Alternative models for productive upland forestry
Model 2: Sitka spruce mixtures with alternative conifers

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Summary

Upland forestry in Britain is currently dominated by two management models - (a) even-aged medium-rotation plantations of predominantly Sitka spruce (*Picea sitchensis* [Bong.] Carr.) and (b) conservation or ecological restoration of native woodland with minimal production outputs. To meet emerging objectives and address current challenges to sustainable operation, a wider range of upland forestry management models should be considered. Emerging objectives include mitigation of climate change by enhanced carbon sequestration and increased production of woodfuel biomass, alongside ecological restoration and enhanced rural development forestry benefits. Key challenges include impacts of predicted climate change, incidence of novel pests and diseases in existing stands and the need to ensure a sustainable long-term relationship between forest productivity and site, soil and freshwater resources. Deployment of mixed-species stands comprising Sitka spruce and one or more alternative productive conifers, potentially capable of completing the rotation, offers the opportunity to enhance inherent stand resilience while retaining the option of a final crop of the species that is currently preferred by many processors. A recent scoping study has evaluated the principal advantages and challenges associated with this alternative model, considering Norway spruce (*Picea abies* L.), Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), silver firs (*Abies* spp.) and western red cedar (*Thuja plicata* Don ex D. Don) as the most likely "companion conifers" to Sitka spruce. Key requirements for research and development are discussed, which would be essential to support wider and more confident operational adoption.

Context

Upland forestry (above 300m asl, but lower in hyper-oceanic districts) is pursued across large parts of Scotland, Ireland and Wales and more restricted areas of England (e.g. Dartmoor, the North York Moors, Cumbria and Northumberland). These upland areas of the British Isles currently represent a major proportion of the available production forestry resource, although characterised by site types with multiple environmental challenges including high elevation and wind exposure, low thermal sum/ growing season accumulated temperature, high rainfall, poorly drained and infertile soils. These factors, together with weak road infrastructure and remoteness from sources of labour inputs and industrial processing outlets, restrict the range of tree species and management models considered. Since the 1960s, only two major forest management models have been operated on any scale within these areas - (a) even-aged medium-rotation plantations of predominantly near-monocultures of Sitka spruce (*Picea sitchensis* [Bong.] Carr.) and (b) conservation or ecological restoration of native species woodland with minimal production outputs. While periodic attempts at greater integration and diversification have been made, progress has been limited and these remain two very distinct paradigms.

Several current challenges have emerged to this position, together suggesting that new management models may be required. On the positive side, there is policy prioritisation of a wider range of "ecosystem services", most pertinently climate change mitigation through increased carbon sequestration in both peatland and forests and increased fossil fuel substitution through production of woodfuel biomass. These services are expected to be realised within a context of emphases on landscape amenity, biodiversity conservation, ecosystem restoration and rural economic development benefits from upland forest management. On the negative side are heightened challenges to the "natural capital" from which these services derive, including adverse climate impacts, novel pests and diseases affecting existing tree species choices and the specialisation of the UK timber processing sector, favouring a narrow range of commercial "whitewood" conifer species. One approach to these challenges is to develop upland production forestry models based on deployment of mixed-species stands combining existing preferred species with alternative tree species (Mason, 2006a, 2012a&b; Mason and Perks, 2011) in order to enhance inherent resilience while retaining economic timber potential. This paper deals with mixed-species stands combining Sitka spruce (as the preferred upland conifer) with a range of alternative conifer species with proven timber production potential, and the ability to complete a similar forestry rotation. Such stands will mainly conform to either Forest Management Alternatives FMA3 (combined objective forestry) or FMA4 (intensive even-aged forestry) within the terms of the Read Report (Read *et al*, 2009).

