Forest Research

Summary of FR Seed Origin Trials on western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)

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The Research Agency of the Forestry Commission

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Front cover pictures: (Left) Western hemlock in the experiment New Forest 14 planted in 1962. GYC of the seed origins was 16-20 on a clay loam with 870 mm rainfall a year; note extensive regeneration (Right) One of the surviving plot labels at the experiment Thetford 73A showing damage from grey squirrels.

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Executive summary

In a recent review of research, western hemlock (*Tsuga heterophylla* (Raf.) *Sarg.*) was classed as a *secondary species*, i.e. in the past it has been planted on a small scale but has potential for future wider use (Kerr and Jinks, 2015). To ensure the potential of the species is realised there needs to be a scientific basis for future choices of seed origin including comparative data for provenances from Britain and Ireland. Present guidance on seed origins is to favour Vancouver Island (Lines, 1987; Forest Research, 2020). However, it's unclear how these recommendations were supported by analysis of the available data from experiments examining 18 seed origins, including two from Britain and Ireland, established in the early 1960s.

In this project seven of the original experiments were reassessed and analysed, along with the 10-year data, to define the best geographical region for future seed collections. In addition, the literature was examined, including a recent review of the species by Cameron and Mason (2013) and a new analysis by Jinks (2017), as a basis for making suggestions on future work to support the wider use of western hemlock.

The main findings were:

1. Western hemlock is a productive forest tree and generally achieved GYC 14-22 on six of the sites studied.

2. The recommendations for provenance on the FR webpage should be revised to: 'provenances from Vancouver Island and the Cascades of Washington and Oregon are recommended for sites where Ecological Site Classification (ESC; Pyatt *et al*., 2001) indicates western hemlock is suitable, frost risk is low and it is not planted on open, exposed sites. A small number of provenances from the British Isles have performed well in experiments and are worthy of consideration.'

3. The FR webpage suggests western hemlock is 'best suited to moister climates in Britain with >1000 mm rainfall'. Evidence from Jinks (2017) and the sites reported here would support a change to this such as 'can be a productive forest tree on sites with >800 mm annual rainfall with the most productive sites having >1000 mm rainfall'.

4. More work is also required to confirm the timber properties of western hemlock grown in Britain and should be focused on enhancing specific gravity and understanding the causes of enhanced taper and fluting of the lower stem.

1.0 Introduction

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) is currently considered a minor species and the latest figures show that it occupies 10,149 ha of forest in Britain[1] (Gilbert, pers. comm.). This is surprising for a species described as an 'intimate and inseparable species' to Sitka spruce in its native range by Wood (1955); Figure 1 shows its extensive distribution in the Pacific Northwest. In a recent article published in *Scottish Forestry*, Cameron and Mason (2013) explore the poor image of the species in Britain, review the main silvicultural characteristics and timber properties of the species and ask the question: are we ignoring one of our most useful tree species? This article is included as Appendix 1 as it gives a comprehensive overview of western hemlock and its potential to contribute to forestry in Britain.

This report focusses on seed origin variation of western hemlock to update the summary information presented by Lines (1987) and on the Forest Research (FR) species and provenance webpages.

1.1 Objectives of study

In the period 1961 to 1963 a series of 19 experiments were established to examine the effects of seed origin on growth and yield of western hemlock in Britain (Lines and Aldhous, 1962); seven of these experiments were revisited in 2017/18. The objectives of this study are:

1. To examine growth of western hemlock on contrasting sites throughout Britain using seed origin experiments that were planted in the early 1960s.

2. To compare the growth of western hemlock seed collections from its native range with two origins from the British Isles.

3. To make suggestions for further work on western hemlock.

[1] The figures are 6890 ha for privately owned woodlands estimated from the National Forest Inventory and 3259 ha for the Public Forest Estate.

2.0 Seed origin variation in western hemlock

2.1 Experiments

Seed from 16 origins spanning Alaska, British Columbia, Washington and Oregon was available to the Forestry Commission in the late 1950s in addition to two origins from the British Isles (Table 1; Figure 2 and 3). A decision was taken to establish a series of seed origin experiments between 1961 and 1963, which resulted in trials at 19 sites (Lines and Aldhous, 1961, 1962, 1963). For this study, seven of the of the initial sites were located and judged to be 'assessable' (Brecon 5, Fonab 1, Rheidol 3, Alice Holt 130, New Forest 14 and two sites at Thetford 73 (known as 'A' and 'B') (Figure 3).

The sites covered a wide geographical range and also had varying rainfall (620–1450 mm yr^{-1}), temperate (1149-1893 day degrees), soil nutrient regimes (poor to carbonate) and exposure (DAMS 10-17); however, it is worth noting that all the experiments were planted on free-draining mineral soils (Table 2). It should also be noted that six of the seven experiments had some degree of shelter when established, in the form of an overstorey or coppice (Table 2). Good establishment practice was used at each of the sites and only a small amount of beating-up was carried out. At the time of the most recent assessment each of the experiments had been thinned at least once.

For each of the seed origins information was available from the experiment plan on latitude, which was accurate, but data on altitude and 'distance from coast' was much more general (Table 1); no information was recorded for longitude.

2.2 Assessments and analyses

2.2.1 Assessments

The seven sites were assessed between October 2017 and March 2018. Each site was assessed using the same protocol:

1. The diameter at breast height (DBH) of each tree;

2. The total height of the two largest DBH trees per plot (an estimate of top height; in some cases this was a single tree as the plots were small);

3. The form of each live tree was scored using the system: 1 = single, straight clear stem and leader ('potentially excellent timber tree'); 2 = single stem and leader but some kinks in main stem and/or heavy branching ('potential timber tree'); and 3 = neither 1 nor 2 ('candidate to remove in early thinning').

The mean of the height measurements for each seed origin at each site has been taken as an estimate of top height and from this an assessment of General Yield Class (GYC) was made using the top height-age curves for western hemlock in Matthews *et al*. (2013).

Each of the sites had been assessed at year 10 (survival and height) and these data were examined as part of the study.

2.2.2 Effects of seed origin and site

In this study data from the 18 seed origins has been analysed to answer the questions: (1) in which region of the Pacific Northwest (PNW) should seed collections be focussed considering growth conditions in Britain? (2) How does material collected in the British Isles compare with that from the PNW? The seed origins from the PNW were grouped into 5 regions mainly using their geographical locations but also considering other factors such as distance from the coast and rainfall as shown in Figure 2 and Table 1 (Packee, 1990). The two provenances from the British Isles were placed in a separate region to enable comparison with the origins from the PNW.

Each of the seven experiments was a randomised block (Appendix 1) but it should be noted that at establishment the number of trees per plot varied between 100 (3 sites), 36 (1 site) and 8 (3 sites). In the analysis height and survival after 10 years and height, diameter and form data after 56 years were analysed. The response variables height and diameter were analysed by linear mixed models using the method of residual maximum likelihood (REML). The form scores and survival were analysed by generalised linear mixed models (GLMM), fitting a binomial error distribution and logit link function with the dispersion parameter estimated as part of the model-fitting process.

