. Where the two components form part of the same sub-compartment, it can reasonably be assumed that they experience the same elevation, aspect and climatic regime. This latter approach was pursued for examples on the National Forest Estate for the cases of mixed-species sub-compartments of SS/NS, SS/DF, SS/WH, SS/GF, SS/NF,

SS/RC. There are too few examples for SS/JCR, SS/LC, SS/PSF and SS/ESF etc for this approach to be considered reliable. The approach taken here was "if the predicted yield of Sitka spruce is GYC 12, what is the predicted yield of (NS,DF,GF,NF,WH) and what is the predicted mixture yield" given a 1:1 ratio. The latter yields could in principle be adjusted for wood density using data from Ramsey and Macdonald (2013) (e.g. grand fir of GYC 22 contains less kiln-dry biomass than Sitka spruce of GYC 22). It is recognised that this approach assumes that the single-species GYC stand-level modelling approach can be applied to mixed-species stands on a pro-rata basal area basis. This is known to be imperfect as there are mutual effects in mixtures in either sense (Kerr *et al*, 1992). However prior to the calibration of stem-level models directly applicable to mixed species stands of varied shade tolerance, this is the best information available to predict relative yield in mixed stands. Future work by Forest Research employing the Austrian MOSES model will apply here.

A further refinement of this approach should consider the possibility that discrete species components within sub-compartments (relevant mainly to the blocky mixture patterns) may have been planted to reflect local differences in soil conditions. This would have applied particularly during the period prior to ~1965, during which the principle of species-site matching according to ground vegetation was followed after the recommendations of Professor Mark Anderson in "*The Selection of Tree Species*". Forestry Commission soil map overlay information is held for a proportion of sub-compartments on the GIS database. A trial of the deployment of this information to eliminate potentially doubtful examples from the component yield comparisons was conducted. However, due to the fact that soil mapping overlays were available for only 10% of mixed-species sub-compartments of interest, it was not pursued further. Developing this approach further would therefore require fresh soil survey reports.

7. **Technical reporting and dissemination** - the information collected was collated into this illustrated technical report (a) addressing the information requirements of potential adopters of relevant mixtures at the present time (likely to be the more knowledgeable growers) and (b) scoping the requirements for future research and development work in this area to widen the potential "adoption base" for relevant mixtures. Future work may be divided into (i) short-term/ tactical studies such as mensuration and destructive timber sampling from existing mixtures field examples and (ii) longer-term studies requiring the establishment of new trial series. The former category may be amenable to progress within MSc and PhD projects. The contents of the present technical report will be summarised for a subsequent short-article submission to *Scottish Forestry* and can be delivered in the form of an oral presentation at future seminars/ workshops. A leaflet guide may also be valuable.

Results: literature review and technical discussions

The select bibliography resulting from the literature review element of the present project appears at the end of this report. Insights obtained from the review have been used to inform commentary in the various sections of this report. As an overall conspectus, one can say that:- the domestic literature on operation of plantation spruce mixtures with tolerant conifers is rather sparse, with almost all of the sources reviewed dealing with numerous previous studies of predominant "nursing" mixtures combining Sitka spruce with Scots pine, lodgepole pine or Japanese larch (e.g. Cameron and Watson, 2000; Kerr *et al*, 1992; Watson and Cameron, 1995). This has been a much more consistent strand of silvicultural research in British upland forestry since early work at the Lon Mor, Fort Augustus and elsewhere from the 1920's onwards (Zehetmayer, 1960). Earlier interest in the potential of rotational mixtures in the uplands was kindled by Wood (1955) after his return from the Pacific Northwest and was discussed again by Doyle-Davidson (1965) following a year in which the Royal Scottish Forestry Society Silvicultural Group adopted this as its topic. More recently Paterson (1990) addressed the potential of upland spruce mixtures with firs etc. Work in Forestry Commission trial plots at the Gisburn Forest in Lancashire (now conducted over two rotations) has considered the responses of mixtures of spruce and pine with various companion hardwood species (Brown, 1992; Mason and Connolly, 2014). Some studies have dealt with the potential for soil amelioration by sacrificial establishment of nitrogen-fixing hardwood species, such as red alder, together with Sitka spruce on infertile and poorly-drained upland sites. More recent work on the upland adoption of alternative silvicultural systems (reviewed by Wilson, 2013) (for example at Glentress and Wykeham Forests) has involved enrichment of maturing spruce, pine and larch stands with western red cedar, *Abies* firs and western hemlock (Mason, 2006a,b) and subsequent operation of these stands under selection systems.

Review of the published Annual Reports of Forest Research since 1950, together with the online NOLTFOX database, only identified one series of past experiments directly relevant to this study. This was a set of five experiments, established in 1955 on upland sites, comparing the performance of pure stands of Sitka spruce and western hemlock with SS/WH row mixtures established at 1:1. It is apparent that these experiments were established partly in response to R.F. Wood's impressions from a tour of the Pacific Northwest, as described in Forestry Commission Bulletin 25 (Wood, 1955). Four of these trials were in Wales and one in Central Scotland, the latter being destroyed in infancy by vole damage. Two out of the four examples in Wales (Garw/Draethen and Margam) survive, with examples at Carno and Gwydyr having been clearfelled in recent years. Measures have been published after 10 years (Lines and Nimmo, 1965) and 35-45 years of growth (Cameron and Mason, 2013). While hemlock tended to benefit initially from the shelter of spruce, the vigour of the Sitka spruce later dominated the hemlock component, reducing it to a subordinated (now partly suppressed) stand component. These stands were not thinned during their critical competition period. It is understood that a forthcoming publication from Forest Research will analyse unpublished mensurational data from these trials in more detail. While a single Douglas fir/ western hemlock trial was established in 1957 at Broxa, there are apparently no relevant formal research mixtures trials or experiments for the other potential combinations with Sitka spruce (e.g. SS/GF, SS/NF etc.). Discussions with colleagues at Forest Research have not yet identified any additional relevant trials, but some may exist for which records are weaker.

Another principal source of relevant published information is for the silvicultural operation of semi-natural mixed coniferous stands in the Pacific Northwest. Study tours of these forests by Wood (1955) inspired the establishment of the above series of field experiments in Britain. Sitka spruce occurs naturally together in the diverse coastal forests of southern Alaska, British Columbia, Washington and Oregon with Douglas fir, western hemlock, western red cedar, grand fir and Pacific silver fir (Krajina, 1969). There is though only a very restricted natural overlap of Sitka spruce occurrence with noble fir, which is a more inland, montane species. The natural combination of tree species is variable with latitude, elevation and soil regime as described by the British Columbia Biogeoclimatic Ecosystem Classification (BEC) (Pojar *et al*, 1987). These forests are subject to a suite of natural disturbance mechanisms operating at a wide range of spatial and temporal scales, which together with the impacts of logging activity over the past two centuries, has led to a patch-scale occurrence of species and semi-natural stand types (Oliver and Larson, 1996). In these forests, western hemlock and western red cedar initially tend to assume a sub-dominant role due to the more rapid and sustained early growth of both Sitka spruce and Douglas fir. In the absence of disturbance the shade tolerant hemlock and cedar later assume dominance. Mixed secondary stands (mainly naturally-regenerated) are managed for timber production, particularly of Sitka spruce and western hemlock, and combining those two species with Douglas fir and red cedar further south. Experiences of operation of spruce-hemlock stands in coastal southern Alaska are particularly relevant as the growing conditions are likely to be more comparable to those on challenging upland sites in Britain than are those encountered in coastal forest areas further south, as at Vancouver or Washington. To date, regeneration by replanting in the Pacific Northwest has tended to favour highly productive even-aged single-species stands of Sitka spruce and Douglas fir in particular, but there have been some trials of Montane Alternative Silvicultural Systems (MASS), involving operation of planted mixed-coniferous stands on an uneven-aged forestry principle. Other than in these particular trials, the development of non-clearfell silviculture of mixed coniferous stands in the Pacific Northwest has not been mainstream. Some early adverse experiences with selection management of Douglas fir stands in the 1950's tended to deter further work in this area, although there is an emerging strand of alternative selection silviculture on some smaller private landholdings in the region. Selected references for the silviculture of the relevant conifer species in North America are Burns and Honkala (1990), Deal *et al* (1991), Deal and Tappeiner (2002), Erickson and Harrington (2009), Julin *et al* (1993), Oliver and Larson (1996), Singleton *et al* (2003).

Finally, it is worth noting that there is an emerging body of domestic literature on the potential of alternative coniferous species and silvicultural systems relevant to the discussion in this paper, as elements of work to increase diversity and resilience in British plantation forests in response to emerging current challenges from climate change (Green *et al*, 2008; Ray, 2008; Ray *et al*, 2008) and novel pest and disease incidence (Green and Ray, 2009). Earlier treatment of alternative introduced conifer species were the seminal publications of FC Bulletin 30 (MacDonald *et al*, 1957) addressing a wide palette of species and by FC Bulletin 49 (Aldhous and Low, 1974) specifically addressing western red cedar, western hemlock, grand and noble firs. That publication is referenced below in terms of the comparison of GYC yield between species. More recently Wilson (2007, 2010, 2011) has updated this information for a range of the more familiar alternative conifers and valuable summary information is now available from Forest Research for a much wider palette (www.forestry.gov.uk/fr/treespecies). Fairbairn and Neustein (1970) began to examine the relative shade tolerance of the various conifer species used for forestry in Britain and that work has been considerably developed over recent years by Hale (2004). The merits of European silver fir were critically re-examined by Kerr (1999) and Mason (2012b) has considered the potential and role of a wider range of the *Abies* fir species. Silvicultural development relevant to resilience diversification in upland Sitka spruce plantations were addressed by Mason and Perks (2011), Mason (2012a), Ray *et al* (2014), Stokes and Kerr

(2009) and Wilson (2012; 2013) all of which are relevant to mixed-species stand options with spruce and shade tolerant companion species to varying degrees.

Results: field search and rapid survey campaign

Overview

This phase of work has been conducted during the period August to November 2014 and is by no means exhaustive. Field visits have been pursued throughout Scotland, Northern England and Wales, with a limited amount of remote review in Southwest England, relying purely on mapping and air photographic resources. A forestry field tour of Ireland in 2013 in connection with another project suggested that there were also some mixture examples there.

Candidate priority stands for field visiting were pre-identified from prior knowledge, a circular enquiry of the private forestry sector and spatial interrogation of the Forestry Commission/ Natural Resources Wales sub-compartment GIS databases (public version) as at early summer 2014. Although a small number of spruce-hemlock examples in Argyll were notified by UPM Tilhill, it was the National Forest Estates that were the focus for much of the field visit campaign. This reflects the generally greater age of plantations on the National Forest Estate, encompassing the period 1920 to 1965 when upland mixtures were more often attempted. It also reflects the longer history of research trials and experimental plantings on the NFE. An SQL GIS search on principle and secondary species components identified several hundred potentially relevant candidate mixed sub-compartments which were then filtered down for detailed field visit planning based on consideration of access logistics, tree species ratio, stand age and spatial arrangement, with row and intimate mixtures being prioritised for visits. The latter represent only a small minority of recorded sub-compartments comprising two or more species and were pre-isolated (wherever possible) by reference to air photography and more detailed records and advice provided at district level. Discrimination inevitably remained partial. Later on in the project, additional GIS spatial datasets became available from Forestry Commission Scotland allowing for much improved discrimination. Tabulation and consideration of examples visited in the field (or pre-identified for field visits which could not be accommodated within the project timescale) assigned stands to one of two categories: (a) priority examples and (b) secondary/ background interest examples, as below:

Priority examples

These are existing examples that conform to the 'ideal model' of mosaic, line-row or intimate mixtures of the conifer species of interest, based on field inspection during the current project (or in some cases FC and NRW GIS database records). These priority examples are likely to be most relevant to future more detailed mensurational, silvicultural or wood science studies and should, wherever possible, now be reserved/ retained. Those visited in the field during the current exploratory study are shown in Table 1 overleaf, while additional potential candidates identified from enhanced GIS spatial searches, but not able to be visited within the current project, are detailed in digital appendices, to pre-inform any future field search/ visits.