Model operation

This model involves the production of both saw-timber and industrial biomass from mixed-coniferous stands on upland sites. Mixed stands would combine Sitka spruce with one or more alternative productive conifers of equivalent or greater shade tolerance, capable of completing a similar forestry rotation of 35-60 years duration. Such mixtures are often termed “rotational” or “insurance” mixtures, by contrast with the more familiar concept of “nursing” mixtures, where the companion species (typically pine or larch) fulfils a temporary, facilitating role to a spruce crop (Cameron and Watson, 2000; Watson and Cameron, 1995). A range of potential “companion conifers” to upland Sitka spruce are available for consideration, but the most logical place to start is with those conifer species that occur naturally together with Sitka spruce in the oceanic forests of the Pacific Northwest (MacDonald *et al*, 1957; Wilson, 2007, 2011). Those include Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), western hemlock (*Tsuga heterophylla [Raf.] Sarg.*), western red cedar (*Thuja plicata Don ex D. Don*), Lawson cypress (*Chamaecyparis lawsoniana [Murr.] Parlatore*), Pacific silver fir (*Abies amabilis* Doug. ex Forbes) and grand fir (*Abies grandis* [Lamb.] Lindl.). To these we should also add noble fir (*Abies procera Rehder*) which, although actually having only a small area of natural co-occurrence with Sitka spruce, is potentially valuable for exposed British upland conditions. Finally we also include Norway spruce (*Picea abies L.*) which is ecologically comparable to western white spruce (*Picea glauca [Moench] Voss*).

Mixed-coniferous stands of the type considered here would typically be created by planting on intimate, line-row or mosaic patterns or, less ideally, in blocks (groups), although the latter would leave canopy gaps should one species succumb to biotic attack (Figure 1). Planting could be in woodland creation schemes or at restocking. There are also opportunities arising to accept mixed-coniferous natural regeneration in some of our older plantations. Silvicultural management would either be by regular clearfell-restock regimes on exposed upland sites or by adoption of alternatives to clear-felling, with subsequent natural regeneration on the more favourable classes of sites. In either case, regular thinning is beneficial as it offers the opportunity to direct the species composition of the stand, either by selection of one of the components to complete the rotation, or by regulation of a mixed-species final crop stand. Typically, less than half of the initial planting positions are required to form the final crop. This provides the “insurance” element, as any single stand component adversely affected by climate, pest or disease can be removed during the first half of the rotation, without catastrophic loss of final crop volume. Rotation length in regular forestry systems is likely to represent a compromise between ages of maximum mean annual increment (MMAI) of components. The spruce element of the resulting stand would serve equivalent markets to current pure spruce stands, whereas the alternative conifer element may currently tend to serve pulp, pallet and biomass markets, pending future market development.

The scoping study

By contrast with monospecific stands of Sitka spruce or of other conifers, there is a restricted record in upland Britain of deliberate creation and management of mixed-coniferous stands, other than “nursing mixtures” with pine or larch. Nursing mixtures are now less relevant due to the severe impacts of *Dothistroma* on lodgepole pine and *Phytophthora* on larches. Longer-term mixtures have always represented a minor or subordinate approach in British upland forestry. Such mixtures received research attention and some limited operational deployment, particularly during the period 1920 to 1965 (Doyle-Davidson, 1965; Lines and Nimmo, 1965), but only very limited attention in more recent decades. A short scoping study was conducted during 2014 to collate such evidence as is available, partly to inform interested growers as to their options, but mainly to inform the planning of future research. This scoping study used a combination of techniques in a “rapid rural enquiry” approach, including literature review, technical discussions, desk analyses of comparative growth rates and site yield and targeted field visits to key examples.

A select bibliography arising from the literature review appears at the end of this article. There have been very few reported trials of longer-term conifer mixtures in Britain although the famous mixture experiment, conducted in Gisburn Forest, Lancashire since the mid-1950’s, has highlighted the potential productivity benefit of mixtures on upland sites (Brown, 1992; Kerr *et al*, 1992; Mason and Connolly, 2014). Much relevant literature derives from observations of mixed-coniferous stands including Sitka spruce in the natural forests of the Pacific Northwest (*e.g.* Day, 1957; Erickson and Harrington, 2009; Julin *et al*, 1993; McLennan, 2005), particularly Forestry Commission Bulletin 25 (Wood, 1955), following R.F. Wood’s study tour. Recently, relative performance of Sitka spruce, Douglas fir and western hemlock in mixed stands has been considered (Cameron and Mason, 2013), suggesting that western hemlock can form a “stratified” sub-canopy to spruce or Douglas fir.