The structure of the data for modelling was that there were seven experiments (sites) each with between one and 12 blocks (blocks) and the 18 seed origins (seed origins) were treated as samples of the seed regions (regions) within which they were located as described in Table 1. In each model, the effects of sites, regions, and their interaction were defined as fixed (constant + site + region + site.region). The random effects were blocks within sites and seed origins within regions (site.block + region.seed origins). All statistical analyses were undertaken using Genstat 17 (Payne *et al*., 2009).

2.3 Results: seed origin and site

2.3.1 Survival at year 10

- This was generally high for all seed origins planted in the experiments with all regions and six of the seven sites having a survival of >80% (Table 3).
- Analysis showed that there were no significant differences between regions.

2.3.2 Height at year 10

- Analysis showed that heights were significantly different between the regions and that regions 4 and 5 had the tallest trees (and were significantly taller than those in regions 1 and 3, $p<0.05$) (Table 4).
- The seed origins from the British Isles (Region 6) were ranked third tallest at year 10 but were only significantly different ($p<0.05$) to those in Region 1.

2.3.3 Top height

- After 56 years, top height of the seed origins ranged between 17.0 m (Juneau, Thetford) and 32.8 m (Courtenay, Fonab) (Table 1). The estimates of top height were used to give an indication of GYC and these ranged between <12 and >22, with the most productive sites being Brecon, Fonab and Rheidol, followed by New Forest and Alice Holt, with Thetford being the least productive.
- There was no significant difference between any of the regions (Table 5). Those from the British Isles (Region 6) were as productive as those from the PNW.
- There were significant differences between the sites with Thetford (B) being lowest at 20.0 m and Fonab the highest at 29.8 m (Table 5).

2.3.4 Diameter

- After 56 years mean diameters ranged between 18.3 cm (Region 1; Thetford (B) and 45.5 cm (Region 6; Brecon) (Table 6).
- There were significant differences between the regions with the order being 5>4>6>2>3>1.
- There were significant differences between sites but as Fonab, a productive site, had some of the lowest diameters it is difficult to separate the effects of site and differences caused by thinning.

2.3.5 Form score

- Analysis showed there were significant differences between regions with 1,2 and 3 having <80% trees as score 1 or 2 and regions 4,5 and 6 with >80% trees as score 1 or 2 (Table 7).

2.4 Discussion and conclusions

2.4.1 Seed origins

1. When considering the results of these experiments it is important to understand their history. Initially six experiments were established in Scotland in 1960/61 (Lines and Aldhous, 1961) and then a further 13 experiments were added in 1961/62, which were generally in England and Wales. The winter of 1962/63 was exceptionally severe and this resulted in the failure of three experiments and serious dieback on those planted without side or overhead shelter. Of the 16 sites included in the reports of Lines and Mitchell (1969) and Lines *et al*. (1972), six are recorded as being established under the cover of an overstorey. Of these six sites, five were included in this study and only one that was established by afforestation on bare land (Fonab) has survived.

2. The most comprehensive previous analysis of these experiments was carried out by Lines and Mitchell (1969) using data after six years. Results for each of the 16 sites were analysed using ANOVA and this showed that at 10 sites there were significant differences between provenances ($p<0.001$); however, no 'cross site' analysis was undertaken. A large table is presented in which each provenance is shown as a % of the tallest on that site in addition to a ranking. Data on latitude, altitude and rainfall for each the seed collection sites is given as well as latitude, altitude, rainfall and presence of overhead cover, for each of the 16 experimental sites.

3. The main recommendation of Lines and Mitchell (1969) was that it is too early to choose provenances for wider use from the evidence presented but indications were that for exposed sites in northern areas a choice could be made from the northern and high altitude provenances from Juneau, Prince Rupert and Masset, while for sites with overhead cover or in the more southerly parts of the country the southern, low-altitude provenances from Leaburg and Camano Island, together with the home-collected seed from Inveraray, could be used. A good all-round provenance from the middle of the range was that from Courtenay, Vancouver Island.

4. A subsequent (less detailed) analysis of the 10-year data by Lines *et al*. (1972) showed very similar results to that from the six-year data. However, there is a subtle difference in the presentation of the results which tend to be grouped into regions such as Alaska, Vancouver Island, Queen Charlotte Islands and Oregon (similar to the regions in this report). In summary, there was a clear pattern of higher survival and growth of the northern origins on exposed sites, while on the sheltered sites, southern origins (including the Inveraray collection) grew best.

5. An important point about this study is that it reports results mainly from fertile, sheltered sites in the south of Britain. Most of the more testing northerly sites

have not survived, except Fonab 1, which was included in this study. Because of this there is a danger than any recommendations based on this study alone will only be applicable to southern Britain. However, this needs to be balanced against the fact that many of the experiments established on northern, upland sites did not deploy western hemlock in manner that suited its silvicultural characteristics, i.e. it was planted on open, exposed sites. As a result of this the following results and recommendations assume that western hemlock will be used in a way that suits its silvicultural characteristics.

6. Results of the analysis of the data at year 10 show that there were no significant differences between regions for survival. However, there were significant differences in height with those from regions 4 and 5 of the PNW and the two collections from the British Isles being the tallest. This confirms the results of the earlier analysis by Lines *et al*. (1972).

7. Results of the analysis of the data at year 56 indicate that differences between the regions in height have become less pronounced. In fact, for the later assessments the only significant result is for the form of the trees, which indicates better form for regions 4, 5 and 6.

8. A notable difference between this series of seed origin experiments and those for other species such as western red cedar (Kerr, 2019) is the inclusion of two provenances from the British Isles (Inveraray, Argyll, likely origin Oregon; Avondale, Ireland, likely origin northern British Columbia (Lines and Aldhous, 1963)). Interestingly, the Inveraray provenance was seed collected from the first plantation of western hemlock in Britain (Lines, 1987). Both of these provenances have performed well in the trials and provide good evidence that future work on seed origins of western hemlock should include home collected material as a major component.

9. The present recommendation on the FR species and provenance webpage is that 'provenances from Vancouver Island are recommended, although more southerly origins could be used on sheltered sites with low frost risk'. This is somewhat more generic than published by Lines (1987; reproduced below) which is keen to identify good local areas for seed collection rather than broad regions. The results of this study support the recommendations on the FR website but could include: (a) recommended origins to be wider than just Vancouver Island and (b) guidance on home collected provenances. A revised text would be: 'provenances from Vancouver Island and the Cascades of Washington and Oregon are recommended for sites where ESC (Pyatt *et al*., 2001) indicates western hemlock is suitable, frost risk is low and it is not planted on open, exposed sites. A small number of provenances from the British Isles have performed well in experiments and are worthy of consideration.'

2.4.2 Silviculture

1. Western hemlock is a productive forest tree in Britain and with good provenance choice achieved GYC 14-22 on six sites with mineral soils but widely varying rainfall and temperature. This finding supports the thoughts of Wood (1955) that 'it is not possible to suggest any broad climatic limitation which is likely to operate in Britain. It obviously exceeds (in the PNW) the range inside which we operate'. This has been verified by the analysis of Jinks (2017).