Emphasis was placed during the current project on visiting examples identified from the planting period 1950 to 1980, as many older, pre-war examples had been visited during previous studies on alternative species and silvicultural systems conducted by the author. The two previous spruce-hemlock (p1955) mixtures trials at Garw/Draethen and Margam were visited as a priority (with the site at Carno viewed from a vantage to confirm its prior felling). A considerable number of other (non-research) surviving examples of SS/NS, SS/DF, SS/WH, SS/GF, SS/NF and SS/RC "close mixtures" were also identified at locations ranging from the South Wales valleys to the North York Moors and from Aberdeenshire to the Northwest Highlands of Scotland. Many were located and photo-recorded, with basic sub-compartment data extracted (photographs are provided as appendices), and these are likely to provide a very suitable basis for future more detailed mensurational, silvicultural and wood science studies at the MSc or PhD level. It is valuable for the locations of potential exemplar "silvicultural reserve" stands of this type to be known, although there is currently no real protection for them from felling, windfarm clearance and windthrow. It is very likely that further suitable examples of this kind might be identified by targeted continuation of the type of exploratory work initiated within the present project, given additional search/enquiry time. That would form a logical initial phase of any future MSc/PhD research study on this topic.

Secondary/ background interest examples

Given the restricted number of examples with close mosaic, row or intimate mixture patterns, a wider range of locations were also considered (some being field visited) which included "co-deployments" of these relevant species in block-wise fashion within sub-compartments on the same apparent site types (search and identification tables are appended for future reference). Although providing only indirect information on compatibility of species in close mixture, this wider class of examples can be potentially relevant to comparative yield analyses of the type discussed below. Some such "co-deployment" locations were explicit FR research trials (e.g. the Tweedsmuir Pacific silver fir/ spruce trials), whereas others were locations at which blocks of species had apparently been established for less-formalised operational comparison earlier in the life of upland forests (both public and private sector).

Species and regional commentary

There was considerable variation between the species combinations considered in this report in terms of both number of examples identified, context and regional distribution. Generally there were a greater overall number of examples for **Sitka spruce/ Norway spruce** and **Sitka spruce/ Douglas fir** combinations. Fewer field examples were found for **Sitka spruce/ western hemlock**, **Sitka spruce/ noble fir** and **Sitka spruce/ grand fir** combinations and very few for **Sitka spruce/ silver fir** and **Sitka spruce/ western red cedar** combinations.

Sitka spruce/ Norway spruce and **Sitka spruce/ Douglas fir** combinations tended to be more common in older Forestry Commission plantations from the period 1910 to 1960, with most examples being found in Scotland (e.g. Great Glen, Argyll, Galloway and Moray). Most examples displayed informal mosaic patterns arising from mixed original plantings, and in the case of **Sitka spruce/ Norway spruce**, original planting with Norway spruce followed by subsequent reinforcement planting/ beating up with Sitka spruce. **Sitka spruce/ Douglas fir** combinations are largely found on lower ground at the foot of the upland forest slope, often representing better-thinned "trophy stands" - this due to Douglas fir not being planted further up the hill. **Sitka spruce/ Norway spruce** combinations were very often unthinned first rotation stands, typically retained on inaccessible ground at the upper edges of forest blocks.

Sitka spruce/ western hemlock, **Sitka spruce/ noble fir** and **Sitka spruce/ grand fir** combinations were more often apparently deliberate mixed-species plantations from the period 1955-1970 when there was an upsurge in interest in the concept of rotational mixtures. These were more often line-row or intimate mixtures, but with some mosaic examples. Some examples were unthinned, whereas others appeared to have been thinned in recent years. **Sitka spruce/ western hemlock** combinations were a particular feature in parts of South Wales (as with the two surviving FR experiments) and the North of England, whereas **Sitka spruce/ noble fir** combinations were found in Argyll, Aberdeenshire, the Scottish Borders and North Wales. **Sitka spruce/ grand fir** combinations were more occasional and scattered.

Results: desk analysis of ecological site suitability

This desk analysis sought to explore whether the proposed species pairings with Sitka spruce represent viable choices that could potentially be deployed on the same upland site types in Britain. While there is evidence from the Pacific Northwest of natural site compatibility for SS/DF, SS/WH, SS/GF, SS/PSF and SS/RC, this does not apply to SS/NS and SS/NF, and caution must be applied to any extrapolation from distant ranges to British conditions. The method involved an overlay of species suitability grids for climate (AT_5 v MD) and soils (SMR v SNR) for the component species as presented by FC Bulletin 124 (Pyatt *et al*, 2001). A conservative "weakest-link in the chain" approach was employed here - i.e. the suitability of the mixture could never exceed the suitability of its least suitable component species.

There are however arguments that mutual facilitation effects between species in silvicultural mixtures may result in "the whole being more than the sum of its parts". This has been demonstrated in the case of "nursing mixtures" between Sitka spruce and lodgepole pine, where Sitka spruce has been able to operate on sites for which it should be unsuitable alone. The facilitation there is mainly by means of improved soil aeration and nutrient uptake. Work at Gisburn Forest referred to above has also suggested that there can be a "mixture gain". It is quite possible that more exposure-sensitive companion species such as western hemlock may perform better initially on upland sites in mixture with Sitka spruce than they would alone. That would appear to be the lesson from the FR p1955 SS/WH trial series in Wales. However there is insufficient information available at present to rely in detail upon these effects.

As discussed below, combinations that can prudently be recommended for planting in terms of the Ecological Site Classification scheme would currently be overall ***Suitable/ Suitable*** or better, preferably expected to remain so out to 2080 under climate predictions. It should be borne in mind that the suitability envelope for some mixtures could be extended if the early demise of one of these species is accepted - for example in eastern Scotland, Douglas fir or western red cedar might be able to "continue alone" under more droughty conditions from 2050 onwards, with the spruce element having therefore to be harvested earlier. That implies accepting a species combination which is currently ***Suitable/ Suitable*** or better, but which declines to predicted ***Suitable/ Marginal*** by 2050 and even ***Suitable/ Unsuitable*** by 2080. That decision must remain at the owner's/ manager's discretion considering risk appetite. Species components which are already ***Marginal*** should be avoided in current plantings. Similarly with species combinations predicted as ***Marginal/ Marginal*** (or worse) by 2050.

Climatic co-suitability

By definition on this basis, current climatic suitability of sustained Sitka spruce mixtures is equivalent to, or more restricted than, the suitability of Sitka spruce component alone [see digital Figure 1 for ESC climate suitability grid composites]. In most cases, the effect of introducing any companion species is to restrict the applicability to the more sheltered and climatically benign sub-sector of the climatic range tolerable to Sitka spruce, eliminating the colder, more exposed component of the Sitka spruce range. This is a fairly marked restriction of range in the case of the more "lowland" conifers - Douglas fir, grand fir and western red cedar, and a fairly mild restriction in the case of the hardier species - western hemlock, noble fir and Pacific silver fir. Norway spruce assumes an intermediate position in this respect. In terms of exposure tolerance in particular, only noble fir is equivalent to Sitka spruce in hardiness, tolerating up to DAMS Score 22. Pacific silver fir is suggested as ***Suitable*** up to DAMS 20, Norway spruce and grand fir up to DAMS 18 and Douglas fir, western hemlock and western red cedar only up to DAMS 16 [see page 30 of FC Bulletin 124 for support].

Tolerance of drought is inferior in noble fir and Pacific silver fir as compared to Sitka spruce, but better in the cases of Douglas fir (markedly so), Norway spruce, grand fir, western hemlock and western red cedar (moderately so) [see page 29 of FC Bulletin 124 for support].

In terms of future climatic suitability of species considered here, predictive modelling results have only been published for England, Scotland and Wales on a (suitability shift) spatial mapping basis to date for Sitka spruce, Norway spruce and Douglas fir. This has not been undertaken for the other potential companion species, although their future suitability can be assessed on a non-spatialised/ individual site basis. In broad terms, under the 2050high and 2080high emissions scenarios, both spruce species become much less suitable in many eastern upland parts of the three countries respectively and unsuitable in drier lowland areas. Douglas fir is less severely affected in Scotland, but appears more vulnerable in England and Wales. The reader is referred here to the mapped outputs from Forestry Research currently made available at www.forestry.gov.uk/fr and being continually updated with fresh results.

Soil co-suitability

By definition here, soil suitability of sustained Sitka spruce mixtures is equivalent to, or more restricted than, the suitability of Sitka spruce alone. For **Sitka spruce/ Grand fir** and **Sitka spruce/ western red cedar** mixtures, it appears that the entire suitability range of Sitka spruce is theoretically available from the outset. This is also the case for **Sitka spruce/ Pacific silver fir** mixtures, with only the Slightly Dry SMR class in contention, which is sub-optimal for Sitka spruce in any case, given climatic predictions. It must be noted that we have few if any convincing field examples of the SS/PSF mixture. From observation, considerable caution should be exercised over the deployment of western red cedar and grand fir on nutrient poor, wet sites where they are unlikely to perform as well as Sitka spruce. There is a strong interaction with site exposure. For **Sitka spruce/Norway spruce** mixtures the only difference appears to be a reduction from ***Very Suitable*** to ***Suitable*** on Very Rich sites which are uncommon in the uplands. As one might expect from field experience, **Sitka spruce/ Douglas fir** mixtures are more constrained in their upland site tolerance, with Wet and Very Moist soils essentially excluded from use. For **Sitka spruce/ western hemlock** mixtures, the weighting is toward the better drained and less fertile site types with Wet and Very Rich soils both considered ***Unsuitable*** for this combination. However western hemlock has been shown to perform tolerably well in some trials on upland peaty gley and peaty podzolic sites. **Sitka spruce/ noble fir** mixtures are suitable for a narrower range of SMR (Very Moist to Fresh) to limit drought cracking risks. [see digital Figure 1 for ESC soil quality grid composites].

It is recommended that the outputs of these desk analyses using the methods of the Ecological Site Classification are considered in assessing the site suitability of potential upland mixture combinations, but are better calibrated with local site-based knowledge and field experience. Older methods of species-site suitability evaluation may also be very useful here - in particular Professor Mark Anderson's famous text "*The Selection of Tree Species*" (Anderson, 1950, 1961) which presents suggestions on future "ecological species groupings" in terms of their tolerances of soil moisture and soil fertility. This approach is very well aligned with the thinking on deployment of upland mixtures developed in this report. Caution should be exercised as regard's Anderson's original assessment of western red cedar as being suitable for use on poor, upland peats, as later evidence from the Lon Mor and other trials apparently caused Anderson second thoughts, amending the table for his second edition. "Cadman's wheel", recommending tree species combinations for upland forestry in North Wales, is also a highly relevant approach to this issue from the 1950's (Cadman, 1953). Information about the companion species presented by Wilson (2011) may also be useful.

Results: comparative height-age curve family analyses

In predicting compatibility of species in mixture it is important to consider their relative growth rates, particularly during the early period of competitive growth prior to the first thinning (where relevant). Shade tolerance alone is not a good predictor of relative early height growth and persistence under the artificial conditions of even-aged upland plantations. Major differences in relative height growth and vigour might result in suppression of the slower species, especially in the absence of timely thinning interventions on exposed sites. This in turn may influence the optimum initial stocking pattern and species ratio. At the present time we do not have quantitative silvicultural models that are ideally suited to describing the development of mixed stands of Sitka spruce and other relevant conifers in British upland conditions. Classic British stand-level yield models (e.g. Edwards and Christie, 1981), based on repeated mensuration of Permanent Sample Plots (PSPs), emphasise single-species stands. More recent stand-level modelling in Britain has mainly emphasised pure Sitka spruce. A range of individual-level models have been developed in both Europe and North America that have potential to describe stands comprised of several species and age classes. Emphasis in work by Forest Research at the present time is on calibration of the Austrian-derived MOSES model for home conditions and it is likely that this overall approach will become very relevant to yield modelling for mixtures in the future. At the present time, modelling of two-species mixed stands of the type being discussed here is best approached by comparing and combining the outputs from single-species even-aged yield models presented in Forestry Commission Booklet 48 (which is soon to be superseded by an electronic yield modelling environment) [for relevant yield models and curves see Christie and Lewis (1961); Edwards and Christie (1981); Evans and Christie (1959); Hamilton and Christie (1971); Hummell and Christie (1953)]. This approach can only be regarded as a first approximation, as it does not take explicit account of mutual interactions within mixed-species stands, whether beneficial or antagonistic (Kerr *et al*, 1992). Such interactions are likely to be most significant in intimate or single-row mixture patterns where species contact is greatest. The limited published evidence available from the p1955 spruce-hemlock mixtures trials described above suggests that hemlock initially grew more rapidly in mixture with spruce than pure, but was later stratified below the spruce canopy. The author's recent brief inspection of these trials (pending anticipated detailed publication of mensurational data by Forest Research), suggested that subordination of hemlock is now rather more severe.

