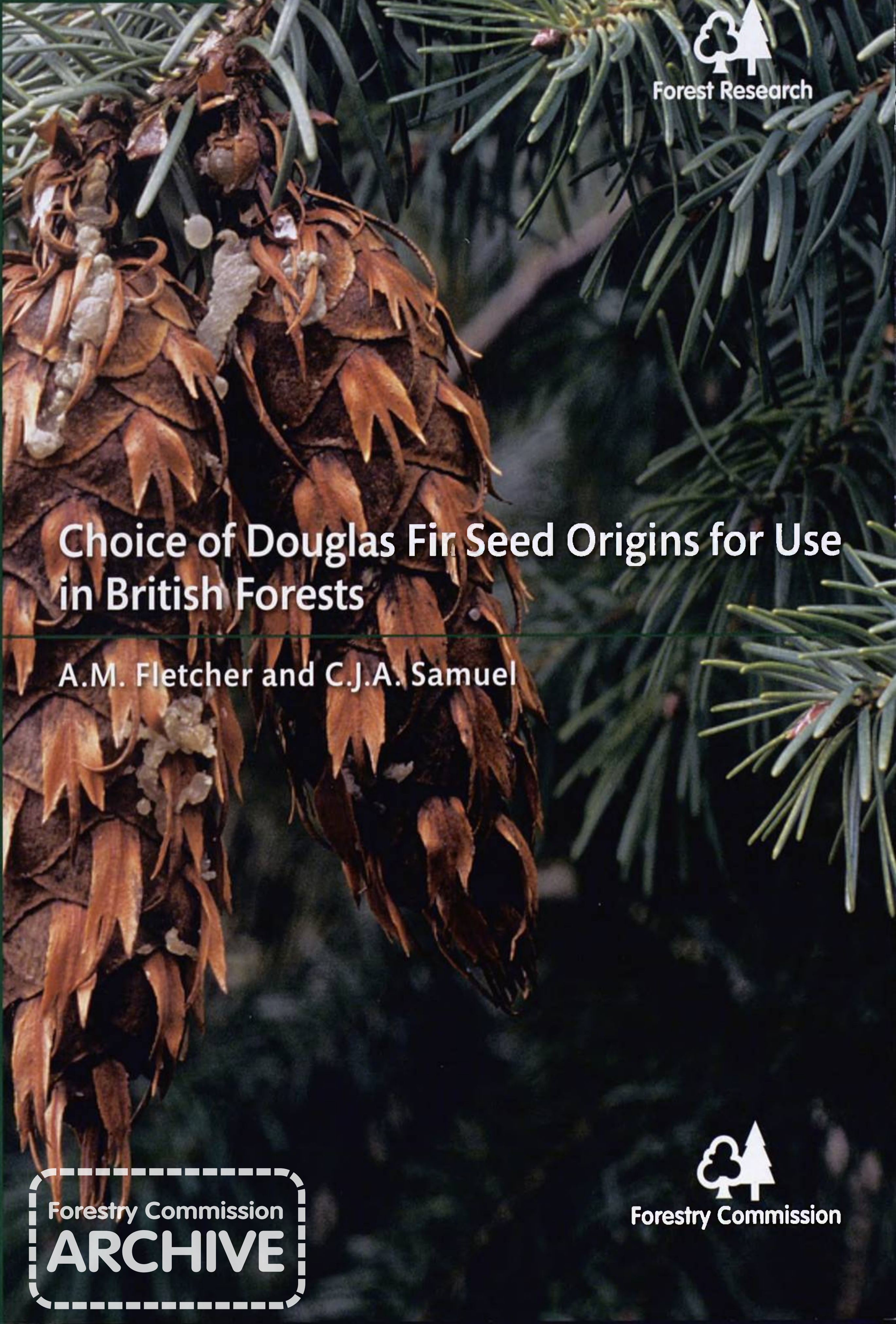
BULLETIN 129



Forest Research

Choice of Douglas Fir Seed Origins for Use in British Forests

A.M. Fletcher and C.J.A. Samuel

Forestry Commission

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Foreword

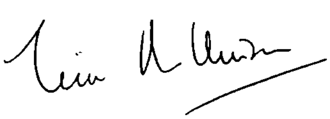
Since its introduction from northwest America in 1827, Douglas fir has proved to be a fast-growing and well-adapted species in appropriate regions of Great Britain.

Studies of the adaptive variation of species introduced into Great Britain have been a fundamental area of research since the establishment of the Forestry Commission. The authors have throughout their careers been involved in the establishment and the interpretation of data from provenance trials. In addition they have extensive knowledge of Douglas fir throughout its natural range in the Pacific Northwest.

The bulletin summaries seed origin research in Douglas fir over a period of 50 years. It provides information on the ecology of the species and the development and refinement of seed origin evaluation techniques. It considers in detail aspects of phenological variation, height and basal area production.

The growth and production data have been used to produce a new series of suitability maps of Great Britain to provide assistance to forest managers when selecting seed origins of Douglas fir. Preliminary results are provided regarding the value of seed from seed orchards established in the Pacific Northwest and in Europe.

The bulletin is an excellent resume of a major area of research by the Forestry Commission.



Tim Rollinson
Director General
Forestry Commission

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Summary

Douglas fir (*Pseudotsuga menziesii*, (Mirb.) Franco) was introduced from Northwest America by David Douglas in 1827. Initially it showed great potential but its use dwindled as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) became the most important commercial species in the 1950s. The species has a wide natural distribution with two varieties recognised, namely the coastal or green variety and the Rocky Mountain or blue Douglas fir. Early experiments demonstrated that the Rocky Mountain variety was unsuitable for use in this country. Two main series of experiments were established in 1953/54 based on the Manning Bonded seedlots and in 1970/72 using 50 seedlots from the International Union of Forest Research Organisations (IUFRO) 1966/68 collections to determine the most suitable seed sources of the coastal variety for planting in Great Britain. The seedlots have been grouped into eight broad regions based on physiographic, ecological and climatic features in order to study growth and adaptive characters and establish trends in performance on a wider geographical scale.

Survival for sources from southern Oregon and northern California was less than 70% and together with susceptibility to frost damage indicates their unsuitability for planting in Great Britain. There were considerable differences in dates of flushing, with the Washington coast seed sources always the latest to flush but also the latest to set bud. The south Oregon sources had the longest growing season and produced a higher percentage of lammas growth, the incidence of which can lead to forking in the main stem. Sources from the interior of British Columbia and the dry areas of northern California produced inferior growth rates. Among the coastal sources there is a general decline in increasing vigour with decreasing latitude. In Washington the coastal sources are marginally better than those from the west side of the Cascades. Branch size and number are important characteristics with regard to timber quality and the southern Oregon sources produced the highest number of branches as well as above average branch diameter. Sources from coastal Washington had smaller branch diameters than those from the Cascades but there was no difference in number of branches.

Seed from seed orchards established both in the Pacific Northwest (PNW) and in Europe were also evaluated in small-scale trials. The results obtained from the PNW orchards were similar to those in the provenance trials. Seed from orchards based on appropriate origins when available could provide a good source of planting stock for use in this country.

The results of the seed source trials indicated the superiority of four of the regions in order of preference Washington coast, south Washington Cascades, north Washington Cascades and north Oregon coast. Material from these areas should perform well over a range of sites in Britain. A seed origin suitability map for Great Britain has been developed to aid forest managers in selecting the most suitable region for particular sites. This is based on multiple linear regressions for ten year height for the four regions regressed onto accumulated temperature (AT5) and moisture deficit (MD). The Washington coast sources were found to be suitable throughout Britain and only south Washington Cascades sources were more productive on some areas. The range of the experimental sites was limited therefore the model does not cover a large part of eastern Britain. A relaxing of the model to take account of higher AT5 and MD values indicates that south Washington Cascades could give better growth in southern and eastern England.

Resumen

El abeto de Douglas (*Pseudotsuga menziesii*, (Mirb.) Franco) fue introducido en 1827 desde el noroeste de América por David Douglas. En sus orígenes, mostró un gran potencial, pero su uso menguó, mientras que la picea de Sitka (*Picea sitchensis* (Bong.) Carr.) se convirtió en la especie comercial más importante en los años 50. Esta especie goza de una amplia distribución natural, con dos variantes reconocidas, a saber, la variedad costera o verde y el abeto de las Montañas Rocosas o abeto azul de Douglas. Los primeros experimentos demostraron que la variedad de las Montañas Rocosas no era adecuada para su uso en este país. Se llevaron a cabo dos series principales de experimentos: en 1953–54, basados en los lotes de semillas Manning Bonded, y en 1970–72, usando 50 lotes de semillas de las colecciones de 1966–68 de la Unión Internacional de Organizaciones de Investigación Forestal (IUFRO, en sus siglas en inglés) para determinar las fuentes de semillas más adaptadas de la variedad costera para plantarlas en Gran Bretaña. Los lotes de semillas se han agrupado en ocho grandes regiones, en virtud de sus características fisiográficas, ecológicas y climáticas, con el objetivo de estudiar las capacidades de crecimiento y adaptación, y establecer tendencias del rendimiento a una mayor escala geográfica.

La supervivencia de las fuentes procedentes del sur de Oregón y el norte de California resultó inferior al 70%, lo cual, junto con su vulnerabilidad ante los daños provocados por las heladas, indica su falta de adecuación para plantarlas en Gran Bretaña. Existieron diferencias considerables en las fechas de desarrollo. Las fuentes de semillas de la costa de Washington, fueron siempre las últimas en desarrollarse pero también las últimas en brotar. Las fuentes del sur de Oregón contaron con la temporada de desarrollo más larga y produjeron un porcentaje más elevado de crecimiento en verano, la incidencia de lo cual puede provocar bifurcaciones en el tallo principal. Las fuentes del interior de la Columbia Británica y las áreas secas del norte de California experimentaron índices de crecimiento inferiores. Entre las fuentes costeras existe una disminución general del incremento del vigor a medida que decrece la latitud. En Washington, las fuentes costeras son marginalmente mejores que aquellas procedentes del lado oeste de las Cascades. El tamaño y la cantidad de las ramas son características importantes respecto a la calidad de la madera. En este sentido, las fuentes del sur de Oregón produjeron el número más elevado de ramas, así como un diámetro de rama superior a la media. Las fuentes procedentes de la región costera de Washington mostraron diámetros de rama más pequeños que los de las especies de las Cascades, pero no existió diferencia en cuanto al número de ramas.

También se evaluaron las semillas procedentes de huertos de semillas situados en el Pacífico Noroeste y en Europa en ensayos a pequeña escala. Los resultados obtenidos en los huertos de la región Pacífico Noroeste fueron similares a los de los ensayos originales. Las semillas procedentes de huertos situados en orígenes adecuados, cuando estén disponibles, podrían ofrecer una buena fuente de existencias plantadas para usar en este país.

Los resultados de los ensayos con fuentes de semillas indicaron la superioridad de cuatro de las regiones. En orden de preferencia: la costa de Washington, Washington Cascades sur, Washington Cascades norte y la región costera norte de Oregón. El material procedente de estas áreas debería dar buenos resultados en varios lugares de Gran Bretaña. Se ha desarrollado un mapa de adecuación de orígenes de las semillas de Gran Bretaña para ayudar a los gestores forestales a seleccionar la región más adecuada para emplazamientos específicos. El mapa se basa en regresiones lineales múltiples a diez años de las cuatro regiones seleccionadas sobre la temperatura acumulada (AT5) y el déficit de humedad (MD). Se descubrió que las fuentes de la costa de Washington se adaptaban a toda Gran Bretaña y sólo las fuentes de Washington Cascades sur eran más productivas en algunas áreas. El alcance de los lugares experimentales fue limitado, por lo que el modelo no cubre gran parte del este de Gran Bretaña. Un esbozo del modelo que toma en cuenta valores AT5 y MD más elevados indica que la región de Washington Cascades sur podría ofrecer un crecimiento mejor en el sur y este de Inglaterra.

Résumé

Le sapin de Douglas (*Pseudotsuga menziesii*, (Mirb.) Franco) est originaire de l'ouest de l'Amérique du Nord et a été introduit en 1827 en Europe par David Douglas. À l'origine, son potentiel était élevé, mais son utilisation s'est raréfiée, car, dans les années 50, c'est l'épicéa de Sitka (*Picea sitchensis* (Bong.) Carr.) qui est devenu l'espèce commerciale dominante. Le sapin de Douglas a une large répartition naturelle et comprend deux variétés : le douglas vert et le douglas bleu. Très tôt, les expérimentations ont montré que le douglas bleu n'était pas utilisable en Grande-Bretagne. Afin de déterminer les sources de semences de douglas vert les mieux adaptées à une plantation dans ce pays, deux séries importantes d'expérimentations ont été menées en 1953/1954 sur les lots de semences Manning Bonded et en 1970/1972 sur 50 lots de semences des collections datant de 1966/1968 de l'IUFRO (International Union of Forest Research Organisations). Afin d'étudier leurs caractères adaptatifs et de croissance et ainsi évaluer des tendances de performances sur une plus vaste échelle géographique, les lots de semences ont été répartis en huit grandes régions, sur la base de critères physiographiques, écologiques et climatiques.

Le taux de survie des sources de semences du sud de l'Oregon et du nord de la Californie était inférieur à 70 %. Ce résultat et une sensibilité au gel ont contre-indiqué leur plantation en Grande-Bretagne. Des différences considérables dans les dates de la vague de croissance ont également été constatées : les sources de semences de la région côtière de Washington sont toujours les plus tardives dans ce domaine et également les dernières à débourrer. Les sources de semences du sud de l'Oregon ont la saison de croissance la plus longue et produisent un pourcentage plus élevé de pousses d'été dont la présence peut entraîner la formation de fourches dans la tige principale. Les sources de semences provenant de l'intérieur de la Colombie-Britannique et des régions sèches du nord de la Californie présentent des taux de croissance inférieurs. Parmi les sources de semences côtières, on constate un déclin général de la vigueur au fur et à mesure que la latitude décroît. À Washington, les sources côtières sont marginalement meilleures que celles de l'ouest de la chaîne des Cascades. La taille et le nombre des rameaux sont des caractéristiques importantes pour la qualité du bois d'œuvre et les sources du sud de l'Oregon produisent un plus grand nombre de rameaux dont le diamètre est également supérieur à la moyenne. Les sources de la région côtière de Washington présentent des rameaux de diamètre plus petit que celles de la chaîne des Cascades, mais le nombre de rameaux est le même.

Les semences des vergers à graines établis dans la région Nord-Ouest Pacifique et en Europe ont également été évaluées lors d'essais à petite échelle. Les résultats obtenus dans la région Nord-Ouest Pacifique sont similaires à ceux des essais de provenance. Quand les semences des origines appropriées sont disponibles auprès des vergers, elles peuvent présenter une source appréciable de matériel végétal pour une utilisation en Grande-Bretagne.

Les résultats des essais menés sur les sources de semences ont permis de distinguer quatre régions, soit, par ordre de préférence : la région côtière de Washington, les South Washington Cascades, les North Cascades et la côte nord de l'Oregon. Le matériel génétique de ces zones devrait s'avérer performant dans de nombreux sites en Angleterre. Une carte des aptitudes pour la Grande Bretagne selon les origines des semences a été développée pour aider les gestionnaires forestiers à sélectionner les origines les mieux adaptées à des sites particuliers. Cette carte a été établie à l'aide de régressions linéaires multiples effectuées sur des arbres de 10 ans et sur ces quatre régions, en fonction des températures cumulées au dessus de 5° (AT5 – accumulated temperature) et du déficit hydrique (MD – moisture deficit). On a trouvé que les sources de la région côtière de Washington étaient adaptées à l'ensemble de l'Angleterre et seules les sources des South Washington Cascades étaient plus productives dans certaines zones. Le nombre de sites expérimentaux était limité et donc le modèle ne couvre pas une grande partie de l'est de la Grande-Bretagne. Un assouplissement du modèle a permis de prendre en compte des valeurs plus élevées de températures cumulées et de déficit hydrique : ce nouveau calcul a indiqué que les semences des South Washington Cascades pourraient présenter une meilleure croissance dans le sud et l'est de l'Angleterre.

Zusammenfassung

Die Douglasie (*Pseudotsuga menziesii*, (Mirb.) Franco) wurde 1827 von David Douglas aus Nordwestamerika eingeführt. Anfangs zeigte sie ein hohes Potential, aber ihre Verwendung ließ nach, als die Sitka-Fichte (*Picea sitchensis* (Bong.) Carr.) in den 50er Jahren die wichtigste Nutzholzart wurde. Die Art hat ein großes natürliches Verbreitungsgebiet und wird in zwei Varietäten, die Küsten- oder Grüne Douglasie und die Gebirgs- oder Blaue Douglasie, gegliedert. Frühe Versuche haben gezeigt, dass die Gebirgsdouglasie für den Anbau in Großbritannien ungeeignet ist. Es wurden zwei wesentliche Versuchsreihen durchgeführt, um die geeignetsten Saatgutherkünfte der Küstendouglasie für den Anbau in Großbritannien zu bestimmen: 1953/54 mit Saatgut von Manning Bonded und 1970/72 mit 50 Saatgutpartien aus den Sammlungen der Jahre 1966–68 des Internationalen Verbandes Forstlicher Forschungsanstalten (International Union of Forest Research Organisations, IUFRO). Die Saatgutpartien wurden nach physiographischen, ökologischen und klimatischen Merkmalen in acht große Regionen aufgeteilt, um Wachstums- und adaptive Eigenschaften zu untersuchen und die Produktionsleistung für einen breiteren geographischen Umfang vorherzusagen.