2. The FR webpage also suggests western hemlock is 'best suited to moister climates in Britain with >1000 mm rainfall'. Evidence from Jinks (2017) and the sites reported here would support a change to this such as 'can be a productive forest tree on sites with >800 mm annual rainfall with the most productive sites having >1000 mm rainfall'.

3. The main conclusion of the review by Cameron and Mason (2013) is that the silvicultural attributes of western hemlock are best suited to mixed species stands and irregular structures rather than planted pure on open sites. The history of these experiments fully supports the recommendation that western hemlock should not be planted on open, exposed sites. Ideally, this should be an assumption when giving advice on the best provenances to use.

4. Cameron and Mason (2013) make the point that western hemlock has a poor image in the forestry sector but has great potential to make a greater contribution (Aldhous and Low, 1974). To close the gap between reality and potential, more work to confirm the timber properties of UK grown western hemlock would be justified. The existing data in Ramsay and Macdonald (2013) and Gil-Moreno *et al*. (2016) is based on small sample sizes and probably tested material from trees grown on open sites, which may not produce the best wood characteristics.

5. The existing literature (Savill, 2019) also makes reference to the characteristic features of the lower stem of western hemlock, enhanced taper and fluting, and more work on these may lead to a better understanding of the causes and how these features that tend to reduce value could be controlled.

Extract from Lines (1987) on western hemlock

'Recommendations

1. Vancouver Island sources, e.g. Courtenay (BC Region 1020), are good general purpose origins, while on dry sheltered sites in the south and east of England, Camano Island, Washington (Region 122) grows very well.

2. For sheltered sites in northern Britain, Alaskan origins are the hardiest, but may later grow less fast than those from the Queen Charlotte Islands.'

3.0 Tables and Figures

Table 1: Summary of the western hemlock seed origin locations and GYC** at the experiment sites

Seed origin	Location	Region	State	Lat. (°N)	Lon. (°W)	Ann. Rainfall (mm)	Dist to coast (miles)	Top height (m) and GYC					
								New Forest	Thetford	Alice Holt	Rheidol	Brecon	Fonab
57(7987)1	Juneau	1	AK	58.5	N/A	2134	0	28.4	17.0	27.8	27.5	28.5	28.7
57(7112)2	Prince Rupert	1	BC	54.5	N/A	2540	0	26.5	21.2	28.0	27.4	27	29
57(7111)1	Massett, QCI	2	BC	54.0	N/A	1422	0	28.0	17.7	29.3	28.3	27.9	30.3
57(7111)2	Skidegate, QCI	2	BC	53.5	N/A	1524	0	27.0	22.4	27.0	30	29.2	30.1
57(7114)1	Terrace; Skeena River (i	3	BC	54.5	N/A	1270	110	27.5	18.7	24.8	28.5	28.5	28.9
58(7118)1	Shuswap Lake (int)	3	BC	51.0	N/A	660-1016	300	26.4	20.8	24.7	28.6	29.5	*
57(7116)2	Courtenay, Van. Island	4	BC	49.5	N/A	1676	0	29.0	23.3	27.1	28.8	29.6	32.8
57(7116)1	Alberni, Van. Island	4	BC	49.5	N/A	660-1016	0	27.6	24.7	24.7	30.4	28.7	31.7
57(7116)4	Ladysmith, Van. Island	4	BC	49.0	N/A	660-1016	0	29.1	24.0	30.9	30	28.2	30.4
57(7116)3	Sooke, Van. Island	4	BC	48.5	N/A	660-1016	0	29.7	24.0	*	30.8	31.3	28.2
57(7973)1	Camano Is, Puget Sound	4	WA	48.0	N/A	483	0	30.8	25.8	32.1	30.6	30.9	29.9
57(7971)1	Forks, Olympic Pens.	4	WA	48.0	N/A	2921	10	28.8	22.8	31.3	29.8	30.6	28.9
57(7975)5	Enumclaw, Cascades	5	WA	47.0	N/A	1168	100	27.5	20.6	28.5	27.6	26.1	29.3
57(7975)3	Randle, Cascades	5	WA	46.5	N/A	1575	100	29.5	24.4	26.9	29.5	29.2	30.6
57(7953)2	Cascadia, Cascades	5	OR	44.5	N/A	1575	80	29.9	24.0	30.5	29.2	30.8	30.4
57(7953)4	Leaburg, Cascades	5	OR	44.0	N/A	1448	70	29.0	22.9	26.0	29.6	28.5	30.8
57(4184)100	Avondale, Co. Wicklow	6	Ireland	53.0	N/A	?	10	25.1	25.6	15.5	30.1	26.1	27.1
58(4131)16	Inverary, Argyll	6	Scotland	56.0	N/A	?	0	29.3	23.7	27.9	30.7	30.6	32.4

Notes:

* Missing plots

**General Yield Classes (GYC) based on Matthews *et al*. (2013).

Alice Holt 130 was planted in 1963 but plants were the same age (56 y.o.) as other sites when assessed.

Colour codes for GYC	
Dark green	≥22
Green	18-20
Yellow	14-16
Red	≤12

Table 2: Summary of experimental sites **(from ESC version 4 and experimental files)**

Site	Lat. (°N)	Long. (°W)	NGR	P. Year	DAMS	AT5	SMR	SNR	Suitability	Ann. rainfall (mm)
New Forest	51.00	-1.70	SU179168	1962	11	1893	4 (moist)	2 (poor)	0.72 Suitable	870
Thetford	52.50	0.62	TF768922	1962	12	1804	6 (sl. dry)	6 (carb.)	0.66 Suitable	620
Alice Holt	51.20	-0.90	SU788424	1963	10	1826	5 (fresh)	3 (medium)	0.63 Suitable	800
Rheidol	52.50	-3.94	SN684840	1962	17	1332	5 (fresh)	2 (poor)	0.52 Suitable	1450
Brecon	52.00	-3.37	SO056379	1962	15	1192	5 (fresh)	3 (medium)	0.67 Suitable	1260
Fonab	56.70	-3.74	NN933542	1962	10	1149	6 (sl. dry)	1 (v. poor)	0.31 Marginal	950

Site	Soil	Silviculture of establishment
New Forest	Clay loam (1)	Planted under 'tall' EL overstorey
Thetford	Podsol (3)	Underplanting of mature Scots pine
Alice Holt	Clay loam (1)	Dense hazel coppice (4-5m) and sparse ash and birch 'poles' (8-12m)
Rheidol	Upland BE (1u)	Planted under 'poor' (10-12 m) EL overstorey
Brecon	Upland BE (1u)	Planted under EL
Fonab	Upland BE (1u)	Bracken covered slope (rough grazing) with deer present

Table 3: Survival (%; year 10) of Seed origins by region and site

Region	Alice Holt*	New Forest	Thetford A	Thetford B	Rheidol	Brecon	Fonab	Mean
1	-	93.3	98.4	71.9	90.9	89.6	93.4	91.0
2	-	92.5	87.5	60.9	88.4	94.3	95.4	90.3
3	-	95.4	89.1	59.4	92.1	96.4	86.8	91.4
4	-	95.2	93.8	67.2	89.8	92.2	83.0	90.0
5	-	94.4	97.7	73.4	86.3	94.0	80.9	88.3
6	-	92.6	89.1	62.5	85.6	84.4	79.5	85.6
Mean	-	94.9	94.2	68.7	90.3	93.6	86.9	

GLMM analysis showed that site (p<0.001) was significant but not region (p=0.334). Means are modelled values whereas site x region data (shaded) are actual means. *Data for Alice Holt were excluded from the analysis as trees were planted into coppice and this had differentially affected results for regions 4-6.