An exploratory study within the present project has compared the Booklet 48 "height-age curve families" for Sitka spruce, Norway spruce, Douglas fir, western hemlock, grand fir, noble fir and western red cedar/ Lawson cypress. No models are available for Pacific silver fir, but it might be predicted that these would be intermediate between those for grand and noble firs. The "crown thinning" model families at 1.5 to 1.8m initial spacing were selected as these are the only ones available across the full set of species of interest. The differences in initial stocking between these species models may compound the comparison of growth on basal area/ volume criteria, but this is considered unlikely to significantly affect height-based comparisons under normal stocking conditions. Graphical analysis was undertaken for the first 30-40 years of growth, with supplementary consideration of optimal rotation for mutual MMAI. (Workings are appended for interest but are not intended for wider publication).

Of the species pairings considered, there appears to be rather good compatibility between **Sitka spruce and Douglas fir** and between **Sitka spruce and grand fir** on co-suitable site types. Very little adjustment is required in rotation length to optimise mutual MMAI in these cases, although there is clearly a premium market for older and larger Douglas fir which does not pertain for Sitka spruce and grand fir, so the Douglas fir component might be extended.

In the case of **Sitka spruce and Norway spruce**, although the curve families are parallel, there is a significant difference in early height-increment of these species for any given GYC, which is most pronounced for the higher GYC curves. There is an apparent difference of 12-15 years in the optimum MMAI rotation for these two species when achieving the same GYC. Clearly this will be more where the actual GYC achieved differs by one or two classes, which is typical of NFE mixed stands. Harvesting the NS at the optimum rotation of the SS component sacrifices some yield in the former, whereas retention of the SS until the optimum rotation for the NS will delay revenue and may well result in oversized material for standard markets. This would suggest that a compromise rotation might be adopted. Care also needs to be taken to ensure that the NS component is not suppressed in line-row or intimate mixtures on productive sites. Surviving examples do not provide a full picture of how mixed spruce stands on upland sites might be managed. They tend to comprise (a) well-thinned "trophy" examples on fertile valley bottom sites and (b) neglected unthinned upper-edge remnants. Some of these stands probably resulted from "beating up" of failing NS with SS.

In the cases of **Sitka spruce-western hemlock**, **Sitka spruce-noble fir** and **Sitka spruce-western red cedar** mixtures, there appear to be rather greater potential difficulties with height-age inter-compatibility for any given GYC. While early mutual shelter from the spruce component is likely to benefit hemlock and red cedar in particular (noble fir is a "tougher customer"), all of these later-successional species struggle to make equivalent height growth to SS during the first half of the rotation, which may even imperil companion survival. On open upland sites, this results both from a "slow start" before the Booklet 48 models even commence, and from a "tailing off" of height-growth after the first 25 years or so. There are significant differences in optimal MMAI rotation length even where GYC is equivalent, whereas there is usually a one or two GYC class penalty. The most severe effects are evident in stands on better (higher GYC) sites. Once over-topped by any significant distance, the weaker component may "go under" silviculturally. While noble fir appears able to maintain itself by virtue of a stiff and robust crown architecture, hemlock and red cedar are less so. To maintain equivalence of these species with SS in a final crop mixture, it may become essential to ensure that preferential thinning commences early (possible in advance of the yield table recommended age - e.g. at 15-17 years rather than 18-20 years). Where that is not likely to be possible for reasons of access or instability, an alternative approach might involve favouring the slower-growing species in the initial mixture at 2:1 or 3:1 ratios. Intimate mixtures are likely to be less operable in such cases than are line-row or mosaic patterns. Delayed planting of the Sitka spruce component in row mixtures might work silviculturally, but is generally prohibitive in terms of operational costs and re-entry weed-control logistics. Once mixed stands of these species are well established, it may become possible to operate them on a multi-canopy basis with fir, hemlock or cedar stratified below the spruce.

The behaviour of **Sitka spruce-Pacific silver fir** mixtures is untested in British forests but might be regarded as comparable with that of **Sitka spruce-noble fir**, rather than that of **Sitka spruce-grand fir**, especially when deployed on exposed and infertile upland site types.

An similar exploratory attempt was made to compare the cumulative production volume v age curves for the various companion species with Sitka spruce. (Workings are appended for interest but are not intended for wider publication). Cumulative volume (as the product of top height and basal area - reflecting biomass accumulation), especially prior to the first thinning, might be regarded as a better indication of vigour and site capture than is top height. Here it appears to be the **Sitka spruce/ Douglas fir** and **Sitka spruce/ western hemlock** mixture combinations that display the best "silvicultural match" in terms of site occupancy. For the other four combinations examined, Sitka spruce appears to achieve the earlier site capture.

Results: comparative site-yield analyses

This section of work sought to examine how the yield performance (in terms of predicted GYC) of the potential companion species might compare with that of Sitka spruce on similar sites. This will allow growers to evaluate any potential yield penalty in return for resilience. The body of evidence used was the predicted GYC data for relevant species components in all sub-compartments on the National Forest Estate where Sitka spruce occupies at least 20% of the area and one of Norway spruce, Douglas fir, western hemlock, grand fir, noble fir or western red cedar also occupies at least 20% of the area. Tertiary components were ignored. For stands less than ten years old, predicted GYC is based on site quality, whereas for many older stands, basic tariff measure is captured by forest district staff on an occasional basis. This overall dataset combines blocky, row, intimate and undefined mixture structures. A rather small proportion are of the close line-row and intimate structure types and comparison of yield based on these alone might be unreliable. While climatic conditions can sensibly be regarded as uniform across species components within sub-compartments, this simplification brings with it the problem of possible differences in soil characteristics, having guided species choice in blocky examples. This is more likely to apply to older examples where "Andersonian" care and attention to vegetation-based species-site matching within sub-compartments was sometimes pursued at time of planting. It is very unlikely to be a systematic (as opposed to accidental) issue for stands less than 45-50 years old. For some of the stands of interest, basic Forestry Commission soil mapping GIS overlays are available, potentially allowing some "split soil" sub-compartments to be "knocked out" of the analyses. An attempt was made to examine its effect on the comparator datasets within the present study, but this was defeated by a low level of spatial correspondence (10%) of mixed stands and soil mapping data. In the main, an *a priori* stratification of the datasets by predicted Sitka spruce GYC will therefore have to stand as a surrogate for climatic and soil conditions.

Forestry Commission Bulletin 49 (Aldhous and Low, 1974) is relevant here as their studies compared pure stands of Sitka spruce, western red cedar, western hemlock, grand fir and noble fir growing on comparable sites across Britain. They did not generally study mixtures directly. However many of the sets of older (p1920-1960) comparator stands that were available to those authors in the early 1970's have since been felled or windblown. As alternative conifers were more widely planted during that earlier period, these were useful examples to study. The typical metric yield class of Sitka spruce on comparator sites considered in Bulletin 49 was GYC 16, whereas in the present study it has been GYC 15.5. This modest difference reflects the wider range of sites considered within the present study, including numerous upland examples of the SS/NS mixture combination. By contrast, at the time of Bulletin 49, the typical SS GYC across the National Forest Estate was around GYC 12 whereas it is now around GYC 14. That difference reflects the adoption of selectively improved Sitka spruce planting stocks. For the other four "minor conifer" species studied for Bulletin 49, Aldhous and Low (1974) generally reported local production yields (LYC) exceeding those of Sitka spruce on the same site types. Their findings can be summarised as:-

For **Sitka spruce and grand fir**: GF LYC = 0.80 + 1.19 x SS LYC.

For **Sitka spruce and noble fir**: NF LYC = 11.85 + 0.42 x SS LYC

For **Sitka spruce and western hemlock**: WH LYC = 8.38 + 0.60 x SS LYC

For **Sitka spruce and western red cedar**: RC LYC = 21.4 - 0.14 x SS LYC

Comparisons between **Sitka spruce and Norway spruce** and between **Sitka spruce and Douglas fir** were not presented, although these were compared with the four minor species.

These authors did provide commentary that comparisons for **Sitka spruce and grand fir** were only available for sites with SS GYC in excess of 14. On low productivity sites these species tended to grow at similar rates, but the advantage of grand fir increased with site quality. For **Sitka spruce and noble fir** the noble fir outperformed Sitka spruce on two-thirds of sites by between 1-3 YC, but with no obvious pattern with site quality. For **Sitka spruce and western hemlock** there was a slight advantage in favour of the western hemlock, although this disappeared on more exposed sites, where Sitka spruce took the advantage. For **Sitka spruce and western red cedar** there was a less consistent picture, but the spruce again tended to perform better on sites at higher elevations (>275m for England and Wales and >150m for Scotland).

Results from the present analyses are detailed in the digital appendices. By contrast with the earlier findings by Aldhous and Low (1974) in FC Bulletin 49, there almost always appears to be a lower site-yield predicted for the companion species than for Sitka spruce. This may in part reflect the competitive pressure exerted by the spruce within mixed stands. The yield penalty for a 1:1 mixture appears to be of the order 4-8% for SS/NS, SS/DF, SS/NF, SS/RC combinations but much smaller and less certain for SS/WH and weakly positive for SS/GF. As in the case of FC Bulletin 49, stands available for such species and mixture comparisons do tend to be on sites with above average yield potential for Sitka spruce, as compared to its overall expectation across the National Forest Estate. In stands with predicted GYC for Sitka spruce of GYC 10 or below, the companion performance becomes variable and erratic. These analyses cannot capture any mutual interactions that might occur in close mixtures. Some adjustment for dry matter density might be relevant here, especially for SS/GF, SS/NF. That could be pursued using kiln-dry timber densities reported by Ramsey and Macdonald (2013).

It should be borne in mind that the Sitka spruce material deployed within the established examples included in comparative analyses considered both by Bulletin 49 and the present study will overwhelmingly remain of the standard unimproved Queen Charlotte Island or similar provenances. Some younger stands may embody selectively improved seed orchard or vegetatively propagated Sitka spruce planting stock. Given the challenges identified above with reconciling initial rates of growth and MMAI for most species combinations involved, there would appear to be rather little advantage in deploying expensive improved Sitka spruce planting stock in such mixtures, and it may even accentuate these issues. Standard QCI material would therefore appear to be the more logical choice at present.

Information and advice: ecological analogues for British upland spruce mixtures

An important factor that should be considered in connection with potential deployment of mixed stands, containing Sitka spruce, in the British uplands is the extent to which these find support from natural ecological "analogues" overseas. It is not possible to identify relevant ecological analogues within the British Isles, due to the local extirpation of the previously native European spruce, fir and hemlock species during the cycle of Pleistocene glaciations. *Tsuga* and *Pseudotsuga* were similarly extirpated from the whole of western Eurasia, with *Picea* and *Abies* each being reduced to one main representative species in western Europe. Prior to these severe climatic impacts, mixed coniferous forests of the types found today in the Pacific Northwest did occur in Europe, and very probably occurred in upland Britain.

Ecological analogues in this context are of particular value in suggesting the ability of stand types, initially established by planting, to perpetuate themselves by natural regeneration as durable, silviculturally compatible assemblages. Such ability depends on several factors, including (a) long-term relationships between tree species, litter decomposition and soil nutrient cycling and (b) stand dynamic and silvicultural interactions between species in terms of relative shade tolerance at the seedling stage, mutual facilitation and competition traits. A number of forestry authors over the years have suggested that long-term adherence to monocultural stands of Sitka spruce is undesirable and may have long-term consequences in terms of soil sustainability. Having said this, very little relevant research has been undertaken in Britain as to the implications for soil development of different combinations of evergreen plantation conifers. Where the aspiration is to employ alternative/ non-clearfell silvicultural systems, there are clear advantages in deploying a suite of species of varying shade tolerance.

Early workers in British upland forestry often favoured mixed stands to reduce the risk of complete failures in an environment where species' ecological tolerances were poorly understood. Also, there was in some cases an aspiration to emulate natural forest types seen on the "Grand Tour" in alpine Europe or on "plant hunting" expeditions in North America. By the early 1950's Professor Mark Anderson at the University of Edinburgh was advocating that plantation forests in more sheltered sub-oceanic areas such as the Tweed Valley could be managed towards the natural ecological analogue of the European montane forests of Norway spruce-European silver fir-beech, which are the main producers of timber in areas such as the French/ Swiss Jura, the Black Forest of Germany and similar forests in the Czech republic. Such forests are typically managed silviculturally using variants of the selection systems. Such aspirations were largely defeated in Britain by a combination of the exposed climate, excessive deer browsing and lack of natural regeneration in fir and beech, coupled with resistance in the forestry profession to move away from the emerging dominant "Sitka spruce model" in favour of an alternative silvicultural model that implied higher management costs.