Mit Saatgut aus dem südlichen Oregon und Nordkalifornien wurden Überlebensraten von unter 70 % erzielt. Aufgrund dieses Ergebnisses und der Frostempfindlichkeit ist diese Herkunft für die Anpflanzung in Großbritannien nicht geeignet. Es wurden große Unterschiede hinsichtlich des Austriebdatums festgestellt, wobei Bäume aus Saatgut von der Küste Washingtons stets zuletzt austrieben und auch als letzte Knospen ansetzten. Die Quellen aus Südoregon hatten die längste Vegetationszeit und produzierten einen höheren Prozentsatz an Johannistrieben, deren Auftreten zu einer Gabelung des Hauptstamms führen kann. Quellen aus dem Landesinneren von British Columbia und den trockenen Gegenden Nordkaliforniens produzierten geringere Wachstumsraten. Bei den Küstenherkünften nimmt die Vitalität im Allgemeinen mit abnehmender geografischer Breite ab. In Washington sind die Küstenquellen kaum besser als die von der Westseite der Kaskaden. Astgröße und Anzahl sind wichtige Merkmale im Hinblick auf die Stammqualität, und die Südoregonherkünfte produzierten die höchste Astanzahl sowie überdurchschnittliche Astdurchmesser. Herkünfte von den Küstenregionen Washingtons hatten kleinere Astdurchmesser als die von den Kaskaden, aber es gab keinen Unterschied in der Astzahl.

Es wurde auch Plantagensaatgut, das in der Nordwestpazifik-Region sowie in Europa erzeugt wurde, in kleinflächig angelegten Versuchen getestet. Die Ergebnisse mit Plantagensaatgut aus der Nordwestpazifik-Region ähnelten denen der Herkunftsversuche. Plantagensaatgut auf der Basis von geeigneten Herkünften könnte eine gute Saatgutquelle für die Verwendung in Großbritannien sein.

Aus den Ergebnissen der Saatgutherkunftsstudien ergibt sich die Überlegenheit von vier Regionen; nach Präferenz geordnet sind dies die Küste Washingtons, die Kaskaden in Südwashington, die Kaskaden in Nordwashington und die Küste von Nordoregon. Saatgut aus diesen Gegenden dürfte für viele britische Standorte gut geeignet sein. Es wurde eine Karte mit der Eignung der verschiedenen Saatgutherkünfte in Großbritannien entwickelt, die Forstverwalter bei der Auswahl von Saatgutherkünften für verschiedene Standorte unterstützen soll. Sie basiert auf multiplen linearen Regressionen für die Höhe nach dem zehnten Jahr und für die vier Regionen unter Berücksichtigung der akkumulierten Temperatur über 5°C (AT5 – accumulated temperature) und des Wasserdefizits (MD – moisture deficit). Man hat festgestellt, dass die Washingtoner Küstenherkünfte für ganz Großbritannien geeignet sind, und dass nur die Quellen von den Südwashingtoner Kaskaden in einigen Gegenden produktiver sind. Das Gebiet der Versuchsstandorte war begrenzt, und daher bezieht das Modell einen großen Teil von Ostengland nicht mit ein. Eine Erweiterung des Modells durch Einbeziehung höherer AT5- und MD-Werte zeigt, dass Samen aus der Kaskadenregion Südwashingtons ein besseres Wachstum in Süd- und Ostengland ergeben könnten.

Crynodeb

Cyflwynwyd ffynidwydden Douglas (*Pseudotsuga menziesi*, (Mirb.) Franco) o Ogledd Orllewin America gan David Douglas yn 1827. Ar y dechrau dangosai botensial mawr ond aeth y defnydd arni ar i waered wrth i befrwydden Sitka (*Picea sitchensis* (Bong.) Carr.) ennill ei lle fel y rhywogaeth fasnachol bwysicaf yn y 1950au. Mae gan y rhywogaeth ddosbarthiad naturiol helaeth gyda dau fath yn cael eu cydnabod sef yr isrywogaeth arfordirol neu wyrdd ac isrywogaeth y Mynyddoedd Creigiog neu ffynidwydden Douglas Glas. Dangosodd arbrofion cynnar nad oedd math y Mynyddoedd Creigiog yn addas i'w ddefnyddio yn y wlad hon. Sefydlwyd dwy brif gyfres o arbrofion yn 1953/54 gyda lotiau hadau Bandiau Manning ac yn 1970/72 gyda lotiau hadau o gasgliadau 1966/68 Undeb Rhyngwladol Sefydliadau Ymchwil y Goedwig (IUFRO) i bennu'r ffynonellau hadau mwyaf addas i'r isrywogaeth arfordirol ar gyfer eu plannu yng ngwledydd Prydain. Mae'r lotiau hadau wedi eu grwpio yn wyth rhanbarth fras ar sail nodweddion ffisiograffig, ecolegol a hinsoddol er mwyn astudio twf a nodweddion ymaddasu a sefydlu tueddiadau perfformio ar raddfa ddaearyddol ehangach.

Roedd y goroesi ar gyfer ffynonellau o dde Oregon a gogledd Califfornia yn llai na 70% ac ynghyd â rhagdueddiad i ddifrod gan rew nodai hyn eu bod yn anaddas i'w plannu ym Mhrydain. Roedd gwahaniaethau sylweddol yn y dyddiadau aeddfedu a'r ffynonellau hadau o arfordir Washington oedd y rhai olaf i aeddfedu bob tro ond hefyd y rhai olaf i flaguro. Gan y ffynonellau o dde Oregon oedd y tymor tyfu hwyaf a chynhyrchent ganran uwch o dwf lamas sy'n gallu arwain at fforchio yn y prif gyff. Roedd y ffynonellau o ganolbarth Columbia Brydeinig ac ardaloedd sychion gogledd Califfornia yn cynhyrchu graddau twf israddol. Ymysg y ffynonellau arfordirol mae graddfa gyffredinol o gryfder cynyddol gyda lledred yn mynd ar i waered. Yn Washington mae'r ffynonellau arfordirol fymryn yn well na'r rhai o ochr orllewinol Mynyddoedd y Rhaeadrau. Mae maint a niferoedd canghennau yn nodweddion pwysig o ran ansawdd y pren a ffynonellau de Oregon a gynhyrchai'r nifer uchaf o ganghennau yn ogystal â diamedr canghennau uwch na'r cyfartaledd. Roedd gan ffynonellau o arfordir Washington ddiamedrau canghennau llai na'r rhai o Fynyddoedd y Rhaeadrau ond nid oedd dim gwahaniaeth yn y nifer o ganghennau.

Cafodd hadau o goedlannau hadau a sefydlwyd yng Ngogledd Orllewin y Môr Tawel ac yn Ewrop hwythau eu cloriannu mewn treialon ar raddfa fechan. Roedd y canlyniadau a gafwyd o goedlannau Gogledd Orllewin y Môr Tawel yn debyg i'r rhai yn y treialon tarddleoedd. Gallai hadau o goedlannau o darddleoedd addas pan fyddant ar gael fod yn ffynhonnell dda o stoc plannu ar gyfer defnydd yn y wlad hon.

Roedd canlyniadau'r treialon ffynonellau hadau yn nodi rhagoriaeth pedair o'r rhanbarthau yn y drefn flaenoriaeth a ganlyn: arfordir Washington, de Mynyddoedd Rhaeadrau Washington, gogledd Mynyddoedd Rhaeadrau Washington ac arfordir gogledd Oregon. Dylai deunydd o'r ardaloedd hyn berfformio'n dda dros amrywiaeth o safleoedd ym Mhrydain. Mae map addasrwydd tarddle hadau i wledydd Prydain wedi ei ddatblygu i gynorthwyo rheolwyr coedwigoedd wrth ddewis y rhanbarth fwyaf addas i safleoedd neilltuol. Seilir hwn ar atchweliadau llinol lluosog ar gyfer uchder deng mlynedd i'r pedair rhanbarth wedi'u hatchwelyd ar dymheredd cronedig (AT5) a diffyg lleithder (MD). Cafwyd bod ffynonellau arfordir Washington yn addas ar hyd a lled Prydain a dim ond ffynonellau de Mynyddoedd Rhaeadrau Washington oedd yn fwy cynhyrchiol mewn rhai ardaloedd. Roedd ystod y safleoedd arbrofi yn gyfyngedig ac felly nid yw'r model yn ymdrin â rhan fawr o ddwyrain Prydain. Mae llacio ar y model i roi ystyriaeth i werthoedd AT5 ac MD uwch yn arwyddo y gallai ffynonellau de Mynyddoedd Rhaeadrau Washington roi twf gwell yn ne a dwyrain Lloegr.

1

Introduction

History of introduction

Douglas fir (*Pseudotsuga menziesii*, (Mirb.) Franco) was one of the first conifer species from northwest America to be grown on a commercial scale in Britain. It was a species of interest to foresters in the first half of the 20th century but over the past 40 years its percentage of the forest estate has decreased due partly to the dramatic increase in the planting of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and also to the types of sites being planted. At the last Census of Woodlands (Forestry Commission, 2003) it comprised 3% of the forest area but 5% of the standing volume of the conifer forest.

Douglas fir is a fast-growing, high-yielding species which will grow on a wide variety of sites but in its native habitat does best on deep, moist, sandy loams where moisture in the soil and atmosphere is plentiful. It does not thrive on compacted, poorly-drained or limestone soils. It is a seral species although in certain situations it is a pioneer species. Less shade-tolerant than its associated species western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), western red cedar (*Thuja plicata* D. Don) and grand fir (*Abies grandis* Lindl.), in the course of succession Douglas fir is replaced by them. Under natural conditions, forest fires are necessary for Douglas fir to persist, thus old trees are particularly resilient to fire. Douglas fir is a wind-sensitive species in Britain and on exposed sites the loss of the leading shoot is a common occurrence. In the Pacific Northwest, it is the most important species for the production of structural timber as well as the leading veneer species for construction grade plywood. It has a high strength to weight ratio compared to species like Sitka spruce.

Archibald Menzies was the first European to discover the species in 1792 at Nootka

Sound on the west coast of Vancouver Island, British Columbia (Menzies, 1923). It was introduced into Britain by David Douglas in 1827 (Figures 1 and 2). The exact location or locations of the first David Douglas collection is not known but it was thought to have been from the area between Fort Vancouver on what is now the border between Washington and Oregon and the Umpqua River in southern Oregon and possibly from the western foothills of the Cascade Range (Douglas, 1914). These early introductions exhibited the relatively fast rate of growth of the species and further introductions were made by John Jeffrey for the Oregon Association and other private collectors such as Hartweg and Lobb in the 1850s (Balfour, 1932).

Figure 1

A portrait of David Douglas (1799–1834) who was born at Scone, Perthshire.

Figure 2

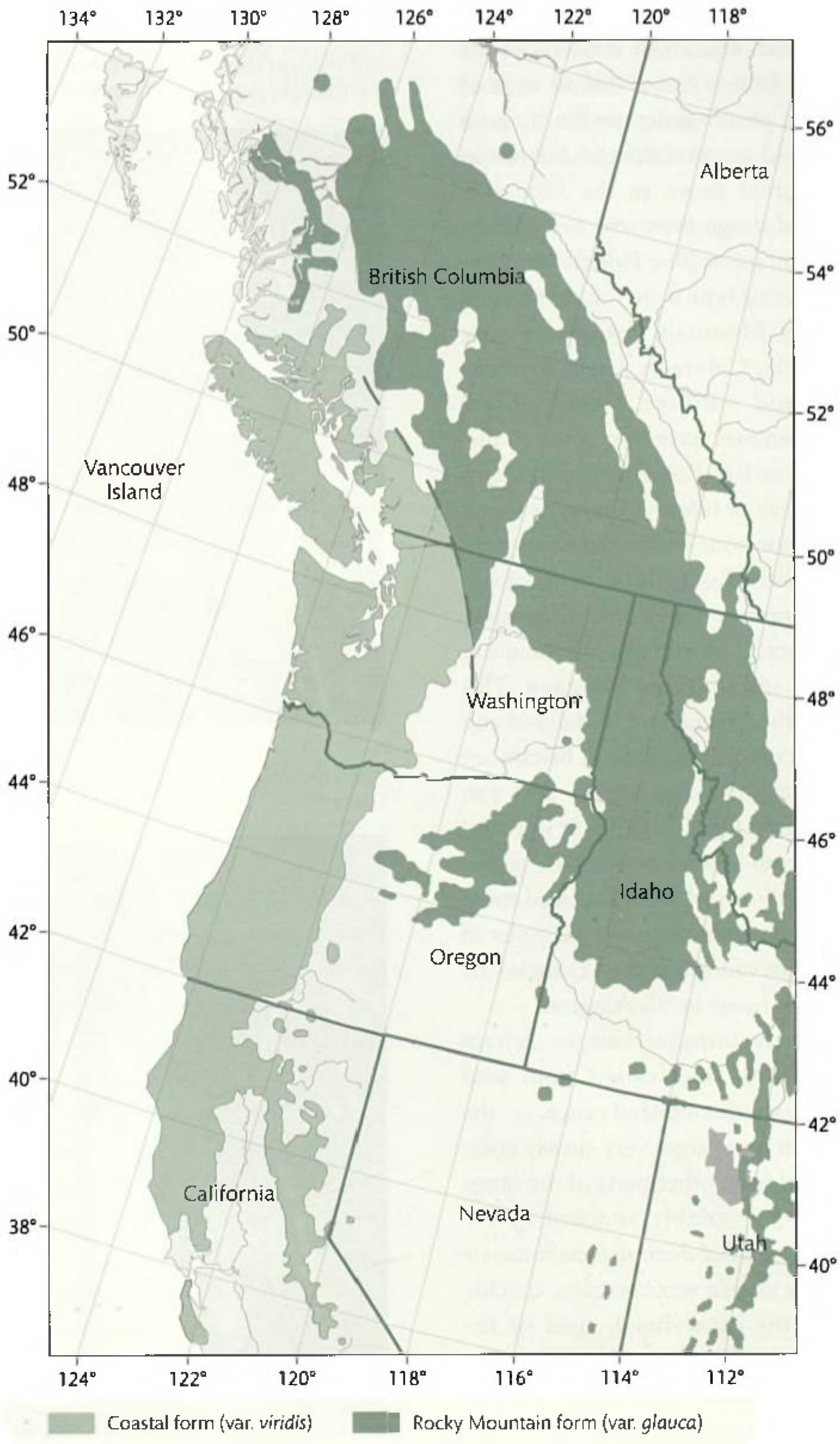
One of the original trees growing at Scone Palace Perthshire raised from seed sent from the Pacific Northwest by David Douglas and sown in 1827.

Natural distribution

Frothingham (1909) indicated the wide natural distribution of Douglas fir (Figure 3, after Burns and Honkala (1990)) with a north–south range of 3400 km from Takla Lake in central British Columbia (55°N) to the Rio Grande, Sierra Madre in Mexico (20°N) and an east to west spread of 1600 km from east of the Rocky Mountains in Colorado (105°W) to the Gardner Canal in British Columbia (128°W). Its altitudinal range is from sea level to 3200 m in the southern Rocky Mountains. Throughout the whole range of the species there is a gradation of forms from the coastal types on the one extreme to the Rocky Mountain or interior forms on the other. Due to the extensive

Figure 3

The natural distribution of Douglas fir.



distribution, two main varieties are recognised. *Pseudotsuga menziesii* var. *menziesii* or *viridis*, the coastal or green Douglas fir type, is confined to the coastal regions to the west of the Coast Range in British Columbia, to west of the crest of the Cascade Range in Washington and Oregon, and to west of the Sierras in northern California down to the Monterey peninsula. *Pseudotsuga menziesii* var. *glauca*, the Rocky Mountain or blue Douglas fir, conforms to the interior type from the central and southern Rocky Mountain regions ranging through Montana, Colorado, Utah, Arizona, New Mexico and northern Mexico. Some foresters and botanists have attempted to distinguish a third variety *Pseudotsuga menziesii* var. *caesia*, the grey or intermediate type found along the transition zone between the two varieties in the northern Rocky Mountain regions including the interior of British Columbia, south-west Alberta, northeast Washington, northern Idaho and northern Montana. This distinction is rather vague and ill-defined and Peace (1948) recommended that in Britain we should only recognise var. *viridis* and var. *glauca*. In its coastal form, Douglas fir is a seral or early succession species in contrast to the Rocky Mountain form which is regarded more as a climax species. Figure 4 shows examples of a younger and an older stand of Douglas fir within its natural range in Washington.