Table 4: Mean height (m; year 10) of seed origins by region and site

Region	Alice Holt	New Forest	Thetford A	Thetford B	Rheidol	Brecon	Fonab	Mean
1	4.14	5.42	4.20	3.16	4.67	4.53	3.52	4.18
2	3.95	6.39	4.71	3.70	5.00	4.90	3.90	4.67
3	4.65	6.02	4.60	3.73	4.59	5.01	2.93	4.49
4	4.44	7.25	4.90	4.19	5.44	5.45	3.40	5.03
5	4.61	6.68	4.71	3.97	5.22	5.50	3.24	4.89
6	4.53	6.58	4.79	3.72	5.32	5.21	2.89	4.72
Mean	4.34	6.51	4.61	3.76	5.04	5.12	3.27	

REML analysis showed that region (p=0.029) and site were significant (p<0.001). Means are modelled values (region SED=0.24) whereas site x region data (shaded) are actual means.

Table 5: Top height (m; year 56) of seed origins by region and site

Region	Alice Holt	New Forest	Thetford A	Thetford B	Rheidol	Brecon	Fonab	Mean
1	27.9	27.4	19.1	16.6	27.4	27.7	28.8	25.1
2	28.1	27.5	20.4	18.2	29.1	28.6	30.2	26.1
3	24.7	27.0	19.7	20.2	28.5	29.1	28.9	25.9
4	29.2	29.2	24.1	21.5	30.0	29.9	30.5	27.7
5	28.0	29.0	23.2	21.9	29.0	28.8	30.3	27.0
6	21.7	27.2	24.1	19.5	30.4	28.6	29.4	26.1
Mean	26.9	27.9	22.1	20.0	28.9	28.6	29.8	
REML analysis showed that region was not significant (p=0.106) but site was (p<0.001). Means are modelled values (region SED=0.987) whereas site x region data (shaded) are actual means.								

Table 6: DBH (cm; year 56) of seed origins by region and site

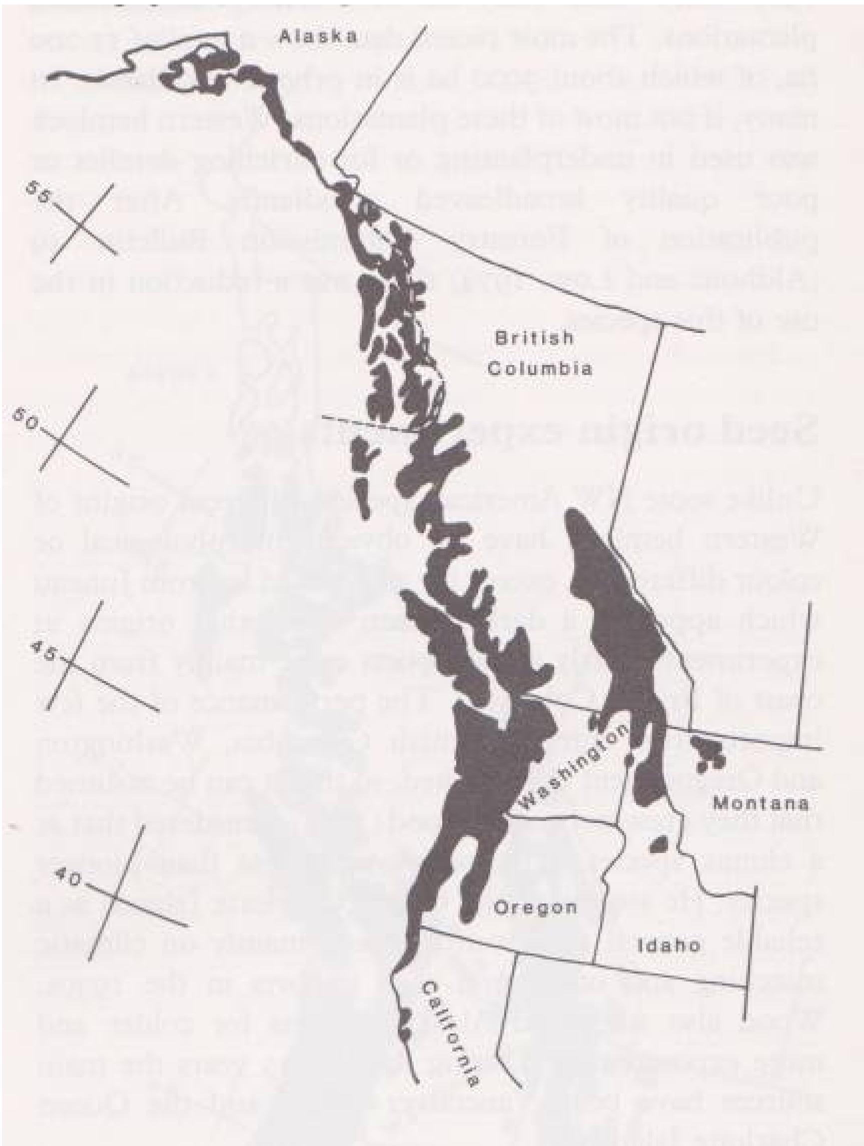
Region	Alice Holt	New Forest	Thetford A	Thetford B	Rheidol	Brecon	Fonab	Mean
1	27.7	38.2	21.0	18.3	27.3	31.6	22.9	26.1
2	29.1	40.2	19.0	21.6	29.1	40.1	25.3	29.7
3	26.8	40.4	19.5	25.5	28.5	38.1	22.6	29.1
4	33.8	42.6	26.9	26.9	29.8	44.1	27.5	33.1
5	33.0	43.7	27.2	28.4	29.6	44.3	28.2	33.5
6	38.0	42.0	26.5	21.4	30.8	45.5	25.6	32.5
Mean	31.0	40.9	23.6	24.1	28.5	41.2	25.4	
REML analysis showed that region was significant (p=0.004) as well as site (p<0.001) but the latter is probably due to differential thinning between sites. Means are modelled values (region SED =1.68) whereas site x region data (shaded) are actual means.								