A "second line of attack" in terms of naturalising the future development of British upland plantations was to accept Sitka spruce, and begin to add in later-successional companion species from the Pacific Northwest forests, by a process of enrichment. This approach was particularly encouraged by insights from W.R. Day and R.F. Wood who both toured these forests during the 1950's, leading to the publication of the seminal FC Bulletins 25 and 28. The forests of the Pacific Northwest run north from San Francisco to Alaska and stretch inland for several hundred miles into the montane and sub-alpine ranges (e.g. Cascades). These forests contain a wide range of complex stand types determined by a combination of climate, site factors and disturbance regimes/ patterns (natural and anthropogenic). These have been recorded and described in detail by Krajina and Klinka at Vancouver over the past six decades, leading to the development of the British Columbia Biogeoclimatic Ecosystem Classification (BEC) which was a guiding influence on development of the FC ESC scheme.

Similar understandings have been developed for the forests of Washington and Oregon. Several key aspects from these forests should be considered in the present context:-

- Sitka spruce and Douglas fir are considered medium tolerant, early-mid successional species that respond to disturbance, while western hemlock, western red cedar and *Abies* firs are considered shade tolerant, later successional climax species that gain dominance through a lack of disturbance. The position for noble fir is less resolved.

- Sitka spruce has a very wide distribution in latitude, running from Northern California to southern Alaska, but a narrow distribution in terms of distance from the sea. Its inland penetration reduces markedly as one travels southwards due to moisture deficit.

- Douglas fir as a component of coastal forests has a very much shorter extension northwards, running out essentially at 51^{O}N, level with the top of Vancouver Island. It is not present at the latitudes equivalent to upland British conditions (54-57^{O}C) which cover the Queen Charlotte Islands. However its range extends much further inland, to encompass much drier, more continental areas and parts of the Rocky Mountains. It has a variety of distinct genotypes/ sub-species that permit this much wider tolerance.

- Western hemlock has a very similar latitudinal range to Sitka spruce, running out with it in southern Alaska, but also extends further inland in a similar way to Douglas fir. Hence in the coastal forests north from California, western hemlock will essentially grow anywhere that any of the other species considered here will grow - it is the "constant companion" and we must consider that when thinking about our forestry.

- Grand fir has a much truncated latitudinal distribution, as with Douglas fir stopping short at 51^{O}N, level with the top of Vancouver Island. However in this more southern range it can extend inland to a considerable degree as with western hemlock. Grand fir is regarded as having considerably more demanding tastes in terms of soils than any of the other species considered here, only favouring moister, more fertile sites.

- Noble fir has a very much more restricted range in both latitudinal and continentality terms. It is not found in British Columbia to any extent and is essentially a species of the Washington and Oregon Cascades. Within that smaller range it is a conjoiner with Douglas fir, western hemlock, western red cedar and grand fir, but rarely with Sitka.

- Western red cedar has a range closely matching that of western hemlock other than that it runs out northwards at 57^{O}N (halfway between the northern limits of Douglas fir/ Grand fir and of Sitka spruce/ western hemlock) and level with N. Scotland.

- Pacific silver fir is less well mapped but appears to run out at about 53-55^{O}N and does not take in the Queen Charlotte Islands. In those areas where it operates in association with Sitka spruce and Douglas fir, it appears to come in "higher on the hill" and possibly on poorer, more degraded soils. This may be significant for our use of it.

- In forests north of 55^{O}N, Sitka spruce and western hemlock are the co-dominants, with some minor companions such as Nootka cypress/ Yellow cedar. Pure stands of Sitka spruce are found here, but are considered to be successional/ transitional. Western red cedar joins into the mix in the latitudinal band between 53 and 55^{O}N.

- In oceanic forests between 46 and 51^{O}N species composition is mediated by climate, elevation and soils but also by time since the last major disturbance. On favourable sites Sitka spruce and Douglas fir a dominant pioneers after disturbance, with western hemlock, western red cedar, grand and Pacific silver firs coming in later to climax. Stands dominated by Sitka spruce can persist on specialist sites, e.g. on alluvial land.

- The beneficial influence of the Gulf Stream in Britain is equivalent to roughly six latitudinal degrees, allowing Douglas fir and western red cedar to persist beyond Bristol, northwards to Inverness. Pacific silver fir would be expected to behave likewise, although it has apparently not been widely tested north of Argyll (56^{O}N). Noble fir appears to have achieved an even greater climatic benefit from our moving it from America to Britain and "down the hill" at the same time. It performs well in Glen Urquhart at 57^{O}N whereas its northernmost American station is at 47-48^{O}N.

In evaluating the import of this information from these European and Pacific Northwest ecological analogues, we must also consider the impact of the more aggressive wind regime in upland Britain, and the possibility of differential soil history and conditions today. Hence:-

- It is unlikely that we can learn very much more from nature as to the effective range of the **Sitka spruce/ Norway spruce** mixture. Observations made in Britain, together with those from Ireland and Denmark, are likely to represent the sum of knowledge.

- For the **Sitka spruce/ Douglas fir** mixture we should expect that, under most British upland conditions, it will usually be the tolerances of the Douglas fir component that will confine the mixture to the more favourable part of the Sitka spruce site range. There may be some situations in eastern Britain where moisture deficit makes Sitka spruce the binding species - i.e. we are trying to push it too far "inland" ecologically. Extreme eastern coastal sites such as Kirkhill, Aberdeen and Kyloe, Berwickshire may have this constraint relieved by occult precipitation from sea mist or "haar".

- We should expect the **Sitka spruce/ western hemlock** combination to be one that would be relevant to most or all of the productive Sitka spruce range in the British Isles on purely climatic/ photoperiodic grounds. However the dislike of western hemlock for exposure and peaty soils will constrain it from the worst of Sitka sites. Whether there are any situations in Britain which are within the tolerance of western hemlock and outside the tolerance of Sitka spruce (e.g. on moisture deficit grounds) is uncertain, and requires further testing by trials. Both species have performed well with 600m rainfall at Weasenham, Norfolk, albeit with atypical selection silviculture.

- The situation for the **Sitka spruce/ western red cedar** combination is probably intermediate between those for mixtures with Douglas fir and western hemlock above. Usually it will be the greater demands of western red cedar in terms of shelter and soils that determine the envelope for the mixture under upland conditions, but there may be situations in the east where the greater moisture demand of Sitka is binding.

- We should expect the **Sitka spruce/ grand fir** combination to be one that is always constrained by the site requirements of grand fir as the more demanding component.

- We are on less certain ground when considering the **Sitka spruce/ noble fir** combination due to the lack of any extensive natural ecological analogue. The likelihood is that their tolerances are effectively coincident for practical purposes, with the exception that noble fir will be less tolerant of peaty and very poor soils. There are suggestions that increasing moisture deficits under predicted climatic change may catch noble fir earlier due to its propensity for more rapid stem cracking. Pacific silver fir may be slightly hardier than noble on peaty soil, softer on exposure.

Information and advice: formation of upland mixed stands including Sitka spruce

Productive mixed coniferous stands, including Sitka spruce as an important element, can be formed on upland forestry sites by following one of four main silvicultural pathways:-

1. Deliberate establishment of even-aged mixtures by planting

   This is the method that is generally associated in most upland foresters' minds with establishment of mixtures at the time of original establishment and subsequent restocking of plantation sub-compartments. Mixtures can be arranged on mosaic, row/ line or intimate patterns. This approach was applied in some first rotation plantations established between, roughly, 1910 and 1965, rather less so since. Initial stocking densities are similar to those that would be applied to pure Sitka spruce - today this would be 2500-3100 stems/ha, but some early examples had closer spacing, with 4000-5000 stems/ha. Mixtures of this type have typically been managed on the clearfell-restock system, with many examples remaining unthinned, or at least under-thinned, throughout the rotation.

2. Spontaneous establishment of even-aged mixtures by natural regeneration

   This situation is becoming much more important as many plantations reach the end of the first rotation, containing stands of a variety of conifer species that are producing seed. Hence more mature pre-war forests in areas such as the Great Glen, Argyll, the Borders, Cumbria and Snowdonia contain many relevant examples. Typically, a sub-compartment will be clear-felled and a "sea" of natural regeneration will quickly colonise the site from neighbouring stands, retained for a period of up to seven years under restructuring proposals within design plans. Some seed may also be deposited by the felled trees, or there may be advance regeneration already in place, especially of heavier shade bearers. The initial stocking can contain any combination of the conifer tree species of interest - typically Sitka spruce and western hemlock, with more local Douglas and *Abies* firs. Initial stocking densities tend to be higher than in planted mixtures - often >10,000 st/ha. In some cases, one species is planted and the others quickly infill by natural regeneration.

3. Enrichment by intruded natural regeneration

   These examples typically arise where a well-thinned, mature, even-aged stand of one conifer species is colonised by advance natural regeneration of one or more other conifer species. This typically occurs in more mature plantations of the type discussed under 2. above, particularly those on more sheltered sites where thinning has been pursued. In many cases the "receiving stand" is of mature Douglas fir or Norway spruce and the colonising species is Sitka spruce and/ or western hemlock/ *Abies* firs, which begin to regenerate earlier. A smaller number of examples involve a "receiving stand" of Sitka spruce being colonised by western hemlock/ *Abies* firs. Such stands are usually well suited to ongoing management under alternative/ uneven-aged silvicultural systems.

4. Enrichment by under/inter-planting

   These are "special cases" where the second and subsequent conifers are deliberately introduced once the first has been established. Pre-war examples were predominantly under-stocked stands of Norway spruce and Douglas fir to which Sitka spruce was added as a more robust option in the "reinforcement planting" process known as "beating up". More recent examples tend to be "enrichment plantings" of alternative shade tolerant conifers such as western red cedar, Norway spruce and Douglas fir into Sitka spruce stands following suitable preparatory thinnings - often as part of silvicultural conversion.

Information and advice: spatial patterns in upland mixed stands including Sitka spruce

Productive mixed coniferous stands, including Sitka spruce as an important element, can be formed on upland forestry sites with one of four main spatial patterns/ arrangements:-

1. Blocky

   The blocky pattern represents "co-deployment" of conifer species within a single sub-compartment rather than any true silvicultural mixture and is the most commonly encountered. The blocks comprise small stands of single species, often reflecting local soil conditions in many forests established prior to around 1965 (e.g. on "Andersonian" principles). The blocky pattern differs from the mosaic pattern in that separate identity/ silvicultural management of the blocks remains feasible - hence they will typically exceed 0.2ha. The advantages of the blocky pattern are relative simplicity of silvicultural management, as felling ages can differ, but at the expense of resilience, as failure of one species will typically leave the sub-compartment poorly stocked without reestablishment.

2. Mosaic

   The mosaic pattern often involves planting species in initial groups or clusters which are generally not intended to form permanent features of the stand structure. Mosaic patterns can also form through natural regeneration processes. The mosaic pattern lies between the blocky and the intimate patterns. Groups will typically be less than 0.2ha in extent but initially should have some "central trees" which only experience competition from the same species. The mosaic pattern may converge on the intimate pattern as the stand develops, especially with selective early thinning and mortality. While regimented forms of the mosaic pattern can be found, most examples involve the planting of groups of one species within a matrix of another on a "plum pudding" basis. The advantages of the mosaic pattern are (a) the ability to differentiate competition and silviculture during the early life of the stand, potentially protecting slower-grown species and (b) the fact that failure of one species will typically only result in moderate/ mild understocking. Stands established on the mosaic pattern typically have a naturalistic landscape appearance and the pattern offers a suitable basis for the establishment of stands that are to be managed on a perpetuated basis under alternative, non-clearfell silvicultural systems. The main disadvantage is that in final clearfell systems, a rotational compromise is often required.