From the early introductions to Britain made in the 1900s, trees raised from seed coming from the southern inland range, i.e. the Rocky Mountain type, grew very slowly compared to material from other parts of the range and were almost invariably attacked by the needle cast fungus, *Rhabdocline pseudotsugae* Syd. The variety *glauca* was therefore quickly discarded. On the other hand, seed of the coastal and intermediate types from the interior of British Columbia was used to establish many early plantations in Britain.

Figure 4

Two examples of Douglas fir growing within its natural range.

a) A younger stand at Matlock in the coastal region of the Olympic peninsular in Washington.

b) An old stand at Illinois Creek in the mid-Washington Cascades.

Wood (1955), in his study of north-west American forests, compared the climate in the Pacific Northwest with that in Britain and related it to the performance of various species in Great Britain. In the case of Douglas fir he concluded that it was a species that experiences much warmer conditions in its natural range than the British summer range of temperatures. Additionally, precipitation across Britain is more than adequate for the growth of Douglas fir. In the natural range of the coastal type, it is subjected to moisture stress in the summer with 10% or less of precipitation in the period June to August inclusive. Despite these differences, Douglas fir has grown well on a wide range of sites in Britain and demonstrated that it is a species with potential, provided that close attention is paid to its site and its silviculture (Macdonald, 1952; Edwards, 1957). A more detailed discussion of climatic factors is given in the section on climate matching.

Seed imports

Large scale importations did not take place until the 1870s–1890s when the Manning Seed Company (renamed Silvaseed in 1970) provided seed, firstly from northern Oregon and then from the glacial outwash plains to the south of the Puget Sound in Washington, the Washington coast and from the neighbouring foothills of the Cascades. The initial early interest in Douglas fir in Britain is demonstrated by the large quantities of seed imported between 1921 and 1930, which totalled 6490 kg, split 56% from British Columbia and 44% from Washington and Oregon. The seed from British Columbia in the 1920s came from the Lower Fraser River area amounting to 2950 kg. Over the period between 1931 and 1950, 74% of the total of 6258 kg of seed imported was from Washington and Oregon. Since 1950 over 90% of imported seed has come from Washington sources. In the last two decades, the western Cascade region of northern and mid-Washington has been the most favoured.

2

Evaluation of seed sources: introduction, phenology and morphology

Introduction

A small number of experiments comparing limited numbers of seed lots from coastal British Columbia but mainly from the interior of the British Columbia (var. *caesia*), were established between 1928 and 1943. These experiments clearly indicated that the coastal types were more adapted to our oceanic conditions than the intermediate type (Peace, 1948). In an experiment planted in 1943 at Glentress Forest with three British Columbian coastal sources and two intermediate sources, at 20 years of age the mean basal area of the coastal sources was four times that of the intermediate ones. The latter were also heavily infested with the needle cast fungus, *Rhabdocline pseudotsugae* Syd. which may have been a partial cause of the reduced growth. In the early years, the intermediate types had superior height growth, as they were far more resistant to the aphid attacks by *Adelges cooleyi* Gill. than the coastal types. Apart from recognising the contrast between coastal and interior material, no specific data from these early experiments have been considered in this report.

The Manning Bonded series

In 1953/54 a more comprehensive series of experiments was established based on the sources known as the Manning Bonded seedlots with 16 sources from Washington and northern Oregon. Detailed information regarding the location, climatic and edaphic features of the sites and growth of the stands from which the seed was collected were provided allowing comparisons to be made with British planting sites. Details of the seed origins are given in Appendix 1 together with letter codes by which their location in northwest

America may be identified on the map shown in Figure 5a. Trials were established on five sites throughout Britain, the locations of which are given in Figure 6 with site details in Appendix 2. Experiments with a range of the Manning Bonded seedlots were also established in a number of other western European countries.

The IUFRO series

Between 1966 and 1970 range-wide collections were made under the auspices of the International Union of Forest Research Organisations (IUFRO) from 182 identified and well-documented sites which were representative of the species in that particular part of the distribution (Fletcher and Barner, 1980). A total of 50 seedlots were selected for testing in Britain, concentrating mainly on the coastal sources (var. *viridis*) since results from previous trials indicated their superiority over interior sources (Lines and Mitchell, 1968). Fifteen sources were lost during the nursery phase and details of the remaining 35 considered in this publication are given in Appendix 1, together with number codes through which their location may be identified on the map shown in Figure 5a.

All the seedlots in both the IUFRO and Manning Bonded series cover a very wide geographic area. For ease of consideration of the wide variation encountered, the sources have been grouped into eight broad regions based on major physiographic, ecological and climatic features pertaining across the natural distribution. These have been devised by the authors specially for this publication. They are based on combinations of the regions and seed zones established by the Western Forest Tree Seed Council in 1966 for Washington and Oregon and the British Columbia Ministry of Forests scheme which operated between 1974 and 1982 (referred to in this publication as the 'northwest American seed zones'). The regions are shown in Figure 5a and the north-west American seed zones structure upon which they are based is shown in Figure 5b. These groups with their abbreviations and colour

Table 1

Grouping of origins in the analysis of Douglas fir field experiments.

Region	Abbreviation used in text	Seed Zones included in region (see Figure 5b)	Colour coding used in diagrams
Interior types			
Interior British Columbia	BCIN	Zones in Regions 2000, 3000 and 5000	
Coast Range			
Coastal British Columbia and Vancouver Island	BCCO	All zones in Region 1000	
Washington coast	WACO	012, 030, 041 (western part)	
North Oregon coast	NOCO	041 (western part), 051, 052, 053, 061, 062	
South Oregon and North California coast	SOCO	071, 072, 081, 082, 090, 091	
East of Coast Range and west side of Cascades			
North Washington Cascades	NWCA	201and 202 (eastern part), 401, 402, 403	
South Washington Cascades	SWCA	411, 412, 421, 422, 430 (except western part)	
Dry Oregon and northern California	DONC	511, 512, 301, 302, 311, 312, 321, 322, 340, 371	
Oregon Cascades, west side (seed orchard lots only)			
North Oregon Cascades	NOCA	261, 452	
Mid-Oregon Cascades	MOCA	262, 471, 472, 481, 482	

Figure 5a

Map of the Pacific Northwest showing locations of the seed sources used in the IUFRO and Manning Bonded seedlots experiments.

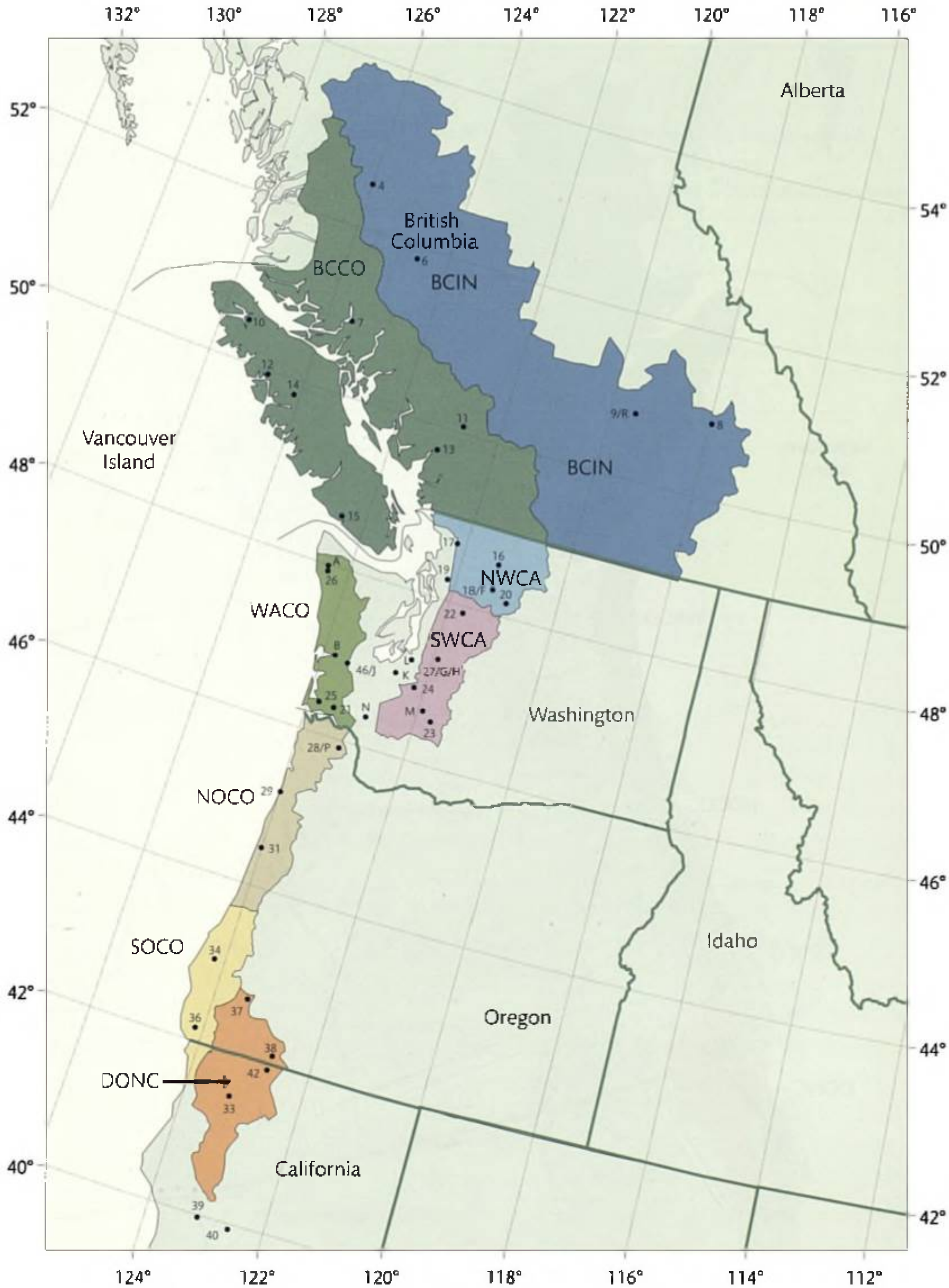


Figure 5b

Seed zones in the Pacific Northwest grouped into the larger regions used in this publication.

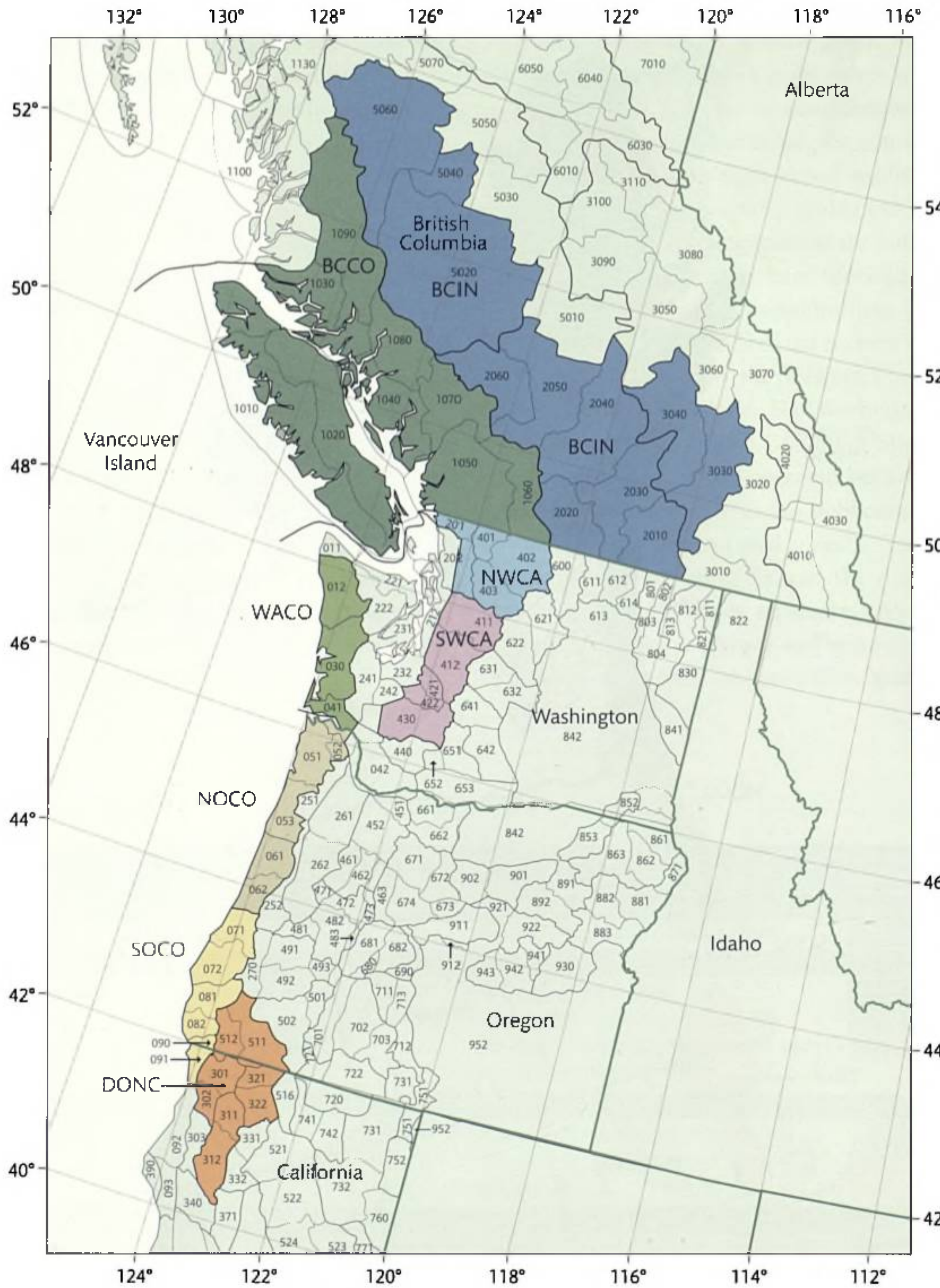


Figure 6

Distribution of forest planting sites used for Douglas fir seed origin tests in Great Britain.

codes, which are used throughout, are described in Table 1 (the last two groups shown in this table will be referred to in the section on seed orchard material). The groups are used when studying growth and adaptive characteristics to establish trends in performance on a wider geographical and ecological scale.

IUFRO nursery phase

The seedlots, along with a commercial seed collection from Elma, Washington (WACO) were sown in two nursery experiments in Scotland (Newton (Grampian) and Tulliallan (Fife)) in 1968 (Lines and Mitchell, 1970) and one in England (Wareham (Dorset)) in 1970 (Pearce, 1980). The most significant factor in the nursery stage was the effect of frosting. However, at Wareham, browning and top dieback resulted from cold easterly winds in January and February which was well correlated with provenance, being most severe in southern Oregon and Californian sources.

At Newton and Tulliallan there were differences in autumn frost damage between sources. Minimal damage occurred in those from latitudes above 50°30'N (BCIN, the interior type and BCCO, the coastal type) but severe damage was found in those from below 45°N, i.e. southern Oregon and northern California (SOCO and DONC). The sources from Brookings and Coquille (SOCO) were severely damaged at Newton and almost eliminated at Tulliallan. Similarly in the material sown two years later at Wareham, a severe frost (–5° Celsius) in mid-November caused heavy losses in seed beds among sources from SOCO and DONC. Management practices (e.g. covering seedlings to reduce frost risk) can overcome some of the problems in the nursery.

Field experiments

Following the nursery stage, there were only sufficient surviving plants of 35 of the 50 sources for the out-planting phase to proceed with sufficient replication at all sites and even then there was a degree of selection within some sources during the nursery stage. The resulting plants were established at seven test sites, details of which are summarised in Appendix 2, together with a summary of the experimental designs and plot sizes used. The location of the sites is also shown in Figure 6. At most of the seven planting sites in the IUFRO series, two experimental designs were used, based on small and large plot sizes respectively. The designs based on smaller plot sizes provided data on survival, frosting, flushing and growth up to 10–15 years from planting whilst those based on larger plot sizes were designed to provide more detailed information on growth and yield up to 30–40 years from planting and to permit thinning to take place. The range of plot sizes used is summarised in Appendix 2.

Survival

Early survival of outplanted stock of Douglas fir is often rather poor and has been a contributing factor against the wider use of the species. Some of the problems are due to nursery practices concerning the type of plant produced and the conditions for lifting and storage. Regimes which can overcome these problems are now more fully understood (McKay and Mason, 1991; McKay and Howes, 1996). Apart from the type of planting stock, either early or late frosting and winter cold can affect Douglas fir in the nursery. As already indicated, there was considerable frost damage to seedlings at the end of the first growing season in the nursery stage of the IUFRO experiments with sources in regions NOCO, SOCO and DONC most affected while seedlings from BCCO were almost untouched. The BCIN seed sources were the first to germinate and the earliest to set bud. The SOCO sources were also affected by cold easterly winds in January and February. Although these sources can be afforded protection in the nursery, this is not possible after outplanting and their degree of adaptation to British conditions must therefore be questioned.

Survival at the end of the first growing season in the field was generally very acceptable but there was variation on some sites. Radnor proved the most uniform with the lowest survival being 88% whilst at Bodmin, Charmouth, Quantock and Craigvinean, all sources had survival above 70%. At Dean, which was the most exposed of the southern sites (a second rotation site on an exposed slope facing the prevailing wind), there were two sources with survival less than 30% while the remainder were above 55%.