Table 7: Form* (year 56) of seed origins by region and site

Region	Alice Holt	New Forest	Thetford A	Thetford B	Rheidol	Brecon	Fonab	Mean
1	0.88	0.95	0.50	0.33	0.43	0.58	0.95	0.74
2	0.94	0.95	0.44	0.33	0.50	0.30	0.96	0.77
3	0.62	1.00	0.50	0.71	0.52	0.50	0.97	0.77
4	0.85	0.97	0.73	0.80	0.58	0.55	0.95	0.82
5	0.80	0.97	0.77	0.90	0.63	0.65	0.96	0.85
6	0.90	1.00	0.90	1.00	0.70	0.55	0.89	0.87
N	250	261	98	69	2204	261	987	
Mean	0.83	0.97	0.68	0.74	0.56	0.74	0.95	

*Form is the proportion of trees with a form score of 1 or 2.
GLMM analysis showed that region was significant (P=0.039) as well as site (P<0.001). Means are modelled values whereas site x region data (shaded) are actual means.

Figure 1: The species range of *Tsuga heterophylla* as shown in Lines (1987)



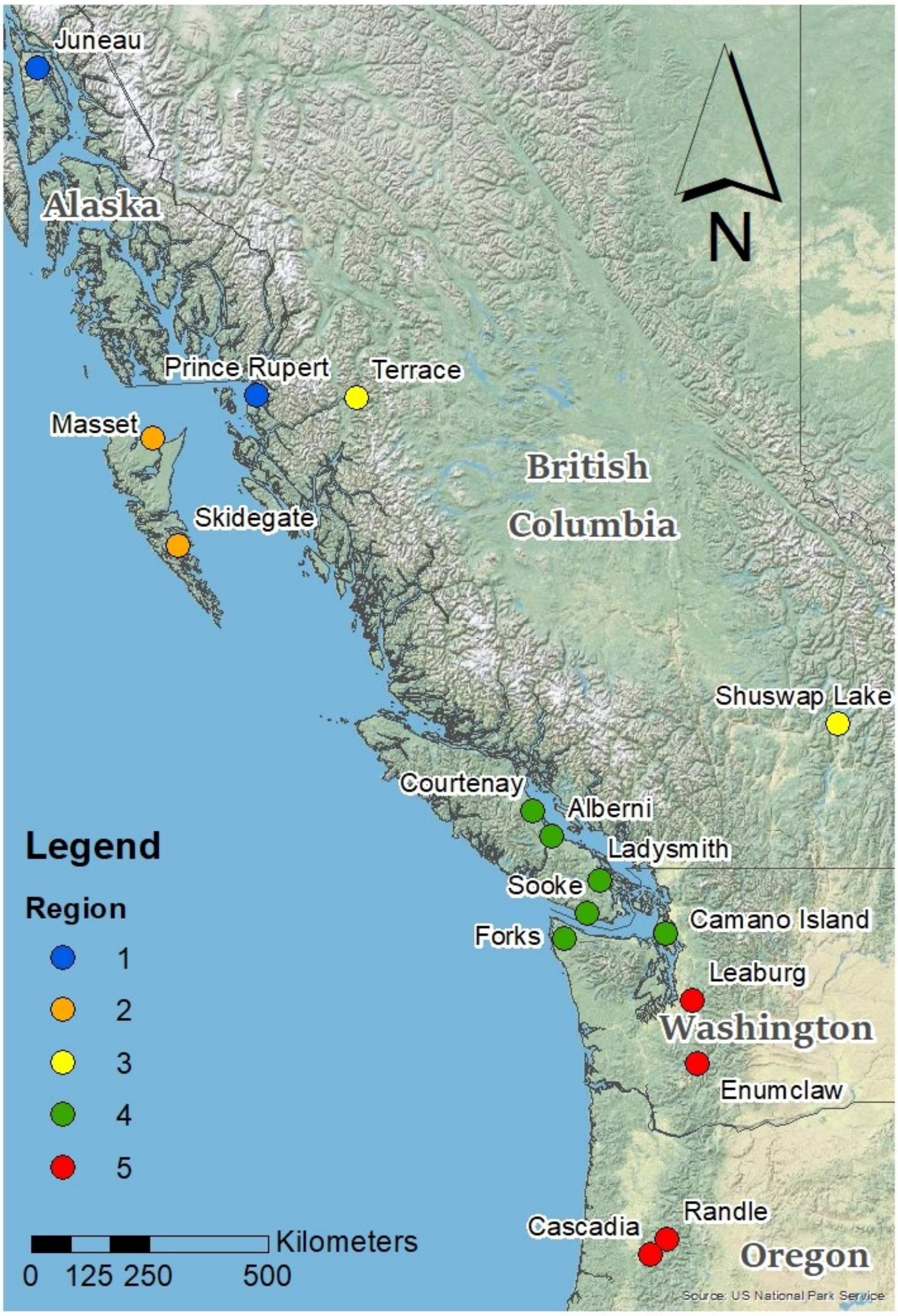


Figure 2: Map showing the approximate locations of the seed collections and how they were grouped into 'regions' for this study

Figure 3: Map showing the approximate locations of the experiment sites in Britain

4.0 References and acknowledgements

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4.2 Acknowledgements

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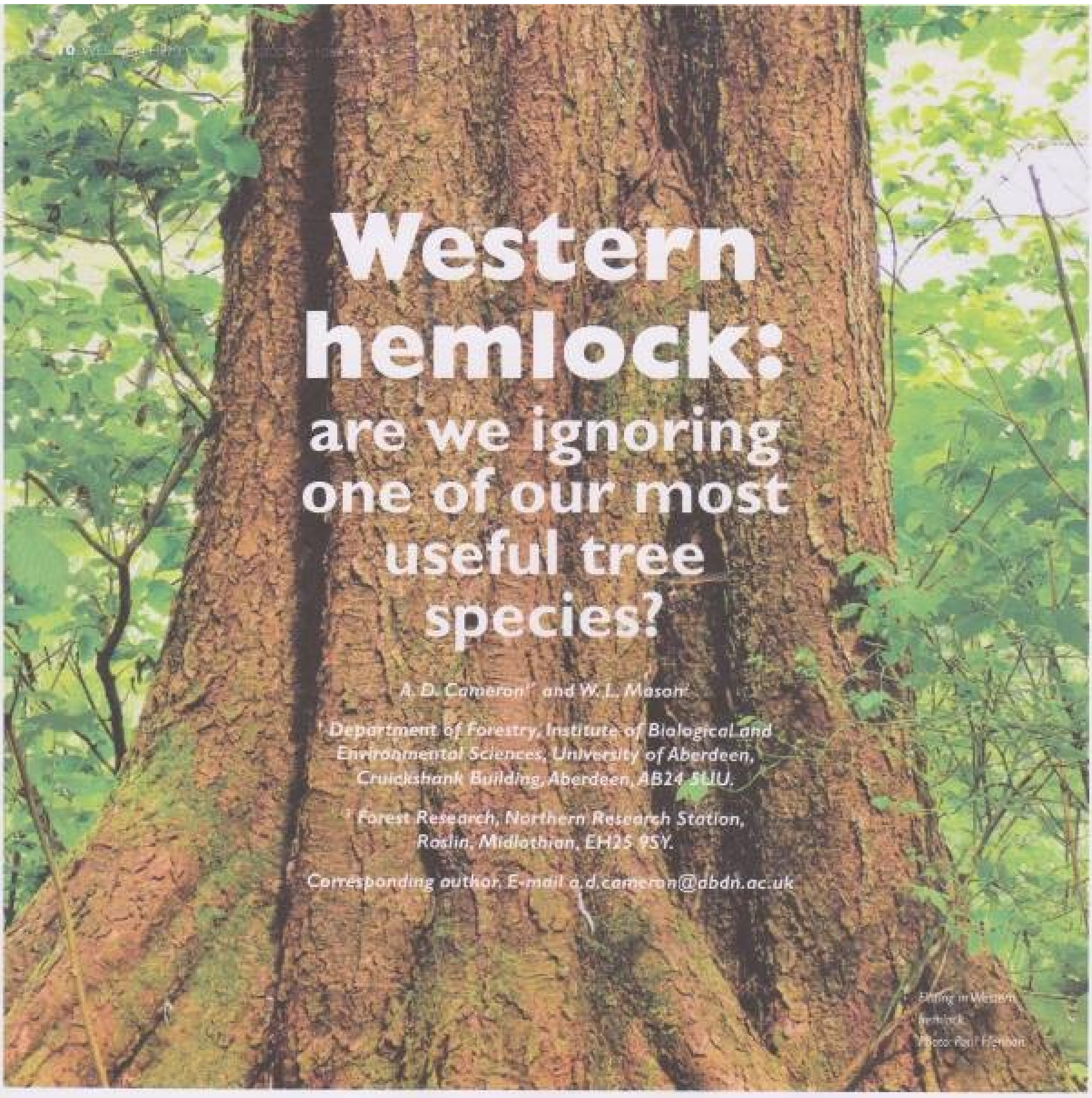
Appendix 1: Note on experimental designs and approach to analysis