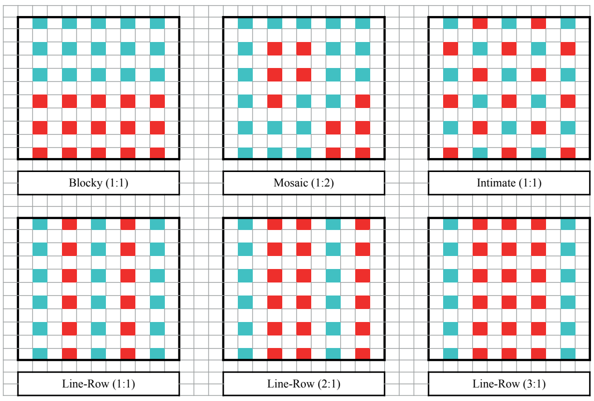

Figure 1 - Patterns in mixed-conifer plantations (turquoise = Sitka spruce, red = alternative conifer).

Mixed stand of Sitka spruce and Douglas fir, Balnacoul, Moray.

Mixed stand of Sitka spruce and grand fir, Kirkhill Forest, Aberdeenshire.

Mixed stand of Sitka spruce and noble fir, Penllyn Forest, N.Wales.

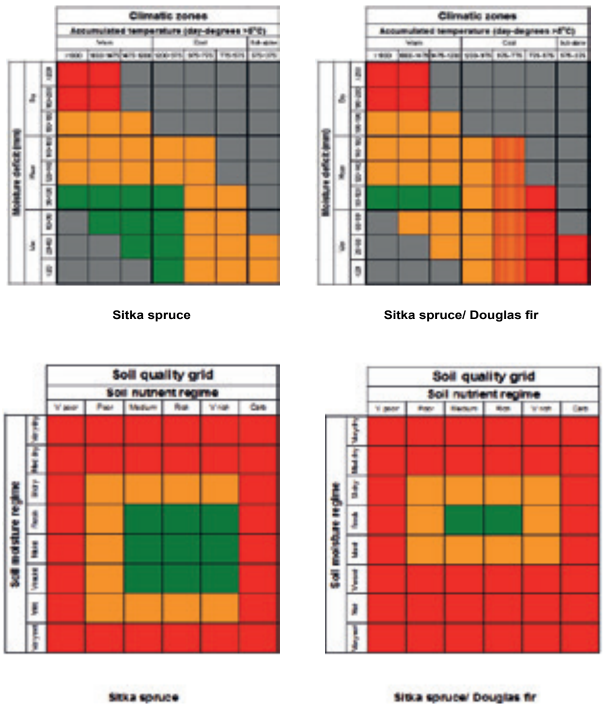

Figure 2 - comparing climatic and soil suitability for pure Sitka spruce and a Sitka spruce/Douglas fir mixture using the Ecological Site Classification [as interpreted from FC Bulletin 124, Pyatt et al. 2001] (red = unsuitable, amber = suitable/marginal, green = very suitable/optimal).

This has the potential to improve timber quality of Sitka spruce, in particular, by restricting juvenile core and side branching through increased competition during early growth phases (Deal *et al*, 1991; Deal and Tappeiner, 2002; Newton and Cole, 2012; Wierman and Oliver, 1979).

Ecological site suitability for these various mixture combinations can be predicted to some extent using the well-established methods of the Forestry Commission Ecological Site Classification (ESC) (Pyatt *et al*, 2001). In many cases, the inclusion of a companion conifer restricts site suitability of resulting mixtures to the more favourable sub-sector of the suitability range for Sitka spruce alone (see Figure 2), although this effect is much less pronounced for mixtures with western hemlock, noble fir and Pacific silver fir, emerging predominantly with tender species such as Douglas fir, grand fir and western red cedar (see also Anderson, 1950, 1961; Cadman, 1953). The assumption is made that no mixture can be more suitable on any given site than its least suitable component species. Generally mixtures can only be prudently deployed where each component species is currently at least "suitable" for the site, and is expected to remain so throughout the anticipated rotation, in the light of predicted climatic change. There may be some circumstances where growers will be willing to deploy mixtures where Sitka spruce is expected to become "marginal" for the site mid-way through the planned rotation, primarily on grounds of increasing soil moisture deficit, at which time it can be harvested. Here, the more drought tolerant companion (*e.g.* Douglas fir) would form the final crop.