At Craigvinean survival was assessed at the end of the sixth growing season and ranged from 83% to 42%. Average survival for WACO was 78%, NWCA 76%, SWCA 75%, NOCO 68%, BCCO 65%, BCIN 55% and SOCO 52%.

In the IUFRO series in Germany, survival was measured in 6 sites at 11 years after planting of 111 seed sources. Overall survival was 70.5% and individual sources ranged from 6% to 91%. For British Columbia sources, survival in BCIN was higher than in BCCO and this trend was the same for east and west of the Cascades in Washington. Survival of the origins from west of the Olympic peninsula and the Washington Cascades was similar. There was a clear trend to extreme mortality amongst lots from southern Oregon of up to 75% (Kleinschmit *et al.*, 1987).

Frost damage

In the earlier series of experiments using the Manning Bonded seedlots, damage by frost was caused at Laiken, Glentress and Shouldham. At Shouldham, one block was established on a flat area subject to frost and this experienced radiation frosts between 1 and 6 May 1959 with temperatures down to -6°C. Spring frosts also occured at Laiken and Glentress in 1957. Sources from WACO were least affected at all three sites with 57% of plants totally unaffected on the frost-susceptible block at Shouldham, whereas the comparable figure for the Washington Cascades regions (NWCA and SWCA) was 46% and 40% respectively and 43% for NOCO sources. The remaining plants were affected to a varying degree and at the end of the season the percentages of plants which had actually died as a result of frost damage were 4% for WACO, 8% for NWCA, 24% for SWCA and 15% for NOCO. Unfortunately there were no seed sources from SOCO or DONC in these trials.

In the IUFRO series, severe autumn frost was only experienced at Craigvinean with freezing temperatures of –3°C on 8 September 1972 with a number of trees damaged. Northerly interior seed sources (BCIN) were least affected with less than 15% damage. Unfortunately at this site there is no material from the southerly DONC zone. There was no clear north/south trend in susceptibility among the coastal sources but the southern ones, SOCO, had the highest average with 33% of plants damaged compared with 21% for WACO.

St Clair (2006), in a common garden test at Corvallis in Oregon studied the growth and phenology of over 600 individual family sources from western Oregon and Washington which were grouped into regions similar to those used in this publication. Shoots from the seedlings were subjected to freezing temperatures in a programmable freezer. Variation in autumn damage to the stems was strongly correlated with the winter temperatures of the original location of the material. Sources from the south Oregon coastal region (comparable to SOCO) suffered the greatest damage at between 40 and 60%. Sources from the Washington and north Oregon coast (comparable to WACO and NOCO) suffered 25–35% damage followed by those from the south Washington Cascades with 15–25% and north Washington Cascades with 15–20%. Coast Range populations suffered more damage than Cascade populations at comparable elevations and latitudes.

Date of flushing

Flushing was also assessed in the Manning Bonded series at Laiken, Glentress and Shouldham and there was a strong correlation between date of flushing and degree of frosting. There were considerable differences in flushing time with the BCIN source being the earliest to flush and WACO sources consistently the latest. Differences in relative times of flushing between sources remained more or less consistent between sites and years. Similar results have been obtained from comparable trials in Ireland (O'Driscoll, 1980), France (Michaud, 1987), Germany (Larsen, 1980; Weisgerber, 1980) and the Netherlands (Kriek, 1974, 1980, 1983).

In the IUFRO series in Ireland (O'Driscoll, 1980), the seed sources from the west of the Olympic peninsula, namely Forks and Humptulips, were the latest to flush. The results from the IUFRO series in Germany also reflect this trend. There was a late frost on 8 May in 1974 and no damage was found on the WACO lots. Within British Columbia, there was a close negative correlation between date of flushing and frost damage (Kleinschmit *et al.*, 1987).

St Clair (2006), in the study already mentioned, found very little difference in the date of flushing between regions with the means varying only by 11 days, but with the Washington coast low elevation populations (comparable to WACO) being the latest at Julian day 113 and the southern Oregon region (western part of DONC), the earliest at day 102.

Growth cessation

Growth cessation is an important characteristic both in the nursery and the early years in the field as it affects both frost hardiness and productivity. Date of bud-setting was recorded in the Manning Bonded series at Laiken and the results followed those of flushing with BCIN being the first to set bud and WACO consistently the latest. O'Driscoll (1980), for 32 sources in the IUFRO series planted in Ireland, measured the length of the growing season which was defined as the period from date of first measurable height growth to the date when no further height growth occurred. The measurements were made over 6 growing seasons and there were wide differences in the length of the growing season ranging from 63 to 154 days with a overall mean of 123 days. The length of the growing season of the lower elevation coastal sources was in excess of those from the higher elevations in the Cascade Range and interior sources by up to two weeks. Within the coastal sources, those from the western side of the Olympic Peninsula (WACO) had the shortest growing season. The Humptulips (WACO) source was unusual in that it had a relatively short growing season which was repeated throughout the duration of the experiment. This was also found by Nanson (1973) in the IUFRO series in Belgium. The main height increment is laid down in a 5 week period corresponding roughly to the month of June. The coastal sources from SOCO had the longest growing season, on average four weeks more than WACO, which results in the better performance of these sources in southern Britain. In the IUFRO trials in Germany, flushing, bud set and length of growing season were measured in the nursery and the latter two factors were found to influence height growth considerably between the ages of 3 and 14 years (Kleinschmit *et al.*, 1987).

St Clair (2006) also made measurements on bud set and the differences between populations were slightly less than for bud burst. The south Oregon coast low elevation populations (SOCO) were the latest to set bud, but only by seven days compared to the earliest which were those from the north Washington Cascades (NWCA). This resulted in the south Washington coast (WACO) families having a growing season of 163 days compared to 177 days for the south Oregon coastal material (SOCO).

Lammas growth

Lammas or free growth was measured because of its contribution to total height increment, but there may be an associated risk of autumn frost damage to such late growth. The number of trees with lammas growth at the end of July was measured at Laiken in 1960, seven years after planting. There was no clear pattern with wide variation between individual sources within regions. The source from BCCO produced the least growth of this type with less than 5% of trees affected compared with Darrington (NWCA) at 35%. Results from Ireland (Pfeifer, 1988) also indicated low incidence of lammas growth in WACO sources with a much higher frequency for Oregon sources (SOCO) and he attributed forking of the main stem to lammas growth rather than to spring frosts. De Champs (1972), in studies in France, found that the average height of trees which produce lammas growth was 25% greater than those which do not. He found that in one third of cases, forking of the main stem was associated with lammas growth rather than spring frosts. Lammas growth may therefore contribute significantly to total height growth up to about 10 years of age, after which its incidence decreases. Lammas growth was measured at 6 years of age in the IUFRO seedlots at Dean and results confirm those from Laiken in that coastal regions BCCO and WACO had the least, but within regions those from higher elevations had less than those from lower elevation. In Ireland forking of the main stem was again found to be associated with lammas growth rather than spring frosts in the IUFRO series.

General conclusions from the analysis of survival, frosting, flushing and lammas growth data

- In the nursery, seedlings and transplants can be damaged by early or late frosts with NOCO, SOCO and DONC giving the poorest survival.

- In the forest, there was a strong correlation between date of flushing and degree of frosting. Sources from WACO were least affected and high elevation sources experienced more damage than low elevation ones.

- Growth cessation determines the length of the growing season and thus the potential for height growth. The SOCO sources had the longest growing season which on average was four weeks more than WACO sources and they also had a much higher incidence of lammas growth.

- Forking in the main stem in the early years is often associated with lammas or free growth. Sources from the coastal regions of BCCO and WACO had the lowest incidence of lammas growth and the least forking.

3

Evaluation of seed sources: growth studies and production

The main results, deriving from the IUFRO series of experiments, are presented on a regional basis for height growth, diameter, basal area, branching and straightness. Where relevant, comparisons are made with the earlier Manning Bonded series. Wherever possible, the performance of material in test has been consistently compared against a commercial seedlot from Elma in the coastal Washington region (WACO) which was included in both the IUFRO and Manning Bonded trials. Seed from the Elma area was the most favoured commercial source at the time the trials were established. Data are presented as bar charts in which the performance of each regional grouping of sources is shown as a percentage of that of the Elma control. The overall site mean and the mean for the control used in the chart, in the units in which the assessment was made, are given against each site label.

This type of bar chart is used to indicate comparative performance of groupings of test material throughout the remainder of this publication. All data from the range of field trials reported here have been subjected to statistical analysis to examine the significance of any differences between regional groupings of test material or individual seed origins within specific groups. However, this publication aims to give practical guidance on origin choice without detailed statistical interpretation. Because of the number of performance characteristics to be considered, the results of statistical analysis are not presented routinely, but specific comments on significance are made where relevant. All bar charts are constructed using the same percentage ranges for performance, so that the comparative variation between groupings for different traits, sites and test series can be observed more easily.

Height growth in the IUFRO series

Height growth at 6 and 10–12 years after planting in the IUFRO series is summarised on a regional mean basis in bar charts in Figures 7 and 8 respectively. The results at 6 years confirm the findings of earlier experiments that the material of the interior type (BCIN) is consistently poorest, on average 30% below the best-performing region. This clearly indicates that material from this region should not be planted in Britain (Figure 9). Results at 10–12 years of age further reinforce these findings and only at the northern site (Craigvinean) does its height match that of sources from any other region. At 6 years the seedlots from the Coast Range area (BCCO, WACO, NOCO and SOCO) generally out-perform those from east of the Coast Range through to the western foothills of the Cascades (NWCA, SWCA and DONC). Within this latter set, sources from the dry areas of southern Oregon and northern California (DONC, present at 4 sites) are consistently poor and are therefore not thought worthy of further consideration.

Within the coastal groupings the performance of the seed sources from Vancouver Island and the mainland coast of British Columbia (BCCO) was considerably poorer than those from the more southerly parts of the area to the west of the Coast Range in Washington and Oregon (WACO, NOCO and SOCO) (Figure 10). At 6 years from planting, these seed sources perform best and are generally superior to those from the Washington Cascades (NWCA and SWCA). At 10–12 years, the more southern coastal sources (SOCO) are usually out-performing the other regions except at the most northern site of Craigvinean. Part of the percentage increase in height is probably due to the greater frequency of lammas growth which will progressively disappear after 10 years of age. The other Washington/Oregon coastal sources (WACO and NOCO) continue to out-perform those from the Cascades, growing consistently taller than NWCA origins whilst being matched by SWCA origins at some sites.

Figure 7

IUFRO series: height at 6 years after planting expressed as % Elma origin.

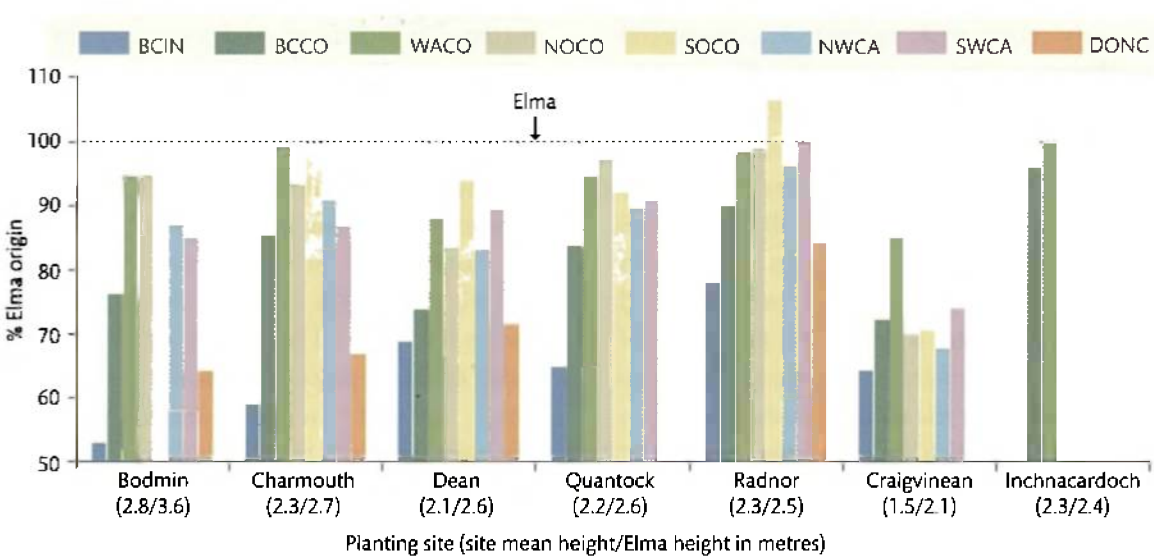


Figure 8

IUFRO series: height at 10–12 years after planting expressed as % Elma origin.

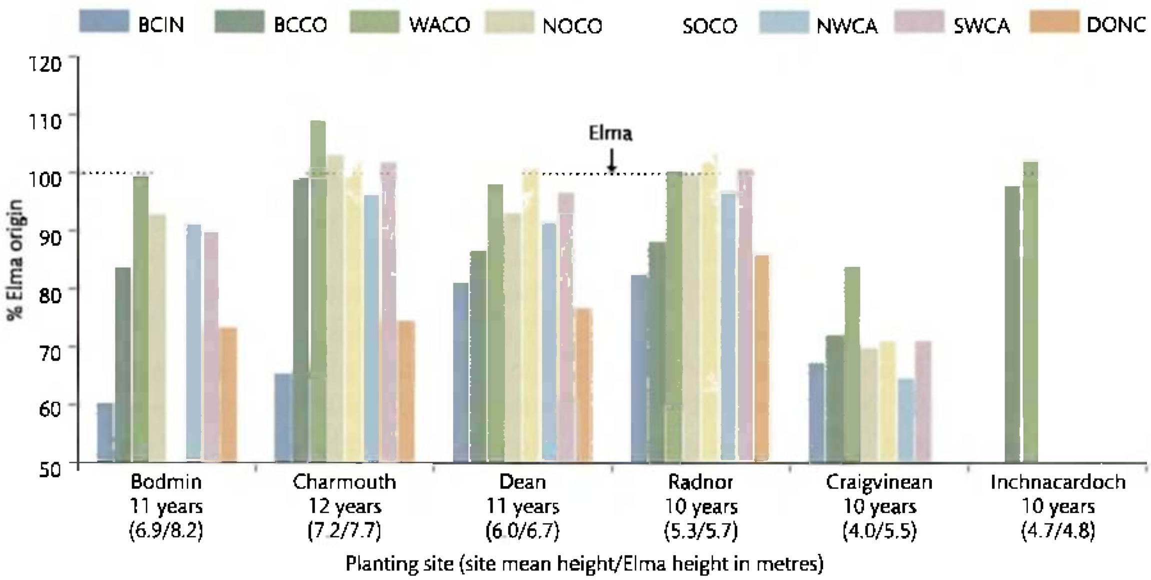


Figure 9

Forks, Washington coast (WACO) on the left compared with Tatla, interior British Columbia (BCIN) in adjacent plots in the IUFRO trial at Radnor, 38 years after planting.

Figure 10

Cathlamet, Washington coast (WACO) on the left compared with Squamish, coastal British Columbia (BCCO) in adjacent plots in the IUFRO trial at Radnor, 38 years after planting.

Height at 10 years after planting has been found to be a good predictor of later production in conifers (Kleinschmit *et al.*, 1987; Samuel *et al.*, 2007) and can therefore be used as the definitive measure of performance up to canopy closure. After this stage, height becomes more difficult to measure and diameter assessments provide for the comparison of production based on basal area. The final 10–12-year height data presented here, therefore, suggest that the Washington and Oregon coastal areas (WACO, NOCO and SOCO), together with the two groupings from the Washington Cascades (NWCA and SWCA), have the best potential for growth in Britain and that sources from interior British Columbia (BCIN) and the dry parts of southern Oregon (DONC) should not be planted in Britain. Sources from coastal British Columbia (BCCO) appear to have limited use except at more northern or difficult sites. Among the groupings favoured, coastal groups generally grow slightly faster than those from the Cascades. Further consideration of growth data can be used to refine this conclusion.

In particular, because of its importance as a reliable predictor of later performance, it is relevant to consider a combined statistical analysis of the height data at 10–12 years across all available sites in the IUFRO series. Analysis of variance revealed highly significant ($p < 0.001$) differences between origin means and site means. The variation between origin means is illustrated in Table 2 in which Duncan's multiple range test has been applied to the ranked overall origin means from the analysis of variance of height at 10–12 years. Some major differences already noted are evident, with WACO origins occupying the highest ranks and BCIN and DONC the lowest. However, the range of variation to be found among NWCA and SWCA origins is higher, each group being represented among the 7 fastest-growing origins and among the 11 slowest. Although the differences among origin means are highly significant and the total range of variation spans 3.2 to 7.1 m, there is only a range of 1 m across the 19 tallest sources whilst across the shortest 10 this is almost 3 m. This is reflected in the range tests in which the tallest 14 origins are not significantly different and a clearer level of separation only emerges between the top and bottom ranking groups of 7 and 11 origins respectively. The slowest-growing origin (1006, BCIN), 1.3 m shorter than the next in ranking, is significantly different from all others.