Experiment	Experiment design as shown in plan	Experiment design assumed for analysis
Alice Holt 130	The plan states ‘randomised block’, the layout was 3 complete blocks with 108 tree plots, 9 x 12 (1.52 x 1.52 m)	A randomised block experiment with 18 treatments (seed origins); only one of the three blocks was ‘assessable’ in 2017/18 and two of the seed origins were missing.
Brecon 5	A randomised block experiment with 18 treatments (seed origins) and 12 blocks. 8 tree plots, 2 x 4	A randomised block experiment with 18 treatments (seed origins) and 12 blocks
Fonab 1	The plan shows 18 treatments (seed origin) in 4 complete blocks. 36 tree plots, 6 x 6	A randomised block experiment with 18 treatments (seed origins) and 4 blocks
New Forest 14	A randomised block experiment with 18 treatments (seed origins) and 4 blocks; 100 tree plots, 10 x 10	A randomised block experiment with 18 treatments (seed origins) and 4 blocks
Rheidol 3	A randomised block experiment with 18 treatments (seed origins) and 4 blocks; 100 tree plots, 10 x 10	A randomised block experiment with 18 treatments (seed origins) and 4 blocks
Thetford 73 A & B	Each is a randomised block experiment with 18 treatments (seed origins) and 4 blocks. 8 tree plots, 2 x 4	A randomised block experiment with 18 treatments (seed origins) and 4 blocks

Appendix 2: Copy of paper by Cameron and Mason (2013)



Western hemlock: are we ignoring one of our most useful tree species?

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Summary

Recent damaging insect and fungal attacks on forest stands in Scotland have highlighted our reliance on a very limited range of commercial tree species and this has initiated discussion on the need to consider alternative species. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) appears to have many of the attributes of a successful commercial timber-producing species. It is adaptable to a wide range of sites, has a good growth rate and desirable timber properties, regenerates freely, and to date has not succumbed to damaging biotic agents. However, western hemlock has a poor image within the forestry sector. This view may in part be based on experience of this species grown in open plantations at relatively wide spacings. In this review we suggest that the silvicultural attributes of western hemlock are better suited to mixed species stands and irregular structures rather than planted pure on open sites. When grown under appropriate conditions, the evidence suggests that the mechanical and working properties of western hemlock timber are equivalent to, or superior than, other commonly grown species.

Introduction

Forestry in Scotland is dominated by a small number of mainly shade intolerant or intermediate species such as Scots pine (*Pinus sylvestris* L.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) that are suited to the clear-cutting system. Foresters are now under pressure to create forests that are more diverse in terms of species and stand structure to meet the multiple and changing needs of society. Furthermore, given the uncertainties associated with projected climate change combined with an increasing threat from introduced pests and diseases, it is recognised that we can no longer afford to rely on a limited number of species to supply the future needs of industry. Discussions on expanding the range of species used in forests in Scotland have highlighted the need for more shade tolerant species to be considered (*e.g.* Wilson, 2007), particularly as interest in developing irregular stand structures has increased. Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) has many of the attributes required to be successful in planted mixed stands and irregular stands in Britain. It is very shade tolerant and regenerates freely even under dense canopy cover. The mechanical properties of western hemlock timber make it suitable for a wide variety of end uses, such as construction and interior joinery. Notwithstanding these positive attributes, western hemlock is generally not held in high regard in Scotland, or indeed elsewhere in Britain. The capacity of western hemlock to regenerate freely has created the reputation of it being 'invasive' and has even resulted in an active policy of eradication. In addition, the timber is generally not highly valued by wood-using industries. The aim of this article is to examine the reasons behind the negative attitude towards this species, to discuss the potential of western hemlock as a quality timber-producing tree in Scotland, and to recommend the most appropriate silvicultural methods to achieve this potential.

Background and site conditions

Western hemlock was introduced into Britain in 1851 and has become naturalised in many parts of the country. It is native to the west coast of North America, covering a latitude range from California to Alaska, and an elevation range from sea level to 2,250 m (Savill, 1991). The species will grow on a range of soil types from gleys to ironpans although best growth is on deep brown earth soils with adequate soil moisture (Burns and Honkala, 1990). Its capacity to grow on drier soils typical of eastern Britain has been acknowledged and the incidence of drought crack in stems was observed to be low compared with Abies species (Aldhous and Low, 1974). It can tolerate periods of water-logging better than Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and will tolerate nutrient poor soils more effectively than other high yielding conifers (Lines 1987). When compared with Sitka spruce, western hemlock has significantly lower moisture and nutritional requirements (Wood, 1955). In common with many other conifer species, calcareous soils should be avoided as it is susceptible to lime-induced chlorosis (Strouts and Winter, 2000). Planting of western hemlock in Britain has been mainly confined to fertile sites at relatively wide (≥ 2 m) spacing where growth rates of 24 $m^3 ha^{-1} year^{-1}$ are possible (Lines, 1987). Currently, there are around 1000 hectares of western hemlock in Britain.