By comparison, prediction of the likely relative increment of Sitka spruce and the various potential companion conifer species in mixed stands in upland Britain is seriously hampered by the lack of any established record of permanent sample plot mensuration and growth and yield modelling for this class of stands, as compared with monospecific conifer plantations, particularly of Sitka spruce. However, comparison of the traditional yield-model curve families, presented by Forestry Commission Booklet 48 (Edwards and Christie, 1981) for the conifer species of interest, suggests that monospecific stands display different patterns of increment during their initial 30-40 years of growth. In particular, western hemlock, western red cedar and noble fir display notably slower early height increment than would Sitka spruce of equivalent General Yield Class (GYC). This has potential implications for silvicultural compatibility in close mixtures with Sitka spruce, and optimum regimes in terms of mixture pattern, ratio and early thinning. Particularly in unthinned mixtures, it may well prove necessary to bias in favour of the companion conifer from the outset. However, it must be recognised that reliance on simple yield models derived from mensuration of monospecific stands of component species are unlikely to give fully reliable predictions of actual yield performance in functional mixed stands.

The recent advent of the public-domain GIS sub-compartment database for the National Forest Estate (Forestry Commission and Natural Resources Wales) allows for "mass comparison" of predicted GYC in the many hundreds of mixed-conifer sub-compartments where Sitka spruce is co-deployed with companion conifers of interest. These lists of relevant sub-compartments capture examples of the intimate, line-row, mosaic and blocky spatial patterns and it is often difficult to distinguish between these by reference to compartment records and aerial photography, without inspection. In most cases it can be assumed that site climatic conditions are uniform at the sub-compartment scale, but some examples of the blocky pattern may indicate that local

Mixed stand of Sitka spruce and Norway spruce, Archiestown, Moray.

Mixed stand of Sitka spruce and western hemlock, St. Gwyddno Forest, S. Wales.

p1955 Trial of Sitka spruce - western hemlock mixture, Draethen Forest, S. Wales.

variation in site soil conditions is reflected in species choice. With that *caveat*, it can be observed (see Table 1) that Sitka spruce is very often the faster grown component in relevant mixed-coniferous stands, such that incorporation of a companion might result in a GYC penalty of the order 5-10% (grand fir is the exception that will often match Sitka spruce GYC on better sites). This may be considered acceptable as a "resilience penalty", but needs to be considered together with information on the relative timber density and strength properties and market values of the various companion species. It should also be noted by contrast that Forestry Commission Bulletin 49 (Aldhous and Low, 1974) reported that the "minor conifers" considered there (grand fir, noble fir, western hemlock, western red cedar) often outgrew Sitka spruce on similar sites, particularly better sites.

The lists of relevant mixed-conifer National Forest Estate sub-compartments, as referred to above, were combined with similar information from UPM Tilhill to visit selected examples of relevant species combinations in upland areas across Northern England, Scotland and Wales (see Plates). This fieldwork was not exhaustive within the confines of the present scoping study, and had as its main aim the pre-identification of some better examples that could form the basis of more detailed surveys involving mensuration, stem quality assessments and increment-coring reconstruction. Emphasis was placed on visiting more mature stand examples, established between 1920 and 1980. A small number of

Table 1 - comparing General Yield Class (GYC) of Sitka spruce and companion conifers in relevant mixed-species sub-compartments on the GB National Forest Estate.

Sitka spruce	Norway spruce		
GYC	GYC	*n for mixture*	% of SS GYC
0	5.2	15	
2	2.5	4	125
4	4.4	25	110
6	6.5	19	108
8	7.6	32	95
10	9.1	74	91
12	10.3	154	86
14	12.0	194	86
16	13.6	171	85
18	14.6	98	81
20	15.9	63	80
22	17.0	30	77
24	16.5	30	69
26		0	
Mean 14.2	Mean 12.0	909	85

Sitka spruce	Douglas fir		
GYC	GYC	*n for mixture*	% of SS GYC
0	8.0	7	
2	12.4	9	620
4		0	0
6	12.0	2	200
8	9.6	5	120
10	10.2	12	102
12	12.2	62	102
14	12.4	97	89
16	14.1	139	88
18	14.7	95	82
20	15.2	81	76
22	17.0	69	77
24	18.6	78	78
26	20.0	2	77
Mean 17.2	Mean 14.5	658	84