When the differences among origin means were examined by comparing group means, these were also found to be highly significant, and there was some variation in the significance of the residual variation between the specific origins within each group. There were significant differences between origins within the BCIN ($p < 0.01$) and SWCA ($p < 0.05$) groups but not within any others. This confirms that in most cases, the regional grouping has encompassed broad geographical and ecological differences effectively.

Because the IUFRO trials were planted across several sites, it was possible to consider changes in seed origin ranking across sites which may indicate the presence of origin x site interaction. For height at 10–12 years, analysis of variance showed this to be highly significant. On bar charts, this will be noticeable as changes in the comparative pattern among group means vary from site to site. The methods used by Finlay and Wilkinson (1963) give useful insight into this type of variation and were applied to the 6 and 10–12 year height data from the IUFRO trials. Using these methods, for each origin, a regression of its performance on the mean performance of all

Table 2

Duncan's multiple range test applied to overall origin means for height at 10 years at the 5% probability level.

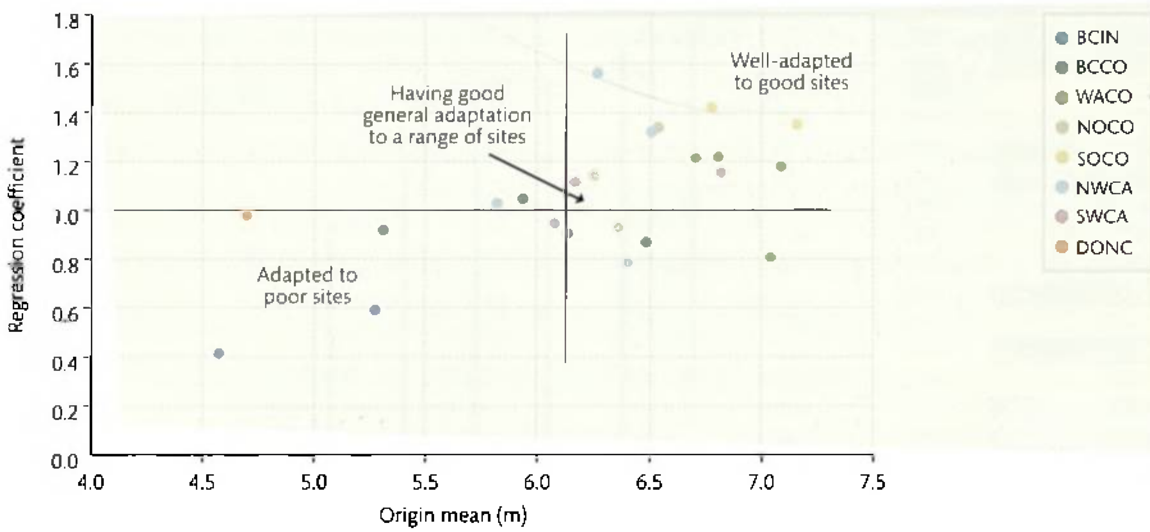
Group	IUFRO number	Height (m)	Means which are not spanned by the same vertical bar are significantly different									
WACO	1089	7.07	│									
WACO	Elma	7.03	│	│								
SOCO	1103	6.93	│	│	│							
SWCA	1075	6.80	│	│	│	│						
WACO	1086	6.79	│	│	│	│						
WACO	1062	6.69	│	│	│	│	│				
NWCA	1054	6.60	│	│	│	│	│					
NOCO	1101	6.53	│	│	│	│	│	│				
SWCA	1063	6.50	│	│	│	│	│	│				
BCCO	1030	6.47	│	│	│	│	│	│				
NOCO	1094	6.35	│	│	│	│	│	│				
BCCO	1029	6.28	│	│	│	│	│	│				
SOCO	1104	6.26	│	│	│	│	│	│				
NWCA	1053	6.26	│	│	│	│	│	│				
NWCA	1050	6.20		│	│	│	│	│				
BCCO	1043	6.19			│	│	│	│				
SWCA	1083	6.16			│	│	│	│				
NOCO	1098	6.15			│	│	│	│				
SWCA	1081	6.07				│	│	│	│			
NWCA	1051	5.93					│	│	│	│		
BCCO	1023	5.93					│	│	│	│		
NWCA	1056	5.81						│	│	│		
BCCO	1012	5.78						│	│	│		
BCCO	1027	5.31							│	│	│	
BCIN	1004	5.27								│	│	
BCIN	1014	4.86									│	
DONC	1146	4.68									│	
BCIN	1013	4.58									│	
BCIN	1006	3.23										│

origins at each site is calculated. Origins with regression slopes greater than 1 are likely to respond to more favourable site conditions, whereas those with slopes less than 1 may only perform relatively well on the poorer sites. Analysis of variance can also be extended to partition the variation attributable to origin x site interaction into a comparison of regression slopes at the regional level and the variation among specific origin slopes within groups. In a similar way to the breakdown of height mean data, there were highly significant differences ($p < 0.001$) among regional group slopes but significance only occurred among individual origin slopes within the BCIN ($p < 0.01$) and the NWCA ($p < 0.05$) groups.

A scatter plot of the regression coefficient against overall mean height for each origin provides a method of interpreting this analysis and is presented in Figure 11 for height at 10–12 years. Six origins for which the individual regression coefficient failed to reach significance have been omitted. In Figure 11, the same colour coding for origin groupings as that used in previous bar-charts has been retained. The overall mean height across all sites has been marked as a vertical line which, together with a mean regression coefficient value of 1

Figure 11

IUFRO series: scatter diagram relating regression slope and origin mean in joint regression analysis of height at 10–12 years after planting.



(marked as a horizontal line), divides the figure into four areas. The type of performance across sites to be expected from origins falling in the most important sectors is also given in the figure.

Origins from both the British Columbian groupings (BCIN and BCCO), together with the single origin from south Oregon/northern California (DONC), tend to fall towards the lower left quadrant of the diagram, indicating that they are adapted to sites with low production potential. This confirms their unsuitability to the range of better quality site-types in Britain in which the potential of Douglas fir is recognised. Most other origins have above-average mean performance and many fall into the upper right quadrant indicating that they will respond well to being planted on more favourable sites with higher growth potential. The greatest potential for growth on the fastest growing sites is shown by the southern Oregon group (SOCO). Evidence supporting the exclusion of these sources in Britain is given on pages 24 and 25. The main cluster of points, therefore, involves the four most favoured groupings (WACO, NOCO, NWCA and SWCA). Previous results are confirmed by this approach with the WACO grouping generally showing greater growth potential than the NOCO group. The groups from the Washington Cascades show similar ability to respond to favourable growing conditions, but would not be expected to grow as fast as the coastal groups. Representitive origins from these four regional groupings in the trial at Radnor Forest are shown in Figure 12. This approach gives more insight into the adaptability and potential to respond to increases in site quality than the study of means alone. However, whilst the position of some individual points on the diagram might suggest particular potential in this respect, more detailed conclusions would be inadvisable since the regressions are based on a relatively small number of sites.

Figure 12

Plots of representative origins of the four main regional groupings of interest in the IUFRO trial at Radnor, 38 years after planting.

a) Forks (WACO).

b) Waldport (NOCO).

c) Arlington (NWCA).

d) Enumclaw (SWCA).

Diameter

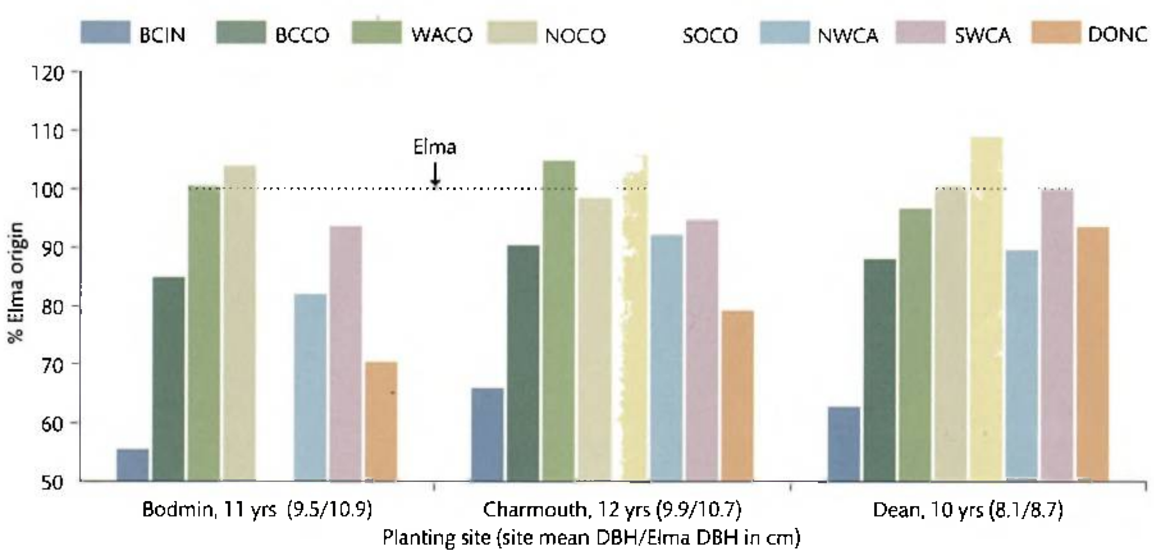
Diameter was measured in the IUFRO series at 10–12 years of age at Bodmin, Charmouth and Dean (Lines and Samuel, 1987) and the similar pattern to height growth obtained is shown in Figure 13. Sources in BCIN again had the smallest diameters, followed by sources in DONC, all of which are from very dry areas with free-draining soils compared to some of the coastal Washington and Cascade sites. Within the coastal regions there was a trend for increasing diameter from north to south, those from SOCO, present at Charmouth and Dean, having the largest diameters. In a similar way to height growth, the Cascade sources were generally out-performed by the coastal ones and sources in SWCA are usually better than those in NWCA. Diameter at Dean and Radnor was measured again at 16 years of age prior to thinning and for the first time at Craigvinean four years later (Fletcher and Samuel, 1990). The clear trend of slower growth amongst the BCIN sources and the superior growth of southern sources continued. The general pattern was very similar to that for height, except for sources from the drier areas in southern Oregon and northern California (DONC) where some of the largest diameter trees were now found. However, because survival in these sources was low, these favourable diameters do not reflect volume production on an area basis, which would be considerably reduced. This would be further exacerbated by the poor height growth noted in Figure 11 resulting in short stems with higher taper.

Basal area per hectare

The IUFRO experiments at Dean and Radnor were re-measured at 25 years after two thinnings and one thinning respectively. Figure 14 shows the results of this converted to cumulative basal area per hectare, which includes all material removed through thinning. The figure also includes the data from the unthinned plots at Craigvinean at 20 years. For basal area

Figure 13

IUFRO series: diameter (DBH) 10–12 years after planting expressed as % Elma origin.



measurements, the section of the experiments based on large plot sizes (see Appendix 2) was used. At Craigvinean, these did not include the Elma source and comparisons were therefore made against the overall mean at that site. At this stage of the crop's development the picture remains almost identical to that previously shown for diameter except for the DONC region where the basal area is higher, particularly at Radnor, due partly to the very small number of trees removed at thinning because of low initial stocking. However, the favourable diameter growth of SOCO sources shown at both 10 and 16 years does not result in consistently high basal area per hectare at this later stage because of poorer stocking density in these sources as a result of lower survival.

The basal area data, therefore, provide better insight into total production potential than early height and diameter measurements and suggest that the southern Oregon grouping of sources (SOCO) lies outside the range of material which would be suitable for use in Britain. The four remaining important groupings (WACO, NOCO, NWCA and SWCA) were considered in a comparison of basal area data from the IUFRO series together with similar data from four sites in the Manning Bonded series in Figure 15. This again supports the general conclusion of the superiority of coastal sources (WACO and NOCO) which is consistently matched by those from the south Washington Cascades (SWCA). These three groupings were superior to sources from NWCA at five of the seven sites.

Stem quality and branching characteristics

There has been a great deal of concern in Britain over the years about the high incidence of juvenile form defects such as stem sinuosity, forking, lammas growth, branchiness and wavy branching, which may have contributed to the more recent decrease in planting of Douglas fir. A major effect on timber strength

Figure 14

IUFRO series: basal area (BA) per hectare at 20–25 years after planting expressed as % Elma origin or % site mean.

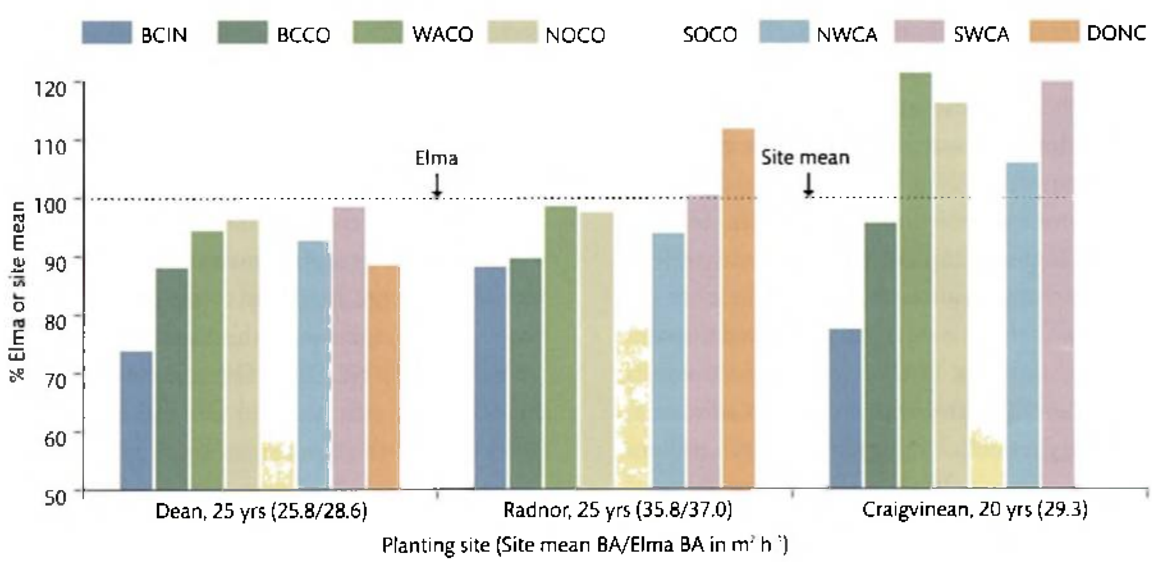
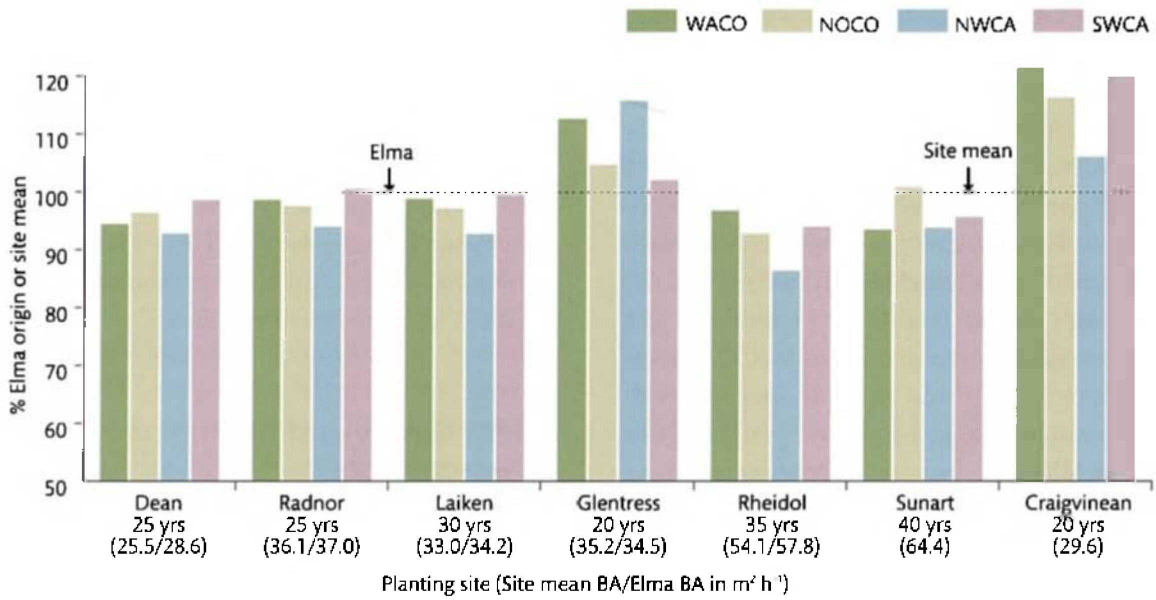


Figure 15

Basal area (BA) per hectare in IUFRO and Manning Bonded series at 20–40 years expressed as % Elma origin or % site mean.