3. Line/row

   The line/ row pattern is an artificial formalised arrangement of alternating rows of each species which can/will persist throughout the life of the stand, although becoming less distinct as the stand matures, especially if well thinned. In 1:1 (50%) mixtures these will usually comprise single rows of each species, whereas in 2:1 or 3:1 mixtures one might find a pattern, for example of 3 rows of western hemlock to 1 row of Sitka spruce or similar. The decision to favour one species, in the initial stocking chosen, may be on the basis that it is the more desirable in terms of timber value or that it is less competitive/ slower grown and needs assistance, especially during the earlier years. The choice of ratio at establishment should therefore be based on the target composition at final felling. Where one species is much less competitive than the other, a 3:1 arrangement may be required to ensure that there is a "defended" central row of that species which does not feel early competition from the more aggressive species. Line/ row patterns have been favoured as they allow fairly convenient visual monitoring of the relative performance of species and some opportunity to intervene by systematic thinning, either to preserve the mixture to final felling age or to selectively favour one of the species, preferred to form the final crop. They can also be suitable for adverse upland situations where a non-thin/ clearfell regime is required. Resilience can be quite strong, as failure of one species, at least during the earlier part of the rotation, will typically allow adjoining rows of another species to "take up the space", avoiding, or at least limiting, understocking at final rotation. Clearly where there is a difference in timber value between species, this may not lead to economic equivalence in final out-turn. The major disadvantage of line/row patterns in mixtures is their artificiality in landscape appearance (the "zebra pattern"), especially on more visually prominent upland sites. Line/ row patterns would generally not be preferred for formation of stands intended to be managed under alternative/ non-clearfell silvicultural regimes, but if that decision is taken later in the life of a stand of this type, conversion is possible by means of suitable "naturalisation" thinning strategies.

4. Intimate

The intimate mixture pattern would ideally feature a randomised spatial assortment of the species involved without any obvious structure. At the time of stand establishment, this is most commonly found in natural regeneration and has rarely been attempted as a deliberate planting pattern - it is actually very difficult to achieve thereby. Regular spatial planting arrangements that represent an approximation to, or simulation of, this ideal model include those where species are alternated within planting rows. Aggregations of individual species can occur, but typically would not include "protected" central trees. As such stands develop biologically and are thinned, the randomising effect of individual phenotypic performance may push the stand closer to the ideal random arrangement. Many stands described on sub-compartment records as being intimate mixtures were not planned as such, being rather accidental assortments resulting from later stand development. Deliberate intimate pattern mixtures should only be considered where the species being deployed are highly silviculturally compatible from the outset, as differential/ defensive thinning is generally impractical until the stand is more mature and selection can begin. Where such silvicultural compatibility is established, intimate mixtures can be highly resilient as even late loss of one component can be compensated. Intimate mixtures can also be highly suitable for the establishment of stands expected to be tended under alternative/ non-clearfell silvicultural systems on more accessible sites. Most forest managers are likely to be deterred from this pattern of mixture by the perceived complexity in management, particularly in segregation of final crop products.

Information and advice: silviculture of upland mixed stands including Sitka spruce

A common perception is that upland mixed stands are more complex and/ or costly to manage than conventional even-aged stands of pure Sitka spruce. While this is not always the case, there are a range of factors which potential adopters of this model of management need to consider in relation to their specific objectives of management and site conditions:-

Site assessment

Greater attention needs to be given to accurate evaluation and classification of the site prior to attempted establishment of mixed stands, as the range of climatic and edaphic conditions under which they will perform well may differ from the tolerances of pure Sitka spruce. The Forestry Commission Ecological Site Classification (ESC) provides a suitable framework for making such evaluations, but requires careful survey and recording of site/ soil conditions. Generally, the greatest likelihood of success will arise where all species are currently, and are predicted by ESC to remain, ***Suitable*** or ***Very Suitable*** throughout the intended rotation. Where one species is currently, or is predicted by ESC to become, ***Marginal***, more careful consideration is then required. It is accepted that some growers in eastern Britain may well wish to plant such mixtures on the "climatic insurance" principle - for example combining Sitka spruce with Douglas fir or western red cedar to "buffer" against future drought damage to the Sitka spruce component, which might have to be harvested in advance of MMAI. Factors that must be considered here include the severity and timescale of predicted threats to the more drought-prone species, the risk that it may become vulnerable to pests or pathogens if operated under climatic stress, operational feasibility of thinning/ early partial harvest and potential understocking of the sub-compartment for the remainder of the crop rotation. Establishment of mixtures where any component is currently, or is predicted by ESC to become, ***Unsuitable***, or where all components are or will become ***Marginal***, is inadvisable.

Establishment, protection and early tending

Here again, a more careful approach is likely to be required than for the establishment of pure stands of Sitka spruce, in order to maximise the chances of success. Some potential companion species dealt with in this report, notably European and Pacific silver firs, may be less available and more expensive to obtain from nurseries than the more common conifers, and may well need to be ordered further in advance under "contract growing" arrangements.

Most of the potential companion species are much more palatable to deer browsing than Sitka spruce, and will necessitate much greater attention to deer control or exclusion measures. Unlike in the standard case of pure upland Sitka spruce crops, the assumption must be that all planting and restocking sites, using the mixtures approach discussed here, will need to be defended by 2m perimeter deer fencing unless unusually effective deer control by culling is, and can be guaranteed to remain, in place. Failure of deer control can result in rapid preferential browsing of the more palatable companion species, with effective convergence onto a stand of pure Sitka spruce. Some variation is encountered between the potential companion species in terms of their susceptibility to residual site pests and pathogens, including *Heterobasidion/ Phomes* and *Hylobius*, which must be appropriately considered.

Many of the potential companion species are much less suitable for establishment on exposed upland sites without "side shelter" - this is certainly so for Douglas fir and western red cedar/ Japanese red cedar, rather less so for Norway spruce, western hemlock, European silver fir and grand fir and noticeably less so for noble fir and Pacific silver fir. This should be taken into account in selecting potential companion species to Sitka spruce in relation to the site conditions, with emphasis on the height, arrangement and prognosis for adjoining stands. Again, inadequate consideration of exposure may result in failure of the companion species. More sensitive species such as the two red cedars should only be considered where there is considerable silvicultural shelter in place for the early part of the rotation, which will often be most effectively secured under ongoing alternative/ non-clearfell silvicultural systems. Experimental stands comprising line mixtures of Sitka spruce and western hemlock have shown that western hemlock experiences some early benefit from mutual shelter from spruce, before beginning to suffer from over-competition as differential height growth takes effect. However this approach is only likely to be able to be effectively exploited where later selective thinning is possible, releasing the competition to protect the slower species. Elsewhere it may be possible to provide early shelter, on otherwise exposed sites, by pre-establishing a "sacrificial" matrix nurse crop on the site, for example of birch and aspen.

Competition from weeds (whether heather, grass or soft herbs) can be more of a problem for many of the potential companion species than for Sitka spruce, which makes earlier growth. Western hemlock and *Abies* firs typically grow more slowly at first and can succumb to strong weed competition, again directing stand composition towards pure Sitka spruce. It may be necessary to give extra attention to effective weed control at establishment and later cleaning of mixed stands, especially where there has been a long *Hylobius* fallow period.

Thinning

Mixtures of Sitka spruce with the various companion conifers considered in this report are suitable for operation under non-thin/ clearfell, standard regular thin/ clearfell and alternative/ non-clearfell silvicultural systems. The choice between these modes of management, as in pure spruce stands, will be determined by a combination of site conditions, exposure, access, available skills and machinery, owner priorities and economic considerations. As compared with pure stands of Sitka spruce, thinning in mixed stands has an added function of regulating and directing species composition alongside its established functions of basal area regulation, form improvement and revenue generation. Generally there will be one or more species that require specific attention in thinning operations intended to regulate competition and preserve the intended mixture ratio. In current British upland conditions, it will almost always be the Sitka spruce component that is the strongest competitor during the early life of the stand, with companion species requiring silvicultural assistance. Under some predicted future climatic conditions, and as mixed species stands mature biologically, more drought and shade tolerant species such as western hemlock and western red cedar may "come to the fore", so that retention of Sitka spruce and Douglas fir components predicates intervention. In situations where thinning will be impractical on grounds of access or instability, it may be necessary to "lock in" a silvicultural advantage for the slower grown companion species by favouring it in the mixture ratio and spatial arrangement, to secure the desired final ratio. Where standard thinning is feasible, the conventional pattern of early systematic and later selective/ crown thinnings will remain relevant, whether the aim is a uniform crop for clearfelling or to prepare stands for perpetuation under alternative silvicultural systems. There may however be a need to ensure that earlier thinning interventions address the silvicultural requirements of slower grown mixture components by selection on species, if not on form, while later interventions will embody the decisions made on retention or early harvest of each component. Use of a suitable stand enumeration/ monitoring protocol such as that set out in Forestry Commission Information Note 45, may be essential in assessing relative growth. More sheltered, mature stands that reach the intended rotation age while retaining a component of shade tolerant companion species should almost always be considered for default adoption of alternative/ non-clearfell silviculture of the group/ irregular selection type.

Information and advice: comparative timber properties of companion species

An important factor for many growers considering adoption of upland mixed stands containing Sitka spruce and alternative conifer species will be the implications for quantities and market value of timber products. Most growers will wish to limit any value penalty. Three main factors must be considered here - (a) what are the inherent properties and values of the timbers of the companion species as compared to Sitka spruce, (b) how might these be manifested in timber grown in British upland mixed stands together with Sitka spruce and (c) what effect will the operation of mixed stands have on the Sitka spruce timber co-produced. To address these questions it is necessary to combine information collated from the native ranges of the tree species involved (i.e. from mature natural timber) and information from previous studies of timber grown in the different conditions of British plantation forestry. The former source of information is extensive and established, but can only be applied with very great care to British conditions, whereas the latter source of information is directly applicable but largely limited to Sitka spruce grown under even-aged monocultural conditions. Domestic information for the companion species and for mixed-species stands is currently inadequate. The available comparative information has been collated by Ramsay and Macdonald (2013). The term “unit value penalty” is used below to refer to timber value per unit weight/ volume. The issue of relative volumes of timber produced by companion species is addressed above.

Spruce

Sitka spruce timber has established volume markets in Britain from which achievable values vary, but are well understood. The markets for Sitka spruce sawlogs (as opposed to small roundwood) are primarily for what is known as “European whitewood” commodity timber meeting the C16 structural stress grade. This is a specification for short-span, limited load-bearing construction uses (e.g. carcassing, house framing kits etc.). There is also a market for similar timber meeting the C24 and higher structural stress grades, for medium and long-span load-bearing uses, but currently a very small proportion home-grown spruce meets such standards due mainly to the immature age of typical harvest and the growing conditions. The species that supply the equivalent markets in mainland Europe are Norway spruce and European silver fir, with the latter generally only comprising a minority of timber packs. Of the companion species discussed here, there is little unit value penalty with Norway spruce.

Douglas fir

Douglas fir is also a species with relatively well established domestic markets in Britain, which actually developed earlier than those for Sitka spruce timber. Good quality, pre-war Douglas fir, grown to rotation ages of 70-90 years and breast-height diameter of 70-90cm, is a premium product which primarily addresses specialist C24 and higher structural markets. This type of material cannot typically be grown on exposed upland plantation forestry sites. Based on North American experience, timber from younger Douglas fir should be able to address commodity C16 structural applications alongside Sitka and Norway spruce of similar age. However there is a lack of confidence in the quality of such post-war Douglas fir grown on upland sites, and it can fail to attract equivalent market values to spruce whitewood. This is likely to be a product of inferior provenance choice, early tending and stand silviculture. At present Douglas fir can be stress-graded either mechanically or visually in British mills. Hence Douglas fir represents an intermediate position where there might well be a unit value penalty under certain circumstances, depending on site quality and stand management.