Sitka spruce	Western hemlock		
GYC	GYC	*n for mixture*	% of SS GYC
0	0.0	1	
2		0	0
4	0.0	1	0
6	1.0	2	17
8	11.5	4	144
10	10.8	5	108
12	11.4	17	95
14	13.4	24	96
16	15.1	35	94
18	16.0	20	89
20	18.3	18	92
22	20.4	15	93
24	19.5	11	81
26	24.5	4	94
Mean 16.0	Mean 15.4	157	96

Sitka spruce	Grand fir		
GYC	GYC	*n for mixture*	% of SS GYC
0		0	
2		0	
4		0	
6		0	
8	2.0	1	25
10	17.0	2	170
12	14.4	5	120
14	14.3	12	102
16	14.9	9	93
18	19.8	13	110
20	20.7	9	104
22	20.8	5	95
24	25.0	2	104
26		0	
Mean 16.8	Mean 17.4	58	104

Sitka spruce	Noble fir		
GYC	GYC	*n for mixture*	% of SS GYC
0	0.0	3	
2		0	
4		0	
6	3.0	2	50
8	6.0	4	75
10	10.6	7	106
12	10.4	15	87
14	14.5	17	104
16	15.2	15	95
18	15.4	10	86
20	18.8	5	94
22	16.5	4	75
24	22.0	5	92
26		0	
Mean 14.5	Mean 13.3	87	92

Sitka spruce	Western red cedar		
GYC	GYC	*n for mixture*	% of SS GYC
0		0	
2		0	
4		0	
6		0	
8		0	
10	10.0	1	100
12	12.0	3	100
14	16.0	1	114
16	14.8	5	93
18	15.5	4	86
20	17.0	2	85
22	22.0	1	100
24	17.0	1	71
26		0	
Mean 16.9	Mean 15.2	18	90

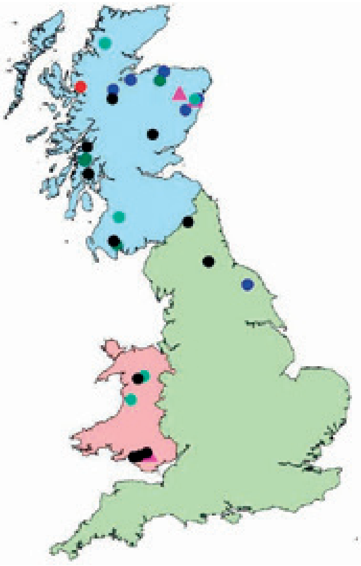

Figure 3 - locations of field example mixed stands visited: blue = SS/DF, green = SS/NS, magenta = SS/GF, turquoise = SS/NF, black = SS/WH, red = SS/RC).

surviving research trials of Sitka spruce/ western hemlock mixtures (established in 1955) were included (Lines and Nimmo, 1965). Examples are widely scattered, are typically under-recorded and often suffer from under-thinning and windthrow, all of which constrain their value as a source of empirical information on likely mixture performance. There are more numerous examples for the Sitka spruce/Douglas fir and Sitka spruce/Norway spruce combinations, fewer for Sitka spruce/ western hemlock and Sitka spruce/ noble fir and very few for Sitka spruce/ grand fir and Sitka spruce/ western red cedar. Certain regional and temporal patterns have been observed, with Sitka spruce/ Norway spruce and Sitka spruce/ Douglas fir combinations being most common in northern Scotland (established between 1920 and 1940), the Sitka spruce/ western hemlock combination being more common in Wales and northern England and Sitka spruce/ noble fir in Wales and western Scotland (in both cases established between 1950 and 1970) as illustrated in Figure 3. Generally, rudimentary block/ group and mosaic mixed-stand patterns predominate over more "classic" line-row and intimate mixtures that are of greater interest, at least for silvicultural research, and possibly for future operational deployment. While the available field examples identified have clear limitations, they would very likely justify further, more detailed mensurational survey, recording and analysis as a MSc or PhD level study, which should be undertaken as a matter of urgency, given the vulnerability of these stands to continued felling (if not silviculturally retained) and to windthrow.

Potential advantages

This proposed model has clear advantages in the current upland forestry situation:-

1 Resilience - It would be likely to enhance the inherent resilience of upland plantations, particularly in respect of novel pests and diseases, by reducing the likelihood of total crop failure. To maximise this benefit, a companion species from a complimentary coniferous genus (*e.g. Abies*, *Pseudotsuga*, *Thuja*, *Tsuga*) should usually be preferred over alternative spruce species, known to be susceptible to potential damaging agents similarly affecting Sitka spruce. Enhancement of resilience to drought-mediated climatic challenges is likely to be rather more limited, and only to apply to those mixture combinations including significantly more drought-tolerant companion species such as Douglas fir and western red cedar.