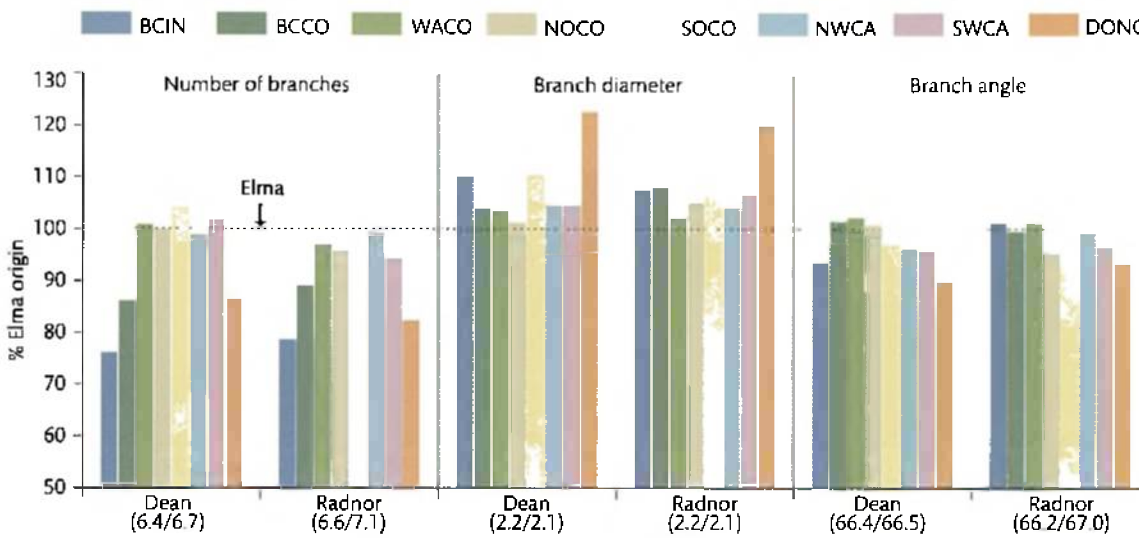


properties is the number, size and distribution of knots. These can be studied in field trials through the assessment of branching traits. Branching characteristics in the form of branch number, diameter and angle were measured in felled trees in the Dean and Radnor experiments at age 16 (Fletcher and Samuel, 1990) and are shown as a bar chart based on regional means in Figure 16. Sources from BCIN produced the smallest number of branches but branch diameter was relatively large especially when expressed as a ratio of stem diameter. The southern Oregon coastal sources (SOCO) had the highest number of branches as well as above-average branch diameter indicating the rough branching nature of these seed sources which is apparent in the actual parent stands in southern Oregon and northern California, which experience a high humidity and an oceanic climate. The sources from coastal Washington (WACO) had similar numbers of branches to those from the Washington Cascades (NWCA and SWCA), but branch diameter was slightly less. Although there were differences between sources in branch angle, these were rather small. A subjective assessment of branching (data not shown) was also made at Craigvinean in which WACO sources were again the most acceptable, followed by those from NWCA and SWCA. Stem form was assessed in the Manning Bonded series at Laiken at 16 years and again at 30 years following two thinnings. The rankings of the individual sources remained more or less the same between these ages, the most notable increases in ranking were made by those from SWCA, which were superior to the coastal sources in WACO and NOCO. Overall, as regards branchiness, number and size, sources from WACO were the most superior.

Stem straightness was assessed visually at Dean and Radnor at 25 years and at

Figure 16

IUFRO series: branching characteristics at Dean and Radnor 16 years after planting expressed as % Elma origin.



Planting site (site mean/Elma mean). Diameter in cm, branch angle in degrees from vertical.

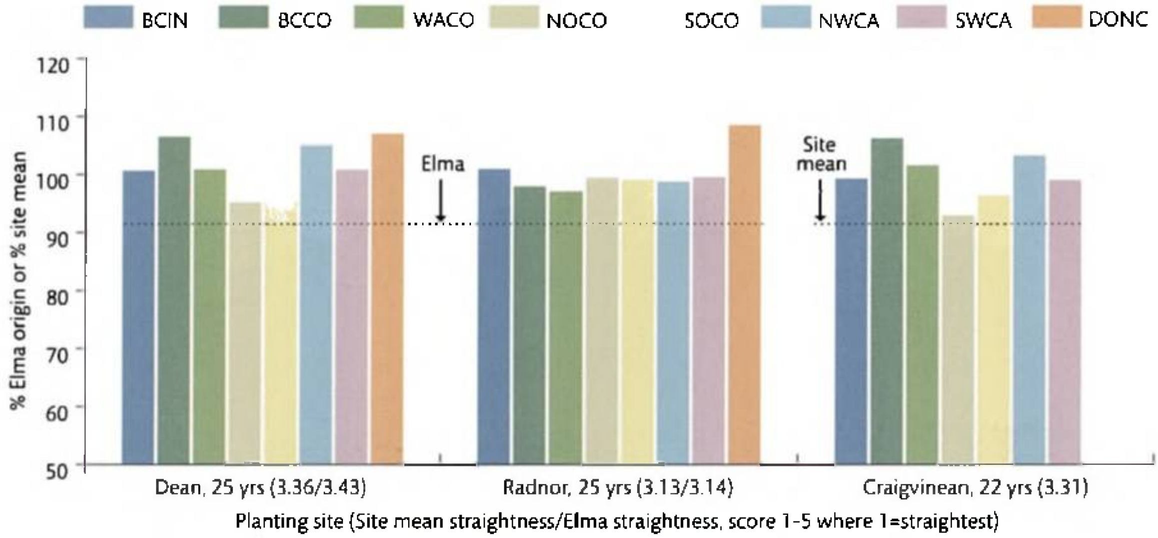
Craigvinean at 22 years (Figure 17). The experiment at Dean had been thinned twice while Radnor had only had one thinning and Craigvinean none. There were differences between sites, among the regions of major interest, that is all excluding BCIN and DONC. At Radnor there were fewer differences between the main regions. At Dean and Craigvinean sources from BCCO and NWCA were the straightest with little difference between WACO and SWCA sources. NOCO and SOCO sources were consistently less straight at both sites.

Taking both branching and stem straightness into account, there was little evidence to differentiate specific regions among the four main groupings (WACO, NOCO, NWCA, SWCA), other than to note the potential for less straight material among NOCO sources.

It is relevant to compare these findings with those from other parts of Europe. In experiments in Germany (Kleinschmit *et al.*, 1995) with 55 sources from the IUFRO collection tested on 8 sites, stem form and branchiness was assessed at 22 years of age. Results were similar to the British IUFRO series. Sources from SOCO were the poorest for stem form in line with the results in the British IUFRO series. The best form was found in WACO and BCCO followed by NWCA. As regards branchiness, SOCO was again the poorest with the best general branching habit shown by sources from WACO and NWCA. The IUFRO material in Ireland (Thompson and Pfeifer, 1995) was assessed for stem form at 25 years of age for the most promising 15 sources, mainly coastal, selected on the basis of results at 9 years after planting. The majority of the sources were from coastal areas and within these WACO and NOCO were the best, followed by BCCO. South Oregon sources (SOCO) were again the poorest. Nanson (1980) assessed thickness of

Figure 17

IUFRO series: straightness score at 22-25 years after planting expressed as % Elma origin or % site mean.



branching in a 22-year-old experiment in the Manning Bonded series in Belgium and found that the sources with the thinnest branches were from Hoquiam and Elma (WACO) whilst those with the thickest came from slow-growing populations in the Oregon Cascades. Sources from the Washington Cascades (NWCA and SWCA) also had above-average thickness of branch.

In summary, it would appear that over a range of sites in the UK and Europe, sources from WACO would be preferred closely followed by those from NWCA and SWCA. Because of poorer branching habit and stem straightness, sources from SOCO should definitely be excluded.

General conclusions from height, diameter, basal area and form

- The interior variety (BCIN) and sources from the DONC region produced very poor growth rates for both height and diameter.
- Amongst the coastal sources there is a general pattern of increase from north to south for both height and basal area although the latter is strongly affected by the poor survival in the SOCO sources.
- The coastal regions outperform the Washington Cascade regions for height and to a lesser extent for basal area.
- Variation in branch angle is small with no distinct trend.
- Sources from the SOCO region have the highest number and diameter of branches and overall the WACO sources are marginally the best.
- There are slight differences as regards stem straightness with BCCO and NWCA the best.

4

Evaluation of seed orchard material

Seed orchards established in the Pacific Northwest

Douglas fir is the major plantation species in the areas to the west of the Cascades in Washington and Oregon and also on Vancouver Island and the lower mainland of British Columbia. Breeding programmes for the species were established as early as the 1950s by a number of US and Canadian organisations with the planting of the earliest seed orchards dating back towards the end of that decade. Since then a large number of orchards have been established and seed surplus to local requirements started to become available in the 1980s. The parents used in some of these seed orchards have been selected in areas which are of interest to forestry in Britain. The orchards were based on trees selected in both the natural forest and second rotation areas, and since they have undergone a selection process their product should be superior to wild seed. In addition, they would provide seed of a more reliable quality from year to year.

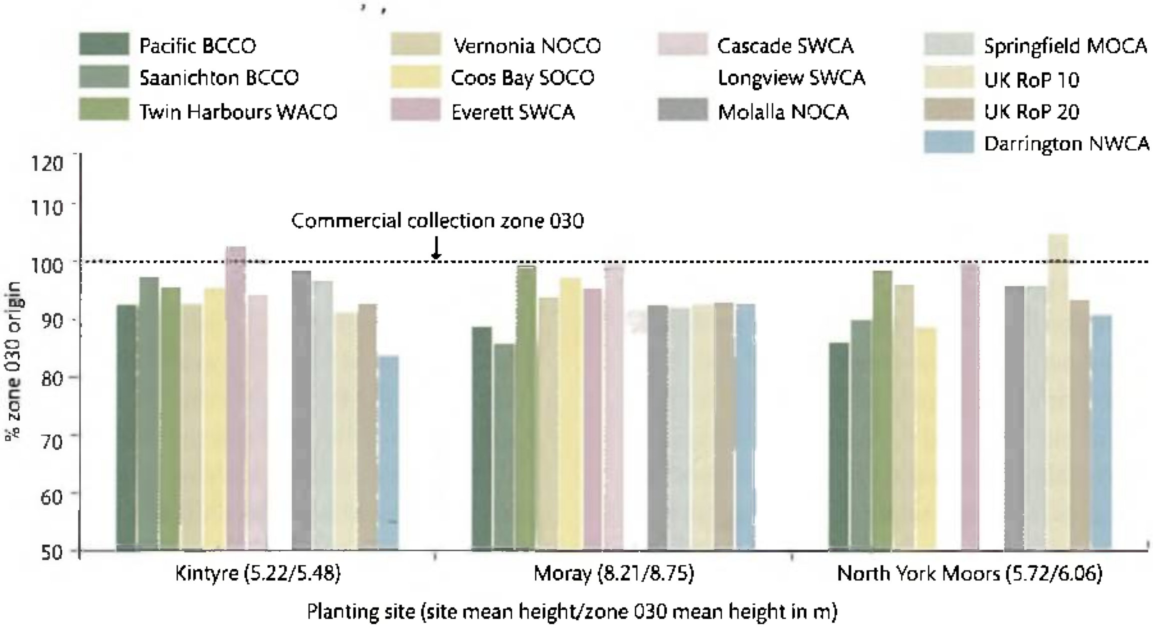
The production of seed in stands in Britain is unreliable with good seed years occurring only every 7–10 years with often heavy seed loss due to the Chalid seedfly *Megastigmus spermotrophus* Wachtl. in the intervening years. There has thus been a heavy reliance on importations of seed from commercial collections in wild stands in Washington and British Columbia. With the prospect of increasing quantities of seed becoming available from seed orchards in the Pacific Northwest, trials were established in 1993 to assess the value of material from these orchards by comparing them with commercial seed lots and seed from older selected stands in Britain. Seed samples were obtained from 12 orchards in British Columbia, Washington and Oregon. See Appendix 3 for details including the northwest American seed zones from which the parental material in each orchard was selected. There is good correspondence between the zones involved and the regional grouping of zones previously used in the analysis of seed origin data, with representation of all the coastal regions and the Washington Cascade regions. The orchards provide additional representation from the Oregon Cascades which have been divided into two further regions which are described in more detail in Table 1. Comparative trials were established on three sites in 1993 (Figure 6 and Appendix 2 for site details). In addition, material from registered UK selected seed stands, together with a commercial seedlot from Zone 030, Washington (the zone in which Elma occurs) (WACO), and a further lot from the Darrington area (NWCA), representing the most commonly favoured areas for importation of seed to the UK, were planted in the trials for comparison purposes.

Height

The results at 10 years after planting are presented in Figure 18. In comparison with the main IUFRO and Manning Bonded series, these experiments were based on small plot sizes. Although orchards within the established regions are shown individually in Figure 18, the general conclusions drawn were based on averages for each region. Some of the patterns established in the IUFRO provenance trials were evident in this material. BCCO seed orchards were inferior to those from WACO except at Kintyre, and inferior to SWCA at all sites. Indeed, they are only on a par with UK seed stands and produced results similar to

Figure 18

North American seed orchards and UK registered stands: height at 10 years after planting (expressed as % of commercial collection Zone 030 origin).



those from the Oregon Cascades (NOCA and MOCA), which have performed better than expected on this occasion. Contrary to previous data, there are minimal differences between the Saanichton orchard (BCCO) which is composed of higher elevation parents and the Pacific orchard composed of low elevation parents (below 1500 feet) from the same seed zone. On the other hand the NOCO and SOCO material has not performed so well as in the IUFRO series. Overall there is little to choose between the material from the orchards composed of parent material from the SWCA and WACO regions. Surprisingly the Zone 030 commercial collection (WACO) outperforms the majority of the orchards and, as in the IUFRO trials, is clearly superior to the commercial Darrington source. The UK seed stands compare favourably with the seed orchards and are equal to or outperform Darrington. The seed stands have been through a selection process having been thinned many times to remove the poorest trees and the seed was collected from the best 15 trees in each stand. This was an intensity of selection of parent material which was likely to be similar to that applied in the selection of the north American seed orchard parents, but likely to be more intensive than that practised for current collections from seed stands in Britain.

These comparative trials have indicated that when surplus orchard seed from north-west America is available it provides a good source of planting stock for use in the UK, although the exact choice of specific orchards will need to be made on the basis of the origin of their parental components. This choice can be based on the general guidance given for wild sources, although orchards from the NOCO region have not performed as well as wild stands from the same area when both are compared with equivalent material from the WACO region. In addition, the most appropriate orchards have matched or exceeded the growth of material from well-adapted UK selected stands. In comparison with imported material from unselected stands, seed orchards are likely to provide more uniform material from year to year.

Comparison of a range of European seed orchards and stands

During the 1990s, the opportunity arose under a project sponsored and partially funded by the European Union (EUDIREC) to establish a series of comparative trials of commercial reproductive material exchanged between participating European Member States. The aim of the trials was to investigate whether material which had resulted from seed stand selection or from breeding work had wider adaptability beyond the source country. In the UK, two trials were planted in 1998 at sites near the England/Wales border (see Figure 6 and Appendix 2 for details). Seed sources were from Belgium, the Netherlands, France and Germany, and further UK sources were included, together with imported material from the IUFRO origins, Darrington (NWCA) and Humptulips (WACO). The UK sources were all from selected seed stands whilst the material from other countries was predominantly from seed orchards with some seed stand material included from Belgium and Germany. Details of each source are given in Appendix 3.

Height and diameter

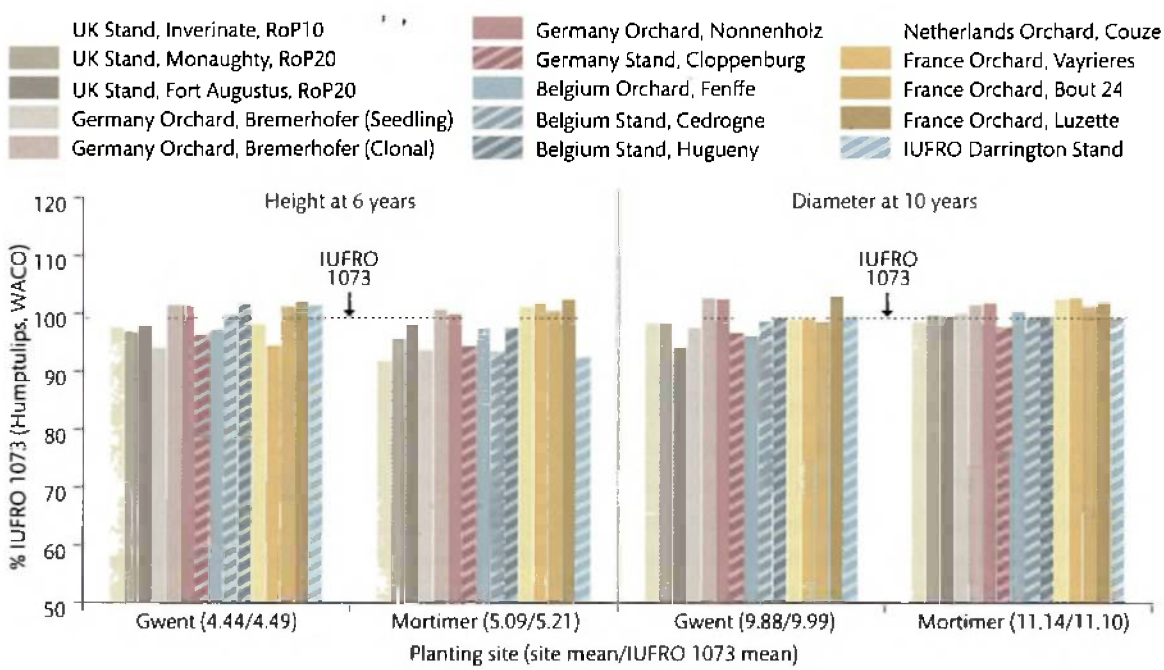
Height was measured at 6 years after planting and diameter at breast height at 10 years together with a subjective score for stem straightness and branching quality. In Figures

19 and 20, colour differences are used to distinguish participating countries, and within countries, patterned bars are used to represent seed stands as opposed to seed orchards. The performance of each source is expressed as a percentage of the IUFRO 1073, Humptulips origin, which represents the Washington coast region (WACO) which would be the most appropriate recommendation for use in Britain. It should be noted that the range of performance was much narrower in this material than that encountered in any other in trials previously considered. Differences among sources only reached significance at Mortimer for height at 6 years ($p = 0.01$) and branching score at 10 years ($p = 0.05$) among the range of characters measured in these trials.