Western hemlock and the *Abies* firs

These are species which can achieve spruce equivalent or near spruce equivalent unit values when grown in their native ranges but do not achieve these unit values in Britain, as yet. We have seen that European silver fir of suitable quality is regarded as European whitewood on an equivalent basis to Norway spruce in Germany, France, Austria, Czech and similar. Little timber of this species has been processed in Britain over the past century, and that which has is atypical of material that might be produced in upland spruce-fir plantations in future. In the Pacific Northwest, the timbers of western hemlock and the various *Abies* firs are marketed as elements of either "spruce-hem-fir" or "hem-fir" lumber categories. These are general purpose interior carpentry and light-construction timbers for short-span applications. They are therefore fulfilling a role that is similar to that for which British Sitka spruce is used. However it must be recognised that this timber is being cut from much older natural forest material that has grown up under the competitive conditions of mature forest stands. This is likely to have very significant effects on growth rate and strength properties of these species. Material of these species that is harvested from British upland plantations is considered very much inferior to that of Sitka spruce from the same site conditions, and is rarely stress graded for commodity structural applications. As a result, no mechanical stress grading is available. Commonly cited defects are fluting and included bark in western hemlock, with low density, brittle fracture and drought-cracking in grand and noble firs (no Pacific fir is processed). These are likely to be a product of ineffective provenance choice, early tending and stand silviculture. Certainly western hemlock is a timber whose inherent properties would be considered comparable to spruce and Douglas fir in the Pacific Northwest trade, the *Abies* firs being thought inherently weaker. Most home-grown material of these species addresses secondary markets such as treated fencing, box and pallet manufacturing, chipwood and industrial biomass, which attract lower values. Alternative constructional applications that do not require bending strength have been proposed and are under development, including massive timber and cross-laminated elements. European silver fir is used for these applications in Germany and Austria, and domestic development of similar outlets could considerably increase the demand level for, and unit values recovered for, *Abies* species. At present, however, western hemlock and the *Abies* firs carry a significant unit value penalty.

Western red cedar, Japanese red cedar and Lawson cypress

These timber address a different market segment to Sitka spruce, namely durable or semi-durable cladding and external carpentry timbers. They are therefore alternatives to larch. However the best material for these purposes is harvested from older stands grown on lowland estate site types, which can accumulate a greater proportion of durable heartwood. Such material can achieve unit values at least equivalent to good spruce or intermediate to premium Douglas fir. However, younger "sapwood" crops from upland site types are rarely brought forward for these markets and unit values are likely to be much lower, more similar to those available for western hemlock and *Abies* firs at the present time. Generally these species require a separate specialist processing chain which is absent from the uplands. At present, therefore, western red cedar would carry an uncertain/ serious unit value penalty.

Effects on timber properties growth under the upland mixture model proposed

Detailed studies of conifer timber properties in relation to silviculture in Britain have been overwhelmingly focussed on pure even-aged crops of Sitka spruce, and to a very much lesser extent Scots pine, Corsican pine, larch and Douglas fir. Until very recently, the other companion conifer species discussed in this report had received very limited wood science attention. Recently a PhD study has commenced at Edinburgh Napier University to study relationships between site, silviculture and timber properties in Norway spruce, western red cedar, western hemlock and noble fir, the results of which are likely to be of considerable interest. Studies of this type are inevitably constrained by available field stands to study.

There have as yet been no reported systematic studies of timber products produced from British upland stands comprising close mixtures of Sitka spruce with shade tolerant conifers. This is largely because there are so few suitable exemplar stands from which to harvest billet material for timber testing and those that do exist are often silviculturally suboptimal. This is an area which should certainly be prioritised in future research and development planning.

Conventional forestry thinking would hold that timber quality tends to benefit from slower, more steady growth rates, achieved under conditions of natural stand competition. This is (a) due to the reduction of the percentage of timber allocated to a juvenile core, which is of lower density and more adverse grain angle, (b) to the suppression of lower branching by the "cleaning" or natural pruning effect and (c) to the reduction of stem taper by "draw-up". These stem improvement effects are often proposed as being most pronounced in later-successional/ shade bearing tree species such as western hemlock and *Abies* firs which are not well adapted to early growth under conditions of full lighting, and may grow abnormally rapidly in stands with standard plantation stocking densities (Cameron and Mason, 2013).

There have however been two strands of domestic research which may be of some tangential relevance here. Firstly, work examining the impacts of operation of Sitka spruce nursing mixtures with pine and spruce on spruce timber quality (Cameron and Watson, 2000; Watson and Cameron, 1995). This work tended to suggest that timber quality suffered in the spruce component where the nursing companion was less able to "hold its own", thereby creating under-occupancy circumstances within which the spruce became heavily branched with wider annual rings. Japanese larch was the most deleterious companion, followed by Scots pine, with lodgepole pine offering the best nurse from a spruce timber quality perspective. These observations might have some relevance to a situation where a mixture of Sitka spruce with, say western hemlock or western red cedar resulted in fairly early suppression of the latter. However a fundamental difference is the greater shade tolerance of these companions which might well allow them to persist as a stratified sub-canopy for some time, cleaning the spruce stems and maintaining steady expansion of the latter. This is the observation that appears to emerge from those few domestic examples that we do have (Cameron and Mason, 2013) and from the Pacific Northwest (Erickson and Harrington, 2009; Deal *et al*, 1991; Hardcombe, 1986; McLennan, 2005; Newton and Cole, 2012; Wierman and Oliver, 1979; Wood, 1955). In any situation where the companion keeps up reasonably with the spruce component, we have no reason to expect a different pattern of timber properties than from pure spruce. The potential effects on the timber properties of the companion species have seen very little study.

The other relevant strand of domestic work is with relation to the impact of transformation to alternative silvicultural systems on timber properties (principally by Macdonald and Hubert, 2002; Macdonald *et al*, 2010). This was work was focussed mainly on Sitka spruce in the context of current transformation of a proportion of pure plantation stands to selection or shelterwood working. A general conclusion was that there might be greater variation in Sitka spruce stem size and quality parameters due to adoption of these systems, involving as they do variable intensity thinning and deliberate opening of gaps. If these were phenomena associated with operation of mixed-species stands of the types discussed here, then similar effects on spruce timber properties might be anticipated. However this is not inevitably the case, as there are essentially two separate decisions involved for the plantation manager (a) whether to operate mixed-species stands and (b) whether to operate these on regular or irregular systems. It appears to be the latter that is the more significant for spruce properties. Macdonald *et al* (2012) do comment that overall effects of adoption of alternative silvicultural systems on the timber properties of shade bearers such as western hemlock are likely to be less pronounced than for Sitka spruce. However there may be significant benefits for timber quality in hemlock, cedar and *Abies* firs of maintaining higher stocking densities in the early life of such stands (Cameron and Mason, 2013) under natural regeneration systems.

Information and advice: potential of Sitka spruce mixtures with Norway spruce

Ecological analogues/ templates

No exact analogues as these two species do not occur together in nature. The two species are not ecologically equivalent. There is no surviving species analogue for Sitka spruce in Europe (any that did previously exist was extirpated by Pleistocene glaciations). The closest species analogue for Norway spruce in western North America is probably western white spruce (*Picea glauca*). That species does form mixed stands and hybrid forms with Sitka spruce.

British record/ experience

Numerous examples of co-deployment of species during the first 40-50 years of upland plantation forestry while their respective site tolerances were being discovered (1910-1960). Particular geographical concentrations in Galloway, Argyll, Lochaber, Great Glen, Moray. Most instances formed "accidentally" by mixed planting stock and reinforcement planting of understocked Norway spruce stands on exposed sites with more robust Sitka spruce. Surviving examples predominantly unthinned stands on inaccessible, steep upper edges of FC forests. Fewer deliberate, systematic mixtures and few examples of well-thinned stands. Norway spruce component is typically one, more often two, GYC classes behind the Sitka.

Deployment context/ site requirements

Most likely to be relevant to restocking of upland Sitka spruce or Japanese larch stands on the more sheltered and productive parts of the site range for these species. Particular relevance in areas where the future climate may become too dry or marginal for Sitka spruce - notably Moray, Aberdeenshire, eastern Borders and North York Moors. Limited advantage in upland Sitka spruce growing areas further west where moisture supply is unlikely to be limiting.

Silvicultural compatibility/ considerations

Planting stock of NS readily available. Establishment more difficult than pure Sitka spruce, but less markedly so than for some other species combinations with Sitka spruce. Differential growth rates suggest mosaic or row/line mixture patterns may be best (the latter at 2:1 or 3:1 in favour of the Norway spruce component, unless regular thinning is feasible and intended). Overall yield likely to be reduced by 1-2 GYCs as compared with pure Sitka spruce, based on current parameters, but this may alter on drier sites. Rotation often extended to 60-70 years.

Advantages/ Resilience Benefits

May confer marginally greater resilience to drought than pure Sitka spruce stands in climatically marginal eastern upland areas. Likely to be more productive than pure Norway spruce stands in areas where Sitka spruce remains suitable out to 2050 under ESC/UKCP09 models. Timber is familiar and easily marketable as with Sitka.

Challenges/ Drawbacks

Main drawback is the reduction in yield and revenue on most sites where Sitka spruce is available as a viable option. Offers very little improved resilience to pest and disease risks as many are common to both spruces or indeed worse for Norway. Stands may require careful management by thinning to preserve the Norway spruce component if established on row/line or intimate patterns. Likely to be unsuitable for deployment on exposed, poorly drained upland moorland, based on experience during first 50 years of upland afforestation. Equation may be more favourable on better drained eastern heaths.

Information and advice: potential of Sitka spruce mixtures with Douglas fir

Ecological analogues/ templates

There is a strong ecological analogue in the productive mixed coniferous forests of the coastal lowland Pacific Northwest, notably in the Olympic and Cascade areas of Washington State, on Vancouver Island and along the coast of southern and central British Columbia. Both species are considered early to mid successional (as compared with hemlock and cedar) and are the primary producers of commercial softwoods from managed stands/ plantations.

British record/ experience

There are many examples of co-deployment of these species in older first rotation forests on the National Forest Estate, dating from 1910-1940. The best examples are found in sheltered upland valley localities such as the Moray Firth lowlands, the Great Glen, Argyll, Galloway Forest Park, Borders, Lakes and North Wales. Fine examples include the p1910-1930 mixed stands at "Acquisition 1" at Fort Augustus, Mackenzie's Grove at Loch Awe, Glentress, Cairn Edward, Grizedale and Gwydyr Forests. Surviving examples are informal mixtures on lower, sheltered ground, now managed under alternative/non-clearfell silvicultural systems. GYC is typically comparable, but lower for DF than for SS on some more productive sites.

Deployment context/ site requirements

Most likely to be relevant to restocking of upland Sitka spruce or Japanese larch stands on the more sheltered and productive parts of the site range for these species. Particular relevance in areas where the future climate may become too dry or marginal for Sitka spruce - notably Moray, Aberdeenshire, eastern Borders, North York Moors, mid Wales. Some suggestions that Douglas fir may later be able to be pushed "further up the hill" under a warming climate.

Silvicultural compatibility/ considerations

Planting stock of DF readily available. Establishment is considerably more difficult than for pure Sitka spruce due to palatability and intolerance of exposure in the DF. Mosaic, row/line and intimate mixture patterns are all potentially relevant where regular thinning is feasible/ intended. Overall GYC may be reduced as compared with pure Sitka spruce on better sites, but higher timber values may compensate the grower. Rotation often extended to 60+ years.

Advantages/ Resilience Benefits

May confer significantly greater resilience to drought risks than pure Sitka spruce stands in climatically marginal eastern upland areas. Should also confer enhanced composite resistance to current and emerging pests and diseases due to the different genus. Might prove more productive than pure Douglas fir stands in upland areas where climate and soil conditions are more marginal for Douglas fir. Timber is familiar and can be comparable/ superior to spruce.

Challenges/ Drawbacks

Major drawbacks is the more demanding nature of Douglas fir as a species, confining prudent deployment of this mixture combination to the more favourable spectrum of the sites currently used for upland forestry with Sitka spruce and Japanese larch. The combination is unsuitable (pending climate change and further research trials) for exposed upland site types. Greater sensitivity to browsing and more difficult establishment will tend to increase costs. Limited experience of protracted operation in line/ intimate mixture patterns implies that where thinning will be more difficult, some aggregation in a mosaic pattern may be prudent.

Information and advice: potential of Sitka spruce mixtures with western hemlock

Ecological analogues/ templates

There is a good ecological analogue in the productive mixed coniferous forests of the coastal lowland Pacific Northwest, particularly in northern areas of British Columbia and south-eastern Alaska, but also on Vancouver Island and the Olympic/ Cascades area. Southern stands also contain Douglas fir, western red cedar and *Abies* firs. Sitka spruce is often held to have superior stem form/ timber properties when grown in mixture with hemlock than if pure.

British record/ experience

There is quite a limited record with mixed stands of Sitka spruce and western hemlock in Britain. Occasional examples can be found from the period 1920-1940 but most stem from a short upsurge of interest between 1955 and 1970, following R.F. Wood's commentary on the potential of this species combination, following his travel in the Pacific Northwest. Wales, and particularly the forests of the South Wales valleys, are major foci, but there are examples in NE England and Scotland. The tendency appears to have been establishment of 1:1 (50%) line-row mixtures, as in the Forest Research trial series, planted in 1955. In predominantly unthinned examples, stratification often saw hemlock subordinated. WH GYC is typically 1-2 behind SS. Many stands of this type (also inc. DF) are now formed by natural regeneration.