2 Productivity - By contrast with alternative upland management models deploying predominantly native hardwood trees (Wilson and Cameron, 2014), this model is likely to retain more of the biomass volume production associated with pure Sitka spruce crops. Any yield penalty by inclusion of a companion conifer looks to be relatively modest and manageable, and there are some arguments that operation of well-managed mixed-species stands can enhance overall site productivity in some cases. Value generation is affected by both volume production and unit timber values and will be discussed below. However, the ability to sustain volume production of coniferous "whitewood equivalent" timber is likely to have key sectoral economic benefits.

3 Silvicultural benefits - Expanded deployment of mixed-species stands of introduced conifers is likely to open-up a range of silvicultural opportunities that are less easily developed within pure upland Sitka spruce stands. In particular, use of more shade tolerant companion species such as western hemlock and Pacific silver fir may allow for the development of two-storied "stratified" stand structures, enhancing the final crop quality in Sitka spruce components by restriction of juvenile core and suppression of heavy side branching. Advance natural regeneration of these more shade tolerant conifers (Hale, 2004; Nixon and Worrell, 1999), well before final felling age, is also likely to have advantages for the adoption of alternative silvicultural systems to clear-felling on more exposed upland sites (Patterson, 1990, Wilson, 2013).

4 Environmental and amenity benefits - This class of benefits is likely to be more modest for mixtures involving two or more introduced evergreen conifers than for those introducing native and other hardwoods (Mason, 2006b). In particular the benefits of a hardwood component for visual amenity, soil amelioration and biodiversity habitat quality are all likely to be much greater. However conifer diversification alone may have benefits for soil amelioration, especially where western red cedar is included, or for visual amenity, especially where noble fir is included. These benefits are of particular significance where upland stands of larch need to be restocked following, or in anticipation of, *Phytophthora* damage. Further research into the soil, freshwater and biodiversity relations of the different companion conifers is now required as a priority.

Perceived challenges

This proposed model is, however, accompanied by clear challenges in the current upland forestry situation:-

1 Establishment - There are greater costs and logistical issues associated with establishment of mixed-coniferous stands of the type discussed here on upland sites as compared with monospecific spruce plantations. For some companion conifers, notably Pacific silver fir, planting stock is currently more difficult to obtain and much more expensive. In almost all cases in Scotland, and elsewhere, mixed-conifer planting and restocking sites will require deer-fencing or more intensive deer culling due to the greater palatability of the companion conifers as compared with Sitka spruce. Some of the companion conifers will not establish well on exposed upland sites without silvicultural shelter from "top and side", and the accompanying spruce may only partially fulfil that need. Current preferential forestry grant rates for woodland creation with "diverse conifers" might partly offset the resulting additional costs, but may not be available where Sitka spruce remains a major element of the stand. In the case of restocking, the recent decline in the applicable grant rates imply that most additional establishment costs would fall to the forest owner. Effective control of the deer populations in British upland districts should be seen as an enabling requirement for restock diversification.

2 **Silvicultural complexity** - Management of upland mixed-coniferous stands of the type discussed here may result in more complex and expensive silvicultural and harvesting operations as compared with pure spruce stands, but this is considered a less significant cost issue than those applying for establishment/ restocking. Where it is possible to thin mixed-coniferous stands, regulation of species composition needs to be considered alongside regulation of basal area and improvement of stand quality, and this may increase unit thinning costs. Marking, as opposed to "feller-select" working, is only likely to be necessary where conversion to irregular silvicultural systems is intended. Also, harvested products (from both thinnings and final crop) will typically require segregation by species for purposes of marketing and processing, which may increase harvesting costs.