Figure 19 gives height at 6 years and diameter at 10 years. There were general similarities in these two measures of vigour at different ages. The material grew faster at Mortimer than at Gwent and although there were changes in ranking between sites, there is consistent performance among a number of origins. Closer consideration of the 10 year diameter data shows that, in general, seed stand material showed poorer growth than that from seed orchards, none of the seed stands exceeded the Humptulips control. This is particularly so among the German sources where the orchard material normally exceeds or equals that of Humptulips. One of the three French orchards is superior at both sites, the remaining two, together with those from Belgium and the Netherlands exceed Humptulips only at the faster-growing Mortimer site. The data therefore indicate that the potential for good growth in Britain is more likely to be

Figure 19

European seed sources comparison trials: height at 6 years and diameter at 10 years after planting expressed as % IUFRO 1073, Humptulips (WACO).



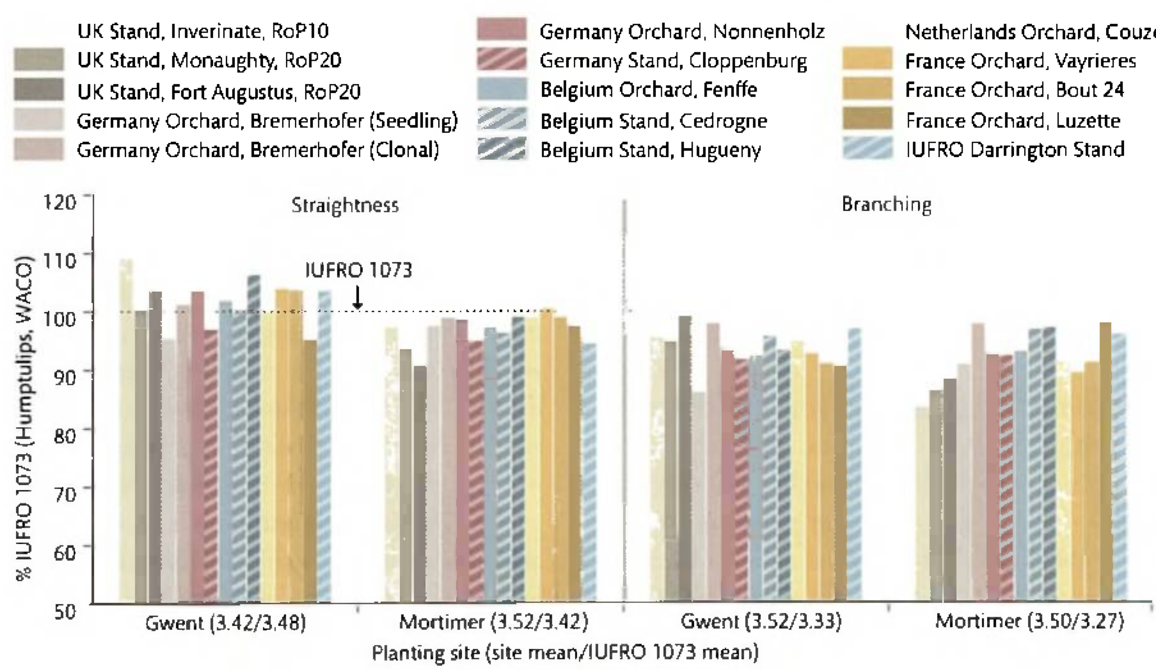
achieved on faster-growing sites. This could, of course, be the result of tree improvement programmes being based on selections within better-adapted origins or the selection of parental individuals which were adapted to more productive sites. Despite the narrow performance range and lack of significance between sources, the results do suggest that seed available from European seed orchards could be used in Britain, provided attention was paid to the origin of the parents in order to avoid poorly adapted material.

Stem straightness and branching

Stem straightness and branching characteristics are summarised in Figure 20. For stem straightness, a number of sources are similar or superior to the Humptulips control at the Gwent site (these include the three British seed stands) whereas at Mortimer, only one French orchard just exceeds Humptulips in straightness. For branching, Humptulips remains superior to all origins at both sites, although there is a wider range of expression of this characteristic than for straightness with significant differences among origins at Mortimer. For both traits, there are good sources to be found in all countries and the performance of British seed stand material more often matches that of European orchards than for diameter. This is to be expected since the heritability for branching and straightness is higher than that for growth characteristics. The narrow spread of variation encountered in these quality traits does, however, make interpretation and specific recommendations difficult.

Figure 20

European seed sources comparison trials: straightness and branching scores 10 years after planting expressed as % IUFRO 1073, Humptulips (WACO).



5

Climate matching

In selecting Douglas fir seed sources for planting in Britain, trials have repeatedly been made to select material on the basis of similarity in ecological variables between the place of origin of the source and the place of planting. As a species, Douglas fir covers a very wide geographic and climatic range from north to south, but more especially in an east-west direction. In the main Douglas fir areas, and especially in some of the river valleys and prairies in Washington and southern British Columbia, the species grows well on dry, warm soils of sandy moranic outwash and volcanic ash, but gives way to western hemlock, western red cedar and Pacific silver fir (*Abies amabilis* (Dougl. ex Loud.)) on the cold fresh soils on the mountain sides above 500–800 m.

It is difficult to obtain complete climatic matching and too little attention has perhaps been paid to the following facts about its native range:

i) most of the precipitation in the regions from which seed is obtained decreases in the winter when Douglas fir is not making active growth;

ii) in most areas it is exposed to summer drought and to air humidity below that found in Britain;

iii) in the higher humidity/wetter areas, it is replaced by other species especially on colder soils.

Nevertheless it is possible to find similarities for Britain on the coast of Washington and British Columbia where the seasonal progress of temperature matches quite well. However, these locations are at least 2° of latitude south of their British counterparts, since at a given latitude, Britain is warmer than the Pacific coast. Away from the strictly oceanic conditions, although individual measures may match, it is difficult to match all measures. Allowances have to be made because in the Coast and Cascades Ranges, Douglas fir grows at high elevations, but even utilising the rule of thumb that 1 degree south corresponds with 100 m increase in elevation, it is difficult to match accurately. Rainfall patterns are perhaps the hardest to interpret. The climatic details of representatives from the main regions of interest are given in Table 3 along with a comparison to typical Douglas fir sites in Britain. Total precipitation in Britain is generally less than in the Pacific Northwest but the most striking feature is the difference in average rainfall patterns. In Britain there is a slight decrease in the summer months whereas in the Pacific Northwest this decrease is much more pronounced with minimum levels in July and August. Precipitation during the growing season (April–September) expressed as a percentage of the total in the natural range averages 25% compared to British sites at 40 to 50%; for July and August the respective figures are 4% and 15%. The summer rainfall deficit leads in its native area to early cessation of growth and hence earlier lignification and commencement of latewood formation.

Table 3

Climatic details of Douglas fir seed collection areas in North America and typical planting sites in Britain.

Region	Seed Zone	Name	Latitude °N	Longitude °W	Elevation (m)	Precipitation (average, cm) Annual	Precipitation Summer[1] Apr–Sept	Precipitation Summer[1] July/Aug	Temperature (Celsius) Average Year	Temperature Average Summer Apr–Sept	Temperature Absolute Max.	Temperature Absolute Min.	Frost-free days
North America													
BCCO	1020	Nanaimo	49.25	123.87	26	105	26(25)	6(6)	10	14	38	-17	205
	1050	Chilliwack	49.12	122.01	10	170	49(29)	11(6)	10	15	38	-19	184
WACO	030/241	Elma	47.00	123.42	76	150	36(24)	5(3)	10	15	40	-15	184
	012	Forks	47.83	124.40	120	292	66(23)	12(4)	10	13	38	-19	174
	030	Hoquiam	47.00	123.83	3	158	36(23)	7(4)	10	13	36	-6	190
	041	Naselle	46.37	123.73	10	282	58(21)	9(3)	-	-	-	-	220
	041	Cathlamet	46.30	123.27	155	223	43(20)	7(3)	-	-	-	-	200
NOCO	51	Tillamook	45.92	124.00	8	239	56(23)	7(3)	11	13	39	-18	182
	052	Vernonia	45.83	123.25	232	127	28(22)	3(2)	10	15	40	-17	188
SOCO	082	Brookings	42.05	124.28	52	205	38(19)	3(2)	11	13	38	-6	269
NWCA	202	Sedro Woolley	48.50	122.22	17	113	35(31)	6(5)	10	15	38	-19	183
	403	Darrington	48.25	121.58	168	199	43(22)	7(4)	10	14	40	-24	145
SWCA	412	Enumclaw	47.15	121.93	399	128	46(36)	8(6)	10	13	38	-14	160
	430	Packwood	46.62	121.67	323	135	27(20)	4(3)	10	14	35	-16	146
	430	Castle Rock	46.28	122.90	35	147	31(21)	5(3)	11	15	41	-25	175
Britain													
Northern Highlands		Fort Augustus	57.13	4.67	21	110	44(40)	15(13)	8	10	30	-16.7	222
Southern Highlands		Faskally	56.72	3.77	94	83	38(45)	14(17)	8	10	30	-19.6	214
Midlands/Marches		Shawbury	52.08	2.67	72	67	35(52)	13(19)	9	13	35	-21.4	296
SW England		Exeter	50.73	3.42	32	78	32(41)	11(14)	10	13	32	-9	279

[1] For the two columns giving summer rainfall, the percentage of the annual precipitation is given in parentheses.

6

A seed origin suitability map for Great Britain

Although it is clear that sources from the Washington Coast region (WACO) have generally superior performance across the range of trial sites used in these studies, the consideration of climatic differences between the Pacific Northwest and Great Britain suggests that there may be areas in Britain where climatic factors may combine to favour other regional groupings. Samuel *et al.*, (2007) used regression analysis/ models to establish relationships between growth in seed origin trials and climatic factors at trial sites for each of a number of major regional groupings of origins of Sitka spruce. Based on these predictive models, maps were developed showing the most favourable origin grouping throughout Great Britain. A similar approach has been applied to the trial data available for Douglas fir to assist forest managers in decisions on the most suitable origin to plant when Douglas fir is the preferred species.

Neither the IUFRO nor the Manning Bonded Lots series was planted on a large number of sites, so data from both series needed to be combined. The limited number of sites in which consistent data collection took place fall into a narrow longitudinal band which excluded information on the performance of Douglas fir in extreme western and much of the eastern parts of Great Britain. Concentrating on the four main regions of interest (WACO, NOCO, NWCA and SWCA), one or two sources which were common to both series were selected to represent each region and a dataset assembled for height at 10–12 years for each region based on a maximum of seven sites ranging from Bodmin in southwest England to Craigvinean in central Scotland. The assessment of height at 10–12 years has been found to be well-correlated with later performance in conifer species (Lambeth,1980; Gill,1987).

The climatic factors to which Douglas fir is likely to be sensitive are temperature and moisture. Multiple linear regressions were therefore established for 10 year height regressed onto accumulated temperature in day degrees above 5°C (AT5) and moisture deficit (MD) for each of the four regional groups. AT5 is the accumulated number of day x degrees over 5°C and MD is the accumulated monthly excess of evaporation over rainfall, between March and October for the 30-year climatic period. Although the resultant equations accounted for an acceptable proportion of the variation in height (R^2 range 65.3–79.4), only a small number of regression coefficients were significant. Predicted values using these equations therefore had wide confidence intervals. The equations are given in Appendix 4.

The equations for each regional grouping were then used to calculate predicted height using a geographical information system with raster data sets of MD and AT5 at a resolution of 250 x 250 m. WACO sources have been found to be suitable throughout Britain, and so each other regional group was compared with WACO. However, only SWCA sources exceeded the performance of WACO on a consistent basis. Using climatic factors derived from the 1961–1990 climatic period (Jenkins *et al.*, 2007) and soil quality derived from low resolution digital national soils data (Anon, 1982; Anon, 2002), land suitable for planting Douglas fir was calculated using the Ecological Site Classification (ESC) for Great Britain (Pyatt *et al.*, 2001). Figure 21 provides a summary of the suitability of WACO and SWCA from the analysis, and defines: 1) areas unsuitable for Douglas fir; 2) areas suitable for Douglas fir but in which site parameters lie outside the range of those used in constructing the models; 3) areas in which WACO sources are assumed to be preferable, where the model showed no benefit in using SWCA; 4) areas in which the trials showed SWCA to have a 0–2.5% 10 year height advantage over WACO; 5) areas where a 2.5–5% height advantage is predicted for SWCA. For clarity, the resolution of squares has been reduced to 1 km, and this has tended to over estimate the area in which SWCA is predicted to show a 10 year height advantage over WACO. Since Figure 21 is indicative, individual planting sites should be checked using the ESC to ensure Douglas fir is suitable.

It is important to be aware that this map is based on underlying equations in which important statistics fail to reach significance. Nevertheless, it does indicate that there are areas in which SWCA sources, by virtue of their ability to respond to increase in temperature and to tolerate drier conditions, might be used to some advantage in preference to WACO sources. For example, in the areas to the eastern side of the Pennines and the northeast coast of Scotland where drier conditions are generally found. On the western side of England, where moisture is unlikely to be limiting, SWCA is only predicted to be superior in warmer areas, with higher AT5 values. It should be noted, however, that this map indicates that WACO sources would still be the favoured choice for most of the country but that no sources are suitable for those areas of eastern England, East Anglia in particular, where more limiting conditions of moisture and to some extent temperature prevail. This is because the map has been restricted to the prediction of performance only for values of AT5 and MD which lie within the limits of those encountered at the trial sites in the estimation of the regression equations. Clearly, and particularly in eastern England as shown in Figure 21, AT5 and MD values are likely to lie outside these ranges.

It is now widely accepted that an increase in temperature, leading to warmer and drier growing seasons will be a feature of the future British climate as a consequence of climate change. Ray *et al.*, (2002) have produced climate suitability maps for Douglas fir over the next century and much of the future area of suitability will be in southern and eastern England where AT5 and MD values lie outside those used to derive the predictive models. However, a fuller consideration which could relate to the use of the species under changes in a future climate can be given by modifying the indicative approach to origin choice (adopted above) to accept AT5 and MD values which lie outside those on which the models have been based. Figure 22 is a map of origin suitability based on this approach. In the map, the two levels of superiority of SWCA material suggested by the original model have been combined into a single area representing a 0–5% increase in height at year 10. Areas in which SWCA is superior based on values lying outside the model are shown separately to cover the 0–5% and the greater than 5% ranges of superiority. It is immediately apparent that under this relaxed use of the model, SWCA is now predicted to give the best growth throughout much of southern and eastern parts of England and that this is likely to exceed 5% above WACO along the eastern edge of the country. This map also introduces areas in west England, Wales and across Scotland which indicate that the superiority of WACO material would be based on values outside the model. Most of these areas are associated with an increase in altitude within the overall WACO area which lies to the west of Great Britain. This suggests that AT5 values outside those of the model are lower in these areas. However, in south-west and southern Wales and in southwest England, it is likely that AT5 values higher than those in the model would occur. It should be noted, however, that in either situation WACO sources still remain the most productive in either of these circumstances, in particular outperforming NWCA sources which might be thought to be better adapted to the conditions which could be expected at higher altitude.

Figure 22 can therefore be used to distinguish areas suitable for Douglas fir throughout Great Britain in which optimal growth rates are likely to result from either WACO or SWCA sources. Within the areas suggested for SWCA sources, it is important to assess the likely occurrence of frost at each planting site. WACO sources should be used on those sites which, because of aspect or topography, are likely to experience spring and autumn frosts. However, it must be remembered that,

- the map is based more on indicative relationships than significant models,
- extrapolation beyond normally accepted limits has been used, and
- overall differences in growth rate are in any case at best of the order of 5–10% based on 10 year heights.