Deployment context/ site requirements

Most likely to be relevant to restocking of upland Sitka spruce or Japanese larch stands. This mixture is a more flexible option than those involving Norway spruce or Douglas fir and can potentially be operated over much of the range upland of sites currently used for Sitka spruce, but cannot be recommended for very peaty conditions or the most exposed upland site types. Optimal conditions for the combination, however, appear more concentrated on mesic soils.

Silvicultural compatibility/ considerations

Planting stock is readily available for WH, but limited provenance discrimination. Establishment is considerably more difficult than for pure Sitka spruce crops due to palatability and intolerance of exposure in WH and its slower initial growth. Care needs to taken to allow less competitive western hemlock to persist after canopy closure, either by suitable thinning or by establishment mosaic patterns or biasing initial stocking in favour of the WH component. Overall GYC is usually reduced as compared with pure Sitka spruce.

Advantages/ Resilience Benefits

Should confer enhanced composite resistance to current and emerging pests and diseases due to the different genus. There is some limited indication that western hemlock can extend onto droughtier sites than Sitka spruce - trials are required. The hemlock component may clean the Sitka spruce in some situations, effectively acting as a silvicultural nurse, and also helps to control ground vegetation on some more fertile sites, facilitating application of ATC/CCF.

Challenges/ Drawbacks

The principal disadvantages of this combination are (a) partial silvicultural incompatibility between the two component species (WH being less competitive and not maintaining height increment for so long), and (b) the much lower values obtainable for western hemlock timber (although this issue may be addressed by silvics research, breeding and market development). Invasive regeneration and *Heterobasidion/Phomes* susceptibility in WH can be problems.

Information and advice: potential of Sitka spruce mixtures with grand fir

Ecological analogues/ templates

There is a good ecological analogue in productive mixed coniferous stands of the coastal lowland Pacific Northwest, particularly in the Olympic/ Cascade forests of Washington, but also into Vancouver Island. Stands containing grand fir and Sitka spruce tend to grow on lower-lying coastal/ alluvial and foothills sites with good fertility/ moisture. Grand fir timber is usually marketed as part of the second-grade "hem-fir" lumber category which is considered suitable for indoor joinery etc. but usually not for heavy load-bearing applications.

British record/ experience

There is a very limited silvicultural record with mixed stands of Sitka spruce and grand fir in upland Britain. Examples that do occur tend to exhibit "informal" blocky or mosaic patterns, with very few "regimented" line-row mixture examples identified to date for SS/GF. Most examples are on lower lying valley bottom or lower slope sites representing the best 10-20% of the site range for Sitka spruce. There is no geographical concentration, with examples discovered in S. Wales, Aberdeenshire, Argyll and the Borders dating from 1920 through to 1970. Many are very poorly thinned, tall and brittle and very susceptible to storm damage.

Deployment context/ site requirements

Only likely to be relevant to restocking of productive upland Sitka spruce or larch stands on atypically favourable site types combining good climatic shelter with mesic soils of moderate to good fertility. Most of these are likely to be productive valley bottom or lower slope sites in moister areas such as Wales, Galloway, Lochaber and Argyll. The potential of the species in drier areas further east is constrained by its intolerance of summer moisture deficits, which generally induce drought-cracking of the stem. Can be useful for visual landscape/ amenity.

Silvicultural compatibility/ considerations

Planting stock fairly available for GF with some previous provenance research/ discrimination. This combination displays a very high degree of silvicultural compatibility and, on the right sites, could essentially be managed identically to pure Sitka spruce stands. Hence mosaic, line-row and intimate patterns could be employed, although there is very little experience with formal line-row mixtures using this combination. There is often little or no yield penalty as compared to pure Sitka spruce crops on good sites, and there may be a yield gain, although the low density of fir timber must be considered. Rotation length comparable. This is a valid combination for which further trials and research work would be beneficial.

Advantages/ Resilience Benefits

Should confer enhanced composite resistance to current and emerging pests and diseases due to the different genus. Resistance to *Heterobasidion/ Phomes* is notably superior to spruce. Grand fir is a high biomass-yielding competitive species that should "hold its own" with Sitka spruce under the right site conditions, allowing considerable silvicultural flexibility.

Challenges/ Drawbacks

The principal disadvantages of this combination are (a) the very high palatability of grand fir to deer browsing and its intolerance of exposed site conditions, and (b) the much lower values currently obtainable for light, weak grand fir timber (although the latter might be addressed by development of alternative markets including massive/ cross-laminated timber elements).

Information and advice: potential of Sitka spruce mixtures with noble fir

Ecological analogues/ templates

This combination has a much weaker direct ecological analogue as only a very limited area in the Washington and Oregon Cascades where lowland Sitka spruce and montane noble fir co-occur. However it should be noted that montane spruce-silver fir forests are major natural forest assemblages in both the Pacific Northwest (with Sitka spruce and Pacific silver fir) and Central Europe (with Norway spruce and European silver fir) - both are major timber sources.

British record/ experience

There is quite a limited record with mixed stands of Sitka spruce and noble fir in Britain, but somewhat greater than in the cases of western hemlock and grand fir above. This is a species combination that has tended to be used on more demanding upland sites than any of the other four species combinations discussed in detail above, particularly on heather moorland sites. Good examples can be found in N. Wales, Argyll, North West Scotland and the Borders. As with western hemlock, there appears to have been an upsurge of interest in this combination during the period 1955-1970, with a number of informal trials towards the upper forest edges. A variety of spatial patterns were tried, predominantly mosaic, but some line-row/ intimate.

Deployment context/ site requirements

Most likely to be relevant to restocking of upland Sitka spruce or Japanese larch stands. This mixture is a more flexible option than those involving Norway spruce or Douglas fir and can potentially be operated over most of the range of sites currently used for Sitka spruce, but cannot be recommended for peaty conditions or any site likely to become droughty. SS/NF is much more tolerant of exposure than any of the other combinations presented in this report.

Silvicultural compatibility/ considerations

Planting stock is fairly available for NF, but little provenance discrimination to date. Establishment is more difficult than for pure Sitka spruce crops due to palatability of the NF and much slower initial growth that it achieves. By comparison with western hemlock, noble fir is a more persistent species and rather less likely to be suppressed by the Sitka spruce, even where there is a significant difference in early height growth. Hence a range of spatial patterns can be considered in mixed stands, even where thinning is likely to be deficient. The yield performance of the noble fir component has tended to fall 1-3 GYC behind the Sitka.

Advantages/ Resilience Benefits

Should confer enhanced composite resistance to current and emerging pests and diseases due to the different genus. A particular benefit is the ability of NF to match SS in its tolerance of climatic exposure. Consideration should perhaps be given to inclusion of western hemlock in three-way SS/NF/WH mixtures to further increase the resilience - western hemlock does indeed form more extensive areas of natural forest with noble fir in the Pacific Northwest. Also (as discussed below) exploration of the potential of SS/PSF mixtures is a clear priority.

Challenges/ Drawbacks

The principal disadvantages of this combination are (a) partial silvicultural incompatibility between the two component species (NF tending to be highly palatable and to make a much slower start), and (b) the much lower values currently obtainable for noble fir timber (although the latter may be addressed by silvics research, breeding and market development). Reports are emerging of *Phytophthora ramorum* in noble fir in Ireland and SW England. Vigilance and caution is therefore merited when operating it onto/ near infected larch sites.

Information and advice: potential of Sitka spruce mixtures with alternative species

Besides the principle potential companion species dealt with on the preceding pages, there are a range of other species/ species groups that might be considered for mixed stands with Sitka spruce. For these, there is generally little or no direct evidence from British field examples. Hence implementation in the short to medium term is likely only to be on a trial-scale basis:-

Mixtures with European and Pacific silver firs

These are options that do recommend themselves on silvicultural grounds, particularly the potential to combine Sitka spruce (SS) and Pacific silver fir (PSF) on exposed, wet upland sites. Occasional older British stands can be found where a little European silver fir (ESF) survives in mixture with Sitka spruce, but no relevant domestic mixtures have been found with Pacific silver fir, despite natural co-occurrence of Sitka spruce and Pacific silver fir in the Pacific Northwest. Evidence from forest gardens and trial plots where these species have been tested alongside each other on similar site types suggests good potential silvicultural compatibility. Pending the establishment and study of new mixtures trials as recommended below, the most that can be said as yet is that site and silvicultural factors affecting SS/PSF mixtures might well resemble those discussed for SS/NF above, while those affecting SS/ESF mixtures might be intermediate between those discussed for SS/NF and SS/GF above.

Mixtures with western and Japanese red cedars, Lawson/ Leyland cypress and similar

These are options that might be considered for the more climatically and edaphically favourable component of the current Sitka spruce range (lower valley slopes/ floors etc). There are a few examples of SS/RC and SS/LC mixtures across a range of upland site types, but very few have been tended in such a way as to give a good impression of silvicultural potential. Most are very fragmentary, exposed and silviculturally neglected. Pending the establishment and study of new mixtures trials as recommended below, the most that can be said is that SS/RC, SS/JCR and SS/LC mixtures should probably only be considered for those better sites where SS/DF mixtures would become the "first port of call" as discussed above.

Mixtures with Macedonian pine, Serbian spruce and Oriental spruce

These are options that attract current speculative interest as potential "hedges" against drought impacts on Sitka spruce in areas such as the North York Moors and the Borders. Occasional "blocky" co-deployments with Serbian spruce apart, there is little domestic evidence. Serbian spruce growth rates are so much slower than those for SS on similar sites that only a "blocky" co-deployment pattern seems prudent. Oriental spruce as a potential companion most resembles Norway spruce (as discussed above), but is mainly likely to be considered for site types which are, or are likely to become, too dry for Sitka spruce. The best comparator for SS/MCP mixtures might be SS/SP or SS/JL (not considered in this report due to *Dothistroma/ Phytophthora*), which are essentially more of the nursing mixture type. It might be possible to perpetuate MCP in mixture with SS on poor sites - this should be tested.

Mixtures with medium-tolerant and tolerant hardwoods

Although not covered in detail in this study, there is good potential for combinations of SS with productive hardwood species, principally on the better part of its site range (valley sites). Species in the genus *Acer* appear to have the greatest potential and deserve more trials (e.g. sycamore (*Acer pseudoplatanus*) from Europe and big-leaf maple (*Acer macrophyllum*) from the Pacific Northwest). There are some good home examples of SS over intruded SYC.

Conclusions: advantages and challenges of upland Sitka spruce mixtures

The information collated within this technical report presents what might be seen as a "mixed picture" in terms of the current advantages and challenges of upland Sitka spruce mixtures:-

Advantages

- **Resilience -** in most situations, deployment of mixed stands containing Sitka spruce and a second productive conifer species would be likely to reduce the likelihood of total loss of crop value due to a pest or disease outbreak. Whether there is any change in the likelihood of partial crop loss is a more equivocal point - there is no suggestion that Sitka spruce is more likely to succumb than any other species, some argue less. Certain potential companion species might increase resilience to future drought risks.

- **Ecological** - there are cogent arguments that operating mixed-species stands has fundamental long-term ecological benefits in terms of developing more mature forest assemblages that are more likely to be self-perpetuating and are more likely to be in sustainable equilibrium with site and soil. However there is little direct evidence to confirm this in the case of stands composed of introduced conifer species in Britain. It is much better established for the situation where a deciduous component is included.

- **Silvicultural -** there is little doubt that operating mixed-coniferous stands would open up a wider range of future silvicultural development opportunities, primarily by facilitating application of alternative/ non-clearfell silvicultural systems. This would apply particularly where the companion species was more shade tolerant than spruce. Silvicultural development itself may have a wider range of second-order advantages.

- **Productivity -** some studies have shown a mutual facilitation effect/gain in mixed-species forest stands that can increase overall biomass production/ yield as compared with a monocultural situation. Based on evidence collated here (i.e. that is currently available) this is unlikely to be valid for comparisons between Sitka spruce mixtures and pure Sitka spruce stands on sites where the Sitka spruce is well adapted to growth. It may come into play in situations where Sitka spruce is or becomes drought-stressed. Some companion species such as Douglas fir and western red cedar would have the effect of diversifying the range of timber products produced, accessing new markets. Inclusion of a shade tolerant component such as western hemlock may increase the stem quality of the Sitka spruce crop through a "cleaning" effect, raising unit values.