Silviculture

Regeneration potential

In its native range, western hemlock occurs naturally in both pure and mixed stands. Forests comprising mixtures of western hemlock with either Sitka spruce or Douglas fir in the Pacific north-west of North America are recognised as the most productive natural forests in temperate regions (Burns and Honkala, 1990; Smith *et al.*, 1997), and therefore have an important role as carbon sinks. Western hemlock is known to regenerate freely even under quite dense canopies. It is probably for this reason that hemlock has a reputation of being invasive. It will also tolerate suppression in heavy shade for many years and has been reported to respond well with strong apical growth following canopy removal after periods in the shade in excess of 50 years (Burns and Honkala, 1990). Fears that western hemlock will eventually dominate the regeneration pool within mixed species stands have not been borne out by research. An investigation on the effects of partial opening of the canopy in mixed western hemlock-Sitka spruce stands in southeast Alaska showed that both species regenerated adequately provided that the reduction in basal area was sufficient to favour the spruce (Deal and Tappeiner, 2002). This supports findings from studies under British conditions that suggests limiting basal areas for successful regeneration of < 40 m^2ha^{-1} for western hemlock (Hale, 2004) and < 30 m^2ha^{-1} for Sitka spruce (Page *et al.*, 2001; Hale, 2001). By maintaining a lower basal area that favours the less shade tolerant Sitka spruce, foresters should enable successful regeneration of both species.

Western hemlock responds with strong apical growth even after 50 years in the shade. Photo: FCS

Competition within mixed-species stands

Concerns that western hemlock will eventually dominate mixed species stands also appear to be unfounded. Hemlock has been noted to form the sub-dominant species in mixtures with either Sitka spruce or Douglas fir (Smith *et al.*, 1997; Wierman and Oliver, 1979; Wood, 1955). Only where soil moisture and fertility are limiting can the more drought resistant western hemlock come to dominate Sitka spruce (Wood, 1955). The relative dominance of both Douglas fir and Sitka spruce over western hemlock in natural forests is attributable to several factors regarding the dynamics of the species associations. A higher mortality rate was observed for western hemlock than for Douglas fir in stands where the two species grow together (Wierman and Oliver, 1979). The abrasive action of the stiff branches of both Douglas fir and Sitka spruce are thought to damage the delicate leaders of western hemlock (Oliver and Larson, 1996). Sitka spruce was observed to sustain a higher growth rate for a longer period than western hemlock, and eventually overtop and stratify above the hemlock (Harcombe, 1986). Diameter increment in Sitka spruce was found to be greater following thinning in comparison with western hemlock (Newton and Cole, 2012). This is consistent with observations made at Novar Estate near Inverness in Scotland where Sitka spruce is observed to dominate western hemlock where trees are of similar age (Cameron Ross, pers. comm.) and in two experimental plots in Wales (Table 1). In these plots where Sitka spruce and western hemlock were planted pure and in 50:50 mixtures and grown on a non-thin regime, Sitka spruce has become the dominant species in the mixed stand within 30-35 years after planting. Published data for even-aged stands in Britain show that under comparable initial planting spacing and growth rate, Douglas fir and Sitka spruce will sustain a higher height growth rate for a longer period of time than western hemlock (Edwards and Christie, 1981).

Table 1. *Performance of western hemlock in mixture with Sitka spruce in two experiments in south Wales*

Experiment	Age of last assessment	Basal area pure Sitka spruce (m^2 ha^{-1})	Basal area pure western hemlock (m^2 ha^{-1})	Basal area mixture (m^2 ha^{-1})	Sitka spruce as per cent of basal area in mixed plots
Dunraven 1	48	74.8	71.5	25.8	81
Margam 1	34	46.4	n/a	47.8	78

Biotic and abiotic damage risks

Western hemlock is considered to be an unsuitable species on sites planted in the open as it can suffer high losses, mainly due to frost damage, but also from exposure (Lines, 1987), and should preferably be planted in mixture with a faster-growing species to provide protection (Savill and Evans, 1986). The sheltered conditions associated with irregular stands are highly suitable for the establishment of this species due to the presence of a protective canopy cover (Aldhous and Low, 1974). The typically shallow and delicate root system of western hemlock leave this species subject to damage from heavy machinery as well as windthrow in areas of high wind risk (Burns and Honkala, 1990) and highlights the importance of permanent extraction racks and good brash mats to protect the racks.

There are mixed opinions on whether western hemlock is more vulnerable to fungal diseases than other common conifer species on similar sites in Britain. Aldhous and Low (1974) suggested that hemlock may be more susceptible to *Heterobasidion annosum* (Bref.) than grand fir (*Abies grandis* (Lamb.) Lindl.). Western hemlock can be attacked by *Heterobasidion annosum* and *Armillaria* spp., but these fungi are generally restricted to soils with a relatively high pH (Woodward *et al.*, 1998). Hemlock has been traditionally planted on better quality, less acidic soils in Britain and therefore observations on the preponderance of decay in hemlock logs may be confounded by site type. Harvesting damage to standing trees, however, appears to increase the susceptibility of western hemlock to infection in comparison with other species. A study on the occurrence of decay in western hemlock and Douglas fir trees following thinning damage in Pacific Northwest forests showed that over 60% of wounds on hemlock had decay, and that *Heterobasidion annosum* accounted for 80% of the decay volume; whereas, only 23% of wounds on Douglas fir stems had decay fungi present (Hunt and Krueger, 1962). The authors suggested that the protruding flutes at the base of the hemlock may have contributed to the likelihood of damage caused by timber extraction and that skidding was the main cause of damage. A further study on the presence of decay in damaged trees, this time in western hemlock and Sitka spruce in Alaska, indicated that 79% of the hemlock and 53% of the spruce had decay present (Hennon and DeMars, 1997). While excessive extraction damage should be avoided in all managed forests, it would appear that western hemlock may be more susceptible to decay than other commercial species once damage has occurred. There is no evidence of any insect or animal pest that may constitute a particular risk to western hemlock in comparison with other commonly-grown conifer species (Aldhous and Low, 1974).

Stem and wood properties

The strength properties of western hemlock timber, in terms of compression strength, hardness and modulus of rupture, are somewhere between those of Sitka spruce and Douglas fir (Tsoumis, 1991). Sawn hemlock timber has a light, uniform colouration, sands to a fine finish and is resin free. It accepts preservatives moderately well, has good nailing properties and is hard wearing; making this species suitable for a range of uses (Jozsa *et al.*, 1998). The potential of western hemlock in North America was only realised in the 1930s when drying techniques were developed that reduced the incidence of warping, surface checks and cracking in seasoned timber (Jozsa *et al.*, 1998). The timber is currently used as a construction material, where it is often used interchangeably with Douglas fir, and it is also extensively used for interior fittings. Low quality wood is used for paper and particle board manufacture.