3 **Processing economics** - In the current market situation, even if the combined yield of the conifer mixture is comparable with the predicted yield for pure Sitka spruce, there is likely to be lower value generation due to the poor market prices obtainable for timbers of certain key companion conifers. While the timber properties of Douglas fir and Norway spruce are well respected by the processing industry, less is known about western hemlock and the *Abies* firs and it may take time to develop market confidence in these timbers. This "price penalty" is very much a product of the historical preferences (and perhaps prejudices) of British industrial sawmillers, rather than of the inherent timber properties and potentials of the companion species. In the native range of these species in the Pacific Northwest, western hemlock and *Abies* fir timbers are accepted for "spruce-hem-fir" dimension lumber alongside Sitka spruce and Douglas fir. While such markets might be developed for alternative conifers in Britain in the medium to longer-term, at present harvested products of the less favoured conifer species can certainly supply the biomass, pulp, pallet and fencing commodity markets.

4 **Research base** - By comparison with the position for upland Sitka spruce plantations, there is a much weaker domestic research record, and resulting basis of evidence, for mixed-coniferous stands. Key areas where this deficit is felt include provenance selection, establishment practice, silvicultural operation, harvesting logistics and processing/utilisation (notably the lack of mechanical stress-grading settings). This, together with the limited body of empirical evidence available from existing field examples, will tend to restrict adoption of this alternative model in the shorter term to the more knowledgeable/ innovative private estate forestry owners and managers and to those on the National Forest Estate with specific resilience policy mandates. More evidence is clearly required if the more conservative, investment-driven private-sector forestry managers are to be 'drawn in'.

Research and Development requirements

In order to develop the full potential for deployment of Sitka spruce-alternative conifer mixtures in upland Britain, a significant programme of research and development work would now need to be pursued, probably over 20-30 years. A critical requirement is to rejuvenate and reinforce the key concept of long-term upland forestry trials and experiments in Britain, which had formed a central plank of forestry research and development activity between the 1920's and the 1980's. Changes to the availability of, and timescales for, government research funding from the 1980's onwards have compromised our ability to pursue such work on a sustainable basis in support of continued sectoral development. Many pre-established long-term experiments lack adequate maintenance and silvicultural attention and very few new silvicultural series have been established since the 1980's. Fresh work is likely to require additional public funding, preferably on a secured "endowment" basis to negate the deleterious effects of policy and funding fluctuations, but also financial contributions are required from private-sector forestry investment and forest management sectors and, critically, from the timber processing sector. The research requirement emphasises establishment, silviculture and processing/ utilisation:-

1 **Provenance and establishment** - Better information is required on optimum provenance selection in alternative conifers for British upland conditions. Current series of upland provenance trials for Douglas fir, grand fir, noble fir, Pacific silver fir etc. should be sustained and re-assessed and new provenance trial series established for western hemlock in particular. Optimum establishment practice in terms of site preparation, provision of silvicultural shelter and mixture pattern should be investigated in the early years of new long-term mixture trials.

2 **Silviculture and harvesting systems** - A new British-wide series of long-term operational upland mixture trials needs to be established to examine each of the conifer mixture combinations discussed in this paper. These should include examples initially managed on both no-thin and thinned regimes, and also later compare regular clearfell-restock working with operation under alternative systems to clear-cutting on suitable sites. Such work should essentially represent a confident "relaunch" of long-term upland forestry research in Britain.

3 **Timber properties, processing and utilisation** Much more quantified information is required about expressed timber properties of both Sitka spruce and the potential companion conifers grown in mixed stands under British upland conditions. This could begin with non-destructive (acoustic and increment coring) studies

conducted within example stands identified during the scoping study, later proceeding to destructive testing of samples from these stands and those created as new long-term silvicultural trials. Particular emphases should be placed on the effects on the timber properties of Sitka spruce resulting from growth in mixed-coniferous stands and on the actual expressed properties of the timbers of companion species (Macdonald and Hubert, 2002; Macdonald *et al*, 2010; Ramsay and Macdonald, 2013). Development of higher valued-added markets for the latter, such as cross-laminated and massive engineered timber elements, would be beneficial.

Ways forward

In advance of future research, this alternative forestry model should be considered for cautious operational deployment. In order to promote that, it is necessary to produce improved applied information materials for the forest management and timber processing sectors and to engage them more actively in discussions on plantation diversification. A practical workshop or seminar event on the theme of upland spruce mixtures, to disseminate the outputs from the recent scoping study described in this paper, is likely to be relevant to this requirement, as is production of an illustrated shorter-form "practice information note" to support operational deployment of this model by growers in public and private sectors.

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