- **Amenity** - in certain situations there may be landscape amenity benefits to deploying mixed-species stands as opposed to pure upland spruce crops, although this will be less prominent than in the case of former nursing mixtures including larch species. Noble fir is the most visually distinct of the species considered here, followed by western red cedar. In more sheltered situations, where thinning is possible to develop mature final crop stands, mixed stands may enhance recreational amenity potential.

Challenges

- **Unfamiliarity** - there is undoubtedly a challenge arising from the lack of professional familiarity in British forestry with operation of upland mixed crops of this kind. This is essentially a component of the same problem that impedes adoption of alternative/

non-clearfell silvicultural systems in many given situations. This unfamiliarity makes adoption of the proposed model unpopular and may artificially increase quoted costs. It can also make it difficult for growers to secure the appropriate professional advice.

- **Establishment** - in most cases mixtures of the type described here will be more difficult, less reliable and more expensive to establish on upland sites than pure Sitka. The main factors are the need for deer fencing to protect palatable companion species, the greater costs and complexity of selecting and obtaining planting stock and the need to enhance silvicultural shelter and weed control for the more sensitive species. These factors together will often mean significantly higher planting or restock costs. At present, financial assistance from grant-in-aid is insufficient to defray these costs.

- **Management** - in certain situations rotational management of mixed stands of the type proposed may be more complex and demanding than the equivalent required for pure Sitka spruce crops. This will mainly apply in stands that are able to be thinned, where thinning practices will then need to consider the different rates of growth and resulting silvicultural requirements of two or more species. Under non-thin upland regimes this is unlikely to be a major factor where initial mixture patterns are suitable.

- **Productivity** - in most, but not all, situations, there may be some yield penalty from operation of a mixture containing Sitka spruce rather than a pure Sitka spruce crop, although this is likely to be much less significant than in the case of rotational (non-nursing) mixtures of spruce with pine, larch or hardwood species. There may also be a need to adjust the rotation length, especially in non-thinned or lightly-thinned stands, to achieve a compromise between MMAI rotations for the two components. This will often defer the revenue from the spruce component which is usually the faster grown.

- **Timber products** - at present, the timber products of some of the companion species considered in this report, most notably the *Abies* firs and western hemlock, attract significantly lower market prices for equivalent log assortments than Sitka spruce. This can also have an effect on the capital/ discounted revenue valuation of forestry. Some industrial-scale processors in Britain, with specialist high throughput mills, only value the spruce whitewood supplies from home plantations as a utilisable resource. This implies that other elements address lower-value sawn, pulp and biomass demand. These values and perceptions are only partly under-pinned by fundamental properties of the timbers of the species concerned, which are often more highly valued overseas. Some are also directly affected by the way given species have been grown in Britain. This is an area where research and development and innovation can offer solutions.

- **Research** - there is no question that the approach to upland forest management discussed in this report has been seriously under-researched over the past 50 years as compared with the even-aged spruce monocultural model. A particular problem has been the lack of continuity of public-sector financial support for the establishment, maintenance and monitoring of relevant long-term forestry experiments and trials. The current fleet of such experiments is sub-optimal in content and condition. This leads to a situation where the technical advisory platform, which growers are used to having for pure Sitka spruce forestry, is largely absent or highly fragmentary here. Deficits in research-derived understanding impair establishment, silviculture and utilisation of wood products in relation to most of the potential companion species. We also have a lack of well-tended and convincing demonstration/ exemplar sites.

Recommendations: operational opportunities for deployment in the next rotation

The author's opinion is that the body of evidence collated in this study can only justify a current recommendation of cautious/ moderate expansion of this alternative forestry model. Any more confident recommendation would need to await results of new silvicultural trials.

Prudent steps for the next rotation would then appear to include:-

1. **Existing examples** of upland mixtures of the types discussed in this report should be identified across the National Forest Estate and private forestry holdings and considered for inclusion in silvicultural research reserves/ long-term retentions, for example under the terms of UKFS/ UKWAS compliant management plans. The present work will have identified most relevant examples on the National Forest Estate, but private forest managers may well be aware of additional examples. In most cases, existing compartment records should be retained and a current enumeration of the stand obtained using the methods described by FC Information Note 45 or similar. Wherever silviculturally possible, the stand should be retained and operated on a non-clearfell/ CCF basis, but it is recognised that unthinned examples may not allow this.

2. **Restocking** of upland plantation sites currently occupied by <u>conifer species other than Sitka spruce</u> (or native Scots pine within the Caledonian Pinewood Zone) should be considered as a prime opportunity for establishment of new stands comprising mixtures of the types discussed in this report, where this is consistent with owners' and managers' objectives. At present, sites where diseased Japanese and hybrid larch or lodgepole pine crops are being clearfelled present a particular opportunity for this. Careful observation of each species' susceptibility to *Phytophthora* is essential here. Under UKFS and UKWAS crop diversification requirements, it is generally thought preferable to avoid restocking these sites with pure Sitka spruce crops in any case. An exception might be made for Sitka spruce mixtures, and alternative conifer mixtures such as western hemlock: noble fir and western hemlock: Pacific silver fir may also be relevant here. Enhanced site prep., deer control and early tending will be needed.

3. **Restocking** of upland plantation sites currently occupied <u>by crops of pure Sitka spruce or spruce: pine/larch mixtures</u> will often attract an expectation under UKFS etc of conifer crop diversification measures. It is suggested that in the case of the National Forest Estate, a target of 25-35% replacement of pure Sitka spruce with Sitka spruce: conifer mixtures of the type discussed here might be reasonable, sampling a representative range of upland site types. This as part of the function of the National Forest Estate as an exemplar of best practice in developing resilient forest resources. On existing private forestry holdings, it is recognised that such a target will be more difficult to achieve, in the light of investment forestry owners'/managers' preference for commercial spruce and the very limited levels of public grant-aid for restocking. Here, a lower target of 10-15% replacement of pure spruce at restocking may apply. It is recognised that some private estates with a forestry tradition may be more willing.

4. **New planting** of productive conifer plantations in the uplands is primarily being conducted by private investment forestry concerns, but with substantial public financial assistance. Here, UKFS crop diversification standards typically apply and it should be possible to identify a role for deployment of alternative conifers and spruce: conifer mixtures, initially as a minority component of coniferous stocking, perhaps in the range 20-30% of productive area. Again, fencing will be essential in most cases.

Recommendations: enabling and promotional activities

Current levels of awareness in the upland plantation forestry ownership and management sectors as to the potential opportunity presented by mixtures of the types discussed in this report are currently very low, largely restricted to those with a stronger silvicultural interest. Much discussion surrounding the concept of deployment of mixtures, as an aid to increased forest resilience, is rather abstract and often detached from direct operational experience. Some such work, for example in Wales, has tended towards establishment of ambitious assortments of alternative species with a limited track-record and uncertain silviculture. Many in the more commercially-oriented private forest management sub-sector remain sceptical. A range of short-term enabling and promotional activities are therefore worth considering:-

1. **Grants** - those developing the next and subsequent rounds of forestry grants should evaluate how greater assistance and encouragement might be given to growers considering this (and other alternative productive species and silvicultural) models. A partial re-allocation of grant support away from woodland expansion to silvicultural management of existing woodlands is very likely to be a prerequisite in this regard. Specifically, enhanced grant-aid for mixture-relevant forestry operations including deer fencing of restock sites, pre-commercial thinning, detailed stand enumeration and permanent rack installation are most likely to become persuasive. Capital grants, for example for the purchase of selective thinning harvesters or the derivation of sawmill machine stress-grading settings for alternative conifer species may also be relevant. Thought needs to be given to how the private nursery sector can be incentivised to selectively improve and increase market availability of alternative conifer planting stock - this may well require some form of FC "contract growing indemnity scheme".

2. **Information** - an operational guidance/ promotional leaflet for non-specialist forest owners and managers could be produced in conventional and electronic forms. Most or all of the material available is contained within the present technical report and appendices. It is recognised that this report contains more background detail than will be required or desirable for such a less specialist audience. At the expense of some repetition of key information, this report has been structured in a "modular" way to permit extraction of elements into shorter-form guidance materials (e.g. the section on individual mixtures options). An illustrated summary article is also being prepared for publication in *Scottish Forestry* (Spring 2015) which will address this purpose. It is suggested that the Forestry Commission might also look to produce or sponsor the production of a co-authored Information Note or Practice Note addressing this option.

3. **Demonstration** - a short series of regional seminar events promoting this silvicultural option should be held, where possible taking advantage of field examples identified during the present study. Such events could be used to promote the present report, *Scottish Forestry* article and any shorter-form guidance subsequently produced. An event of this kind for the North of Scotland is currently the subject of discussions between the Contractor and the University of Aberdeen (Department of Forestry), and it is anticipated that a relevant event may be held for the South of Scotland in early 2015, following a regional resilience study that the Contractor has undertaken for FC Scotland. Similar events for SW England/ Wales and the North of England would require sponsorship from Natural Resources Wales and Forestry Commission England respectively. It is recognised that the geographical scatter and silvicultural condition of existing field examples is not generally ideal for this purpose, and that advance collection of mensurational and timber data would become valuable in support of this.

Recommendations: research and development requirements

Requirements and opportunities for future research and development can be divided into shorter-term "Phase 1" tactical work, making use of the relevant existing field examples identified within this technical report (and other similar), and longer-term "Phase 2" strategic work that would require the establishment, maintenance and recording of new trial series.

Phase 1 studies

This work would have a timescale of 2-3 years and would be intended to extract the remaining informational value from the existing field examples identified within this study. It is recognised that these examples are often not ideal for the purpose and are frequently vulnerable. In very many instances, establishment detail and thinning history are uncertain or unknown. Hence a fairly rapid "rough and ready data salvage" approach should be applied:-

- **Mensuration** - installation of temporary sample plot enumeration into the existing non-research examples using the methods of FCIN45 or similar, in order to determine, for each species component: top height, basal area, stem density, standing volume. Information on spatial arrangement would also support stand modelling work. Ideally such mensuration would be repeated, wherever stands can be thinned and retained.

- **Wood science** - collection of information about the wood properties of trees of each species in these stands by a combination of visual stem form appraisal, increment coring/ reconstruction, pilometric/ acoustic density testing and destructive sampling for laboratory determination of density and strength characteristics. This information to be deployed to augment that already reported by Ramsey and Macdonald (2013).

It is suggested that such works could now form the subject of a research MSc, MRes or PhD study at the University of Aberdeen, Scottish School of Forestry and or Napier University.

Phase 2 studies

Given the limited domestic record of research into the operation of Sitka spruce rotational mixtures, and the relative scarcity of surviving, silviculturally-developed field examples, there is now a very strong case for establishing a new fleet of long-term "mixtures trials" to test the models discussed in this report. These would more than likely need to be on the National Forest Estate to ensure continuity over the required monitoring period of 30-50 years, with first useful mensurational data expected at ten years following establishment.

The design of such a new fleet of long-term mixtures trials would require careful thought and should encompass a suitable range of relevant upland site types (no-thin and thinnable) across Scotland, the North of England and Wales. Experimental objectives should cover means of establishment, spatial pattern, silvicultural systems, mensuration and timber properties. Subsidiary issues such as provenance selection in alternative conifers, soil development impacts of alternative conifers and harvesting/ site protection should also be captured.

The Contractor is in discussion with the University of Aberdeen and with Forest Research as to how such longer-term research studies might be pursued, although the difficulties in obtaining secure sources of funding for such work in the present climate are well recognised.

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Photographic gallery

Left: Mixed stand of Sitka spruce and Norway spruce, Morayshire.

Right: Mixed stand of Sitka spruce and Norway spruce, Galloway.

Left: Mixed stand of Sitka spruce and Douglas fir, Morayshire

Right: Mixed stand of Sitka spruce and Douglas fir, Argyll

Left: : Mixed stand of Sitka spruce and western hemlock, Glamorgan

Right: Forest Research p1955 SS/WH mixtures trial, Garw, Wales

Left: Mixed stand of Sitka spruce and noble fir, Gwynedd

Right: Mixed stand of Sitka spruce and noble fir, Aberdeenshire

Left: Mixed stand of Sitka spruce and grand fir, Glamorgan

Right: Mixed stand of Sitka spruce and grand fir, Aberdeenshire

Left: Mixed stand of Sitka spruce and western red cedar, Wester Ross

Right: Mixed stand of Douglas fir and western red cedar, the Dean