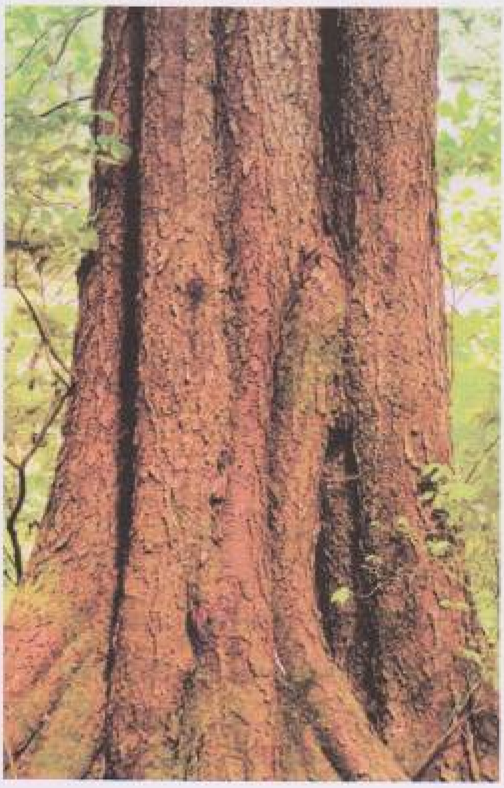
Much of the hemlock timber used in North America in the past came from natural 'old-growth' stands that have a reputation for high quality stems. Increasingly, hemlock is sourced from 'second growth' or plantation stands and significant research emphasis has been focused on timber performance (Jozsa *et al.*, 1998; Bradic and Avramidis, 2007). The fast early growth of western hemlock growing under favourable 'plantation' conditions results in the development of a high proportion of juvenile wood within the stems when compared with trees from natural stands, and this leads to differential longitudinal shrinkage and hence warping of the sawn timber (Jozsa *et al.*, 1998; Bradic and Avramidis, 2007). A high proportion of juvenile wood also has negative effects for the production of Kraft pulp from this species (Kennedy, 1995). The demand for western hemlock timber is also influenced by the incidence of fluting on stems used for sawn timber (McClellan, 2005). It is thought that fluting occurs as a result of a combination of inherited and environmental factors. It occurs throughout the range of the species suggesting a genetic influence; however, an increased incidence of fluting has been observed in even-aged stands and in areas of high winds indicating an environmental effect (Julin *et al.*, 1993). Importantly, a reduced incidence in fluting has been observed where hemlock is subordinate to other species in mixed stands (Julin *et al.*, 1993). Generally, silvicultural practices that encourage rapid growth and wider spacing are associated with more extensive fluting (Singleton *et al.*, 2003). Despite having better strength properties than Sitka spruce, the timber of western hemlock has been regarded unfavourably by British wood processors. The stronger colour also means that it is not readily accepted for pulp and particle board. The variable quality of timber in older stands that have suffered from early frost damage and a subsequent lack of thinning has also made it difficult to sell sawlogs because of the incidence of fluting or otherwise distorted stems. Hence, the use of western hemlock is largely limited to the production of products where quality is not an issue.

Western hemlock in a mixed stand. Notice the lack of strong fluting on the nearest hemlock tree (foreground right).

Conclusions

Evidence from a range of studies suggests that many of the concerns associated with western hemlock as a commercial tree species in Scotland appear to be unfounded. The reputation for poor quality timber may in part be due to the limited experience of this species in this country. There is only a small area of western hemlock stands in Scotland and these mainly comprise pure species growing on relatively fertile sites. Under these 'plantation' conditions, the fast early-growth is known to be associated with excessive development of juvenile core wood resulting in excessive warping of sawn timber (Jozsa *et al.*, 1998; Bradic and Avramidis, 2007). However, early growth of western hemlock can be controlled when grown in mixture with other species, and the tendency of hemlock to stratify beneath a dominant canopy of Douglas fir and Sitka spruce has the effect of suppressing the lower branches of the dominant species resulting in reduced branch and knot size and improved timber quality of the latter. Control of the early growth of hemlock also restricts juvenile wood content leading to timber of a more uniform quality and the consequential effect on limiting the risk of distortion on drying. Sitka spruce and Douglas fir suit the cool maritime climate of Scotland and are the most obvious species to have in mixture with western hemlock. Both species grow well here; Douglas fir preferred on more sheltered and better quality sites, and Sitka spruce used in wetter, more exposed and less fertile areas.

The capacity of western hemlock to tolerate shade combined with the considerable and reliable ability to regenerate emphasises the potential value of western hemlock as a species suited to irregular silvicultural systems. This is particularly true of the selection systems that depend strongly on the presence of shade tolerant species that are responsive to canopy openings. In Scotland, there are few suitable alternative shade tolerant conifer species. In Continental European selection forests, European silver fir (*Abies alba Mill.*) is the favoured shade-tolerant conifer species. More recently, Kerr (1999) has argued that European silver fir could find a new role in irregular, mixed species woodlands, where the regeneration environment may limit aphid damage. Alternative shade tolerant species include



An increased incidence of fluting can occur in even-aged stands and in areas of high winds.
Photo: Paul Hennon.

western red cedar (*Thuja plicata* D. Don) and grand fir from North America. Western red cedar does best on very sheltered sites with heavier lowland soils, limiting its use under Scottish conditions (Aldhous and Low, 1974). Grand fir is a better possibility since it performs well on a variety of site types, but it is prone to drought crack and the timber is generally considered to be inferior to that of other commonly grown conifers (Aldhous and Low, 1974).

The presence of western hemlock in irregular forests, especially when mixed with semi-shade tolerant species such as Douglas fir or Sitka spruce, would convey several advantages to the silviculture of the stand. The tendency of this species to stratify beneath a dominant canopy of Douglas fir or Sitka spruce would enhance the vertical heterogeneity of the stand structure and assist in developing the irregular condition. Western hemlock would have the additional effect of suppressing the lower branches of the dominant species resulting in reduced branch and knot size and hence improved timber quality. The shade that it provides will also reduce the extent of competition from ground vegetation and thus potentially enhance the success of natural regeneration of a range of species if and when a seeding felling is undertaken. The capacity of western hemlock to naturally regenerate freely has a downside where the presence of this species is not desired, such as in areas of native woodland where conservation of native species is of high priority. Given its small seed size that is readily dispersed by the wind, 80 per cent of hemlock seed will fall within 100 metres of parent trees that are 20 m tall (Nixon and Worrell, 1999; Table 2.6). This suggests maintaining a buffer zone of at least 200 metres between mature hemlock trees and sites where it is not wanted. The other main concern with western hemlock is the apparent increased risk of fungal infection and decay as a result of harvesting damage and so additional care is needed during felling operations.

We recommend that on sites that are favourable for planting Sitka spruce or Douglas fir, western hemlock should be considered for inclusion as a 50:50 mixture. The evidence presented in this paper suggests that the hemlock will assume a subordinate role to Sitka spruce and Douglas fir with benefits for both species in the mixture. The hemlock will assist in suppressing the branches on the lower part of the stems of the spruce and Douglas fir while the hemlock will benefit with a reduction in the size of the juvenile core and a reduction in the fluting of the stem base. Natural regeneration of western hemlock should be accepted as a mix with other species and the proportion of each species can be controlled by thinning. Western hemlock is suited to under-plant existing single-species stands where greater structural and species diversity is desired. It is also very suitable in mixed-species irregular stand structures given its shade tolerance and capacity to regenerate and grow under permanent canopy cover.

Acknowledgements

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