Nevertheless, it provides an approach for current and future planting which should relate to any likely increases in the areas in which Douglas fir could gain importance as a timber species in the future, or as a component of an adaptation strategy for forestry.

Figure 21

Areas in Great Britain in which SWCA origins can be expected to show increased height over WACO origins. Areas not currently recommended for planting Douglas fir together with those lying outside the scope of the model used are also indicated.

Figure 22

Areas in Great Britain in which SWCA origins can be expected to show increased height over WACO origins, including extrapolation into areas previously lying outside the predictive model.

7

Conclusions and recommendations

The early experiments planted between 1928 and 1943 firmly indicated that the coastal sources of Douglas fir (var. *viridis*) out-performed those from the interior part of the distribution (var. *glauca*). These findings were also found to be true elsewhere in Europe such as in Belgium (Galoux, 1956) and Germany (Reck, 1980). The IUFRO and Manning Bonded seed-lots were mainly based on the coastal types but included some examples from the interior of British Columbia (BCIN). These latter experiments have clearly demonstrated and confirmed that under British oceanic conditions, sources from interior British Columbia (BCIN) do not perform well and should not be planted in Britain. The data from the growth studies allied to early phenology also indicate the unsuitability of sources from the drier areas in southern Oregon and northern California (DONC).

The sources from the south Oregon coast (SOCO) can have above-average height growth, but stem form, characterised by both straightness and branching, was very poor and this, together with poor survival and susceptibility to frosting, means that sources from this region cannot be recommended for use in Britain. As regards the other coastal sources, those from Vancouver Island and the mainland coastal areas of British Columbia (BCCO) tend to be below average both in production and stem quality. This is an extensive region and the best performing origin at 10–12 years was Squamish. This origin is close to Vancouver and similar to sites from which some of the early importations of seed (1921–1930) took place, and which have subsequently produced first quality stands, especially in Scotland. Material from stands, many of this origin, performed well in the seed orchard comparison trial. Nevertheless, for the coastal areas, the choice is narrowed down to Washington and north Oregon (WACO and NOCO). As far as the Cascades are concerned, the IUFRO experiments only included sources from Washington (NWCA and SWCA). The Manning Bonded series had representatives from the north Oregon Cascades but the growth, survival and resistance to frost were poor. Similar results were found in experiments in Ireland, Belgium, Germany and the Netherlands, therefore sources from the Oregon Cascades can be excluded.

A comparison of the most recently available production data for sources from the four regions WACO, NOCO, NWCA and SWCA, including data from the Manning Bonded series, was given in Figure 15. There was very little difference between the regions as regards basal area with the coastal regions (WACO, NOCO) just having an advantage over the Cascades (NWCA, SWCA) when the data from the Manning Bonded series are included. Within the Washington Cascade area the southern sources (SWCA) are definitely more productive. Regarding the coastal sources, WACO origins have an advantage over NOCO origins especially when frost susceptibility and form are taken into account. Within each of the regions there is a great deal of variation with Elma and Cathlamet (both WACO) consistently the best. In the Irish experiments (Thompson and Pfeifer, 1995), Cathlamet was the best source followed by Humptulips and Forks (both in WACO) and then Arlington (NWCA). A very similar picture was obtained in Germany (Kleinschmit *et al.*, 1995) with Matlock (WACO) being the best followed by Humptulips and Arlington. In the Netherlands (Krannenborg and de Vries, 1995), the recommended areas are south-west Washington coast (WACO) with Cathlamet and Skamokava, followed by Humptulips, Hoh, Matlock and Forks (some of these sources were not planted in the British trials) and then the NWCA region with Arlington, Darrington and Granite Falls. In Belgium (Nanson, 1980), Hoquiam (WACO) is the best for height growth and diameter as well as having the smallest branches. This is followed by Elma, then Darrington and Castle Rock (SWCA). For sites under some oceanic influence in France, the recommendation is for sources from western Washington (WACO) and northwest Oregon (NOCO), similar to those already stated above, but the seed must be harvested from elevations below 450 m. (Michaud *et al.*, 1995). There is therefore a great deal of evidence to suggest that, for oceanic areas of western Europe, sources from the western foothills of the Cascades through to the coast in Washington are the most productive.

A database for the IUFRO series has been established by the French forest research organisation, INRA, and contains information from 15 countries with 108 test-sites, mainly in Europe (Breidenstein *et al.*, 1990). This indicates that Douglas fir is best adapted to the north-western part of Europe and that within this area sources from west of the Cascades in Washington are the fastest growing. In addition, height growth decreases when the elevation of the source increases and no fast-growing sources can be found over 600 m in elevation. A number of sources have been shown to produce fast growth and a high stability across all the sites. These include Chilliwack (BCCO); Hoh River, Humptulips and Naselle (WACO); Vernonia (NOCO); Bacon Point, Sedro Woolley and Darrington (NWCA); and Castle Rock, Packwood and Enumclaw (SWCA).

The early results from the trials involving the comparison of seed obtained from wild stands, North American seed orchards and UK registered seed stands showed that the commercial collections from the Elma area were comparable to the orchards but the orchards will probably provide more uniform material from year to year. Seed from the orchards provides a viable alternative to material from wild stands within the same relevant seed zone or region, while seed from UK selected seed stands, if available, also produces acceptable material. Since the establishment of the trials of North American seed orchard material, changes to the rules for certification of seed under the Organisation for Economic Co-operation and Development (OECD) Forest Seed Scheme have precluded the import of seed from those seed orchards into the European Union. The OECD Scheme is the certification scheme used to provide equivalence under which seed is imported into the European Union from Canada and the USA.

The WACO region covers the north-west American seed zones 012, 030 and 041 (western portion). Elma is at the eastern boundary of 030 where it joins with 241 and because of the superiority of this origin in the trials the extreme western part of 241 could be included for seed collection purposes especially as it contains many very fine managed stands. The SWCA region includes seed zones 411, 412, 421, 422 and 430 (except the extreme western part). NWCA covers seed zones 201 and 202 (eastern parts), 401, 402 and 403. NOCO includes 041, 051, 052, 053, 061 and 062 (Table 1).

Between 1988 and 1991 the European Commission funded a survey of the locations in which the IUFRO collections were made, together with surrounding areas, and subsequently a list of stands and seed collection areas was published from which seed could be collected. Figure 23 shows two of the stands identified by this project. These are currently being used by seed merchants in Washington and Oregon and are the preferred sources if using commercial collections from wild stands. Details of the stands are given in Table 4.

The conclusions to be drawn from these studies are based on climatic conditions encountered during the past fifty years. It is now accepted that these conditions will alter considerably during the next fifty years with increases in atmospheric carbon dioxide and

Table 4

Details of European Commission Seed Collection Areas and Stands.

Region	Seed zone/stand no.	Locations/general areas
WACO	030/20, 21, 22, 23, 30	Humptulips
	030/10, 11, 12	Matlock
	030/10 and 241/10, 11, 12, 13	Elma
	041/21, 40, 41, 42	Cathlamet
	041/50, 52	Naselle
NOCO	041/61, 62	Clatskanie
	052/10, 11, 20, 21, 30, 31	Vernonia, Pittsburg
NWCA	202/11, 20, 30, 31, 60	Arlington, Granite Falls
	403/10-14, 20, 31, 41, 50, 51, 61, 71	Darrington
SWCA	411/10, 20, 30, 40	Sultan, Carnation
	412/50, 70	Enumclaw
	422/10, 31	Mineral
	430/10, 20, 31, 40, 50, 61	Packwood, Randle, Castle Rock

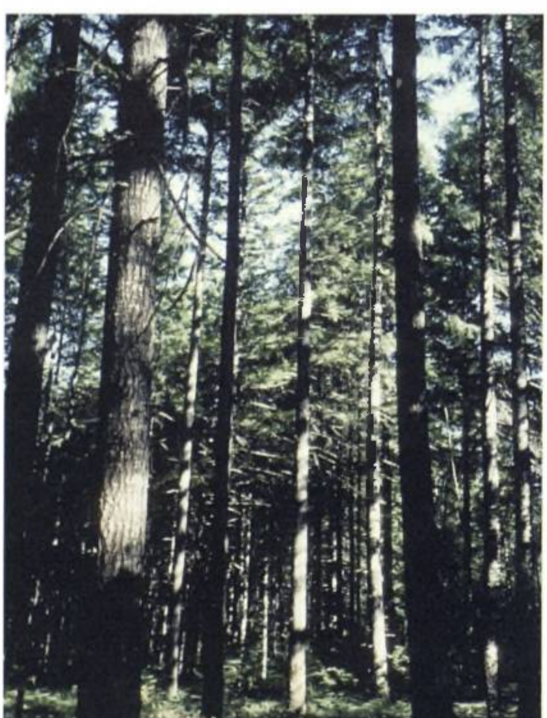
consequently increasing temperatures (Hulme, 2002). Climatic suitability maps produced by Ray *et al.* (2002) indicate a progressive increase in the area of the UK suitable for the planting of Douglas fir under a range of climate-change scenarios predicted for the 21st century. This is particularly so in Scotland whilst in the southern and eastern parts of England the models suggest a reduction in the level of suitability over time. The equations used for predicting origin suitability under current climatic conditions (Appendix 4) show that while WACO sources are able to respond to rises in temperature, their growth is reduced by increases in moisture deficit. SWCA sources, however, respond less favourably to a rise in temperature but show a small increase in growth under increasing moisture stress. This suggests that SWCA origins are at least more tolerant of drier conditions and will be likely to play a greater role in the increased area suitable for Douglas fir predicted by current climate-change models. Their future suitability is likely to extend progressively westwards from the eastern areas for which they are currently recommended. Increasing AT5 will lead to increases in growth which could favour some of the Oregon and northern Californian sources but equally the factors of poor survival, susceptibility to frost and lammas growth could be increased and thus these factors would continue to eliminate these sources. The WACO and SWCA sources will continue to be the most suitable for planting in Britain.

Figure 23

Two stands identified in the EU survey (1988-91).

a) Mud Lake, WACO, zone 241/11.

b) Cispus, SWCA, zone 430/31.

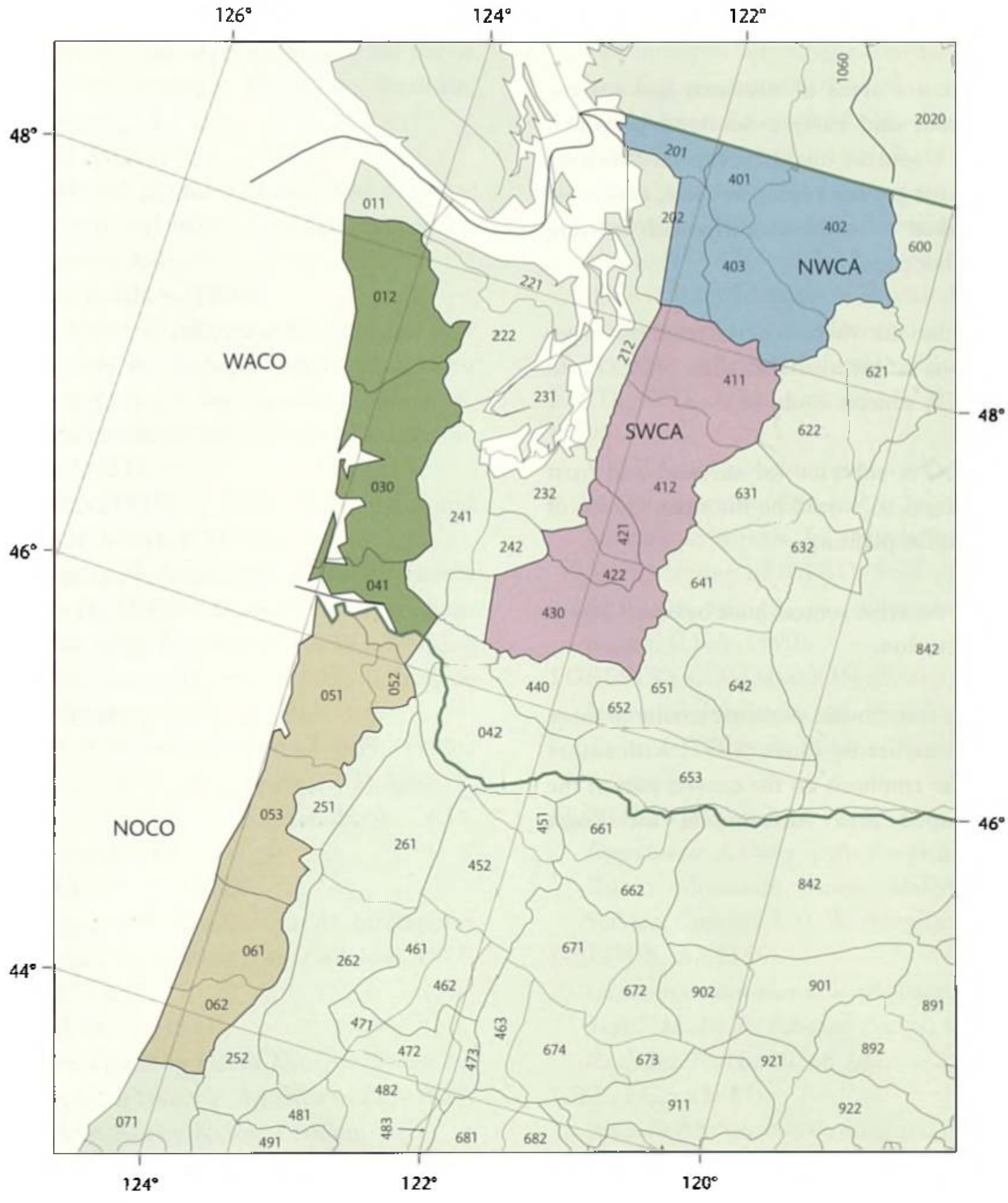


Recommendations

- **Results from the IUFRO and Manning Bonded series indicate that for growth characteristics, seed sources from the Washington coast (WACO), the north Oregon coast (NOCO), the north Washington Cascades (NWCA) and the south Washington Cascades (SWCA) should provide material which performs well over a range of sites in Britain (Figure 24).**

Figure 24

Map of Washington and Oregon showing the four main regional groupings of origins recommended for use in Great Britain.



- There is little to choose between WACO and SWCA sources but the primary choice for the general range of site types suitable for Douglas fir in Great Britain would be WACO.

- There are areas of southern and eastern England and eastern Scotland in which SWCA sources might be expected to have superior growth rates. On these, care must be taken to avoid sites in which frosting could occur.

- In situations where material from these two regions is not available then NOCO and NWCA sources could be used.

- WACO is superior for survival and frost hardiness so would be the main choice of origin for planting.

- In all the areas sources must be below 500 m in elevation.

- These recommendations are similar to those given earlier by Lines (1987) with rather greater emphasis on the coastal part of the U-shaped area surrounding the Puget Sound.

References

ANON (1982).
Soils: Handbook 8 – Organization and Methods of the 1:250,000 scale soils in Scotland – digital vector map of the major soil sub-groups. Macaulay Institute, Aberdeen, UK.

ANON (2002).
1:250,000 digital National Soil Map for England and Wales. Cranfield University, Cranfield, UK.

BALFOUR, F.R.S. (1932).
The history of conifers in Scotland and their discovery by Scotsmen. In: F.J.Chittenden ed. Report of the Conifer Conference, Royal Horticultural Society, 1931, London. pp 177–211.

BREIDENSTEIN, J., BASTIEN, J-C. and ROMAN-AMAT, B. (1990).
Douglas fir range-wide variation results from the IUFRO database. In: Proceedings of the Joint Meeting of IUFRO Working Parties S2.02.05, 06, 12, 14. (Olympia, Washington, U.S.A., 1990).

BURNS, R.M. and HONKALA, B.H. (1990).
Silvics of North America: Volume 1. Conifers U.S.D.A. Handbook 654, Washington DC.

DE CHAMPS, J. (1972).
Lammas shoots of Douglas fir. In: Rapport Annual, Association Foret Cellulose, 1971. pp 173–217.

DOUGLAS, D. (1914).
Journal kept by David Douglas during his travels in North America 1823–1827. William Wesley & Son, London.

EDWARDS, M.V. (1957).
Douglas fir. In: Exotic Forest Trees in Great Britain. Forestry Commission Bulletin 30, HMSO, London. pp 118–126.

FAIRBAIRN, W.A. (1968).
Climatic zonation in the British Isles. *Forestry* **41**, 118–130.

FINLAY, K.W. and WILKINSON, G.N. (1963).
The analysis of adaptation in a plant breeding programme. *Australian Journal of Agricultural Research* **14**, 742–754.

FLETCHER, A.M. and BARNER, H. (1980).
The procurement of seed for provenance research with particular reference to collection in NW America. In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

FLETCHER, A.M. and SAMUEL, C.J.A. (1990).
Growth and branching characteristics in the IUFRO origins of Douglas fir 16 years after planting in Britain. In: Proceedings of the Joint Meeting of IUFRO Working Parties S2.02–05, 06, 12, 14. (Olympia, Washington, U.S.A.,1990).

FORESTRY COMMISSION (2003).
National Inventory of Woodlands and Trees: GB Report. Forestry Commission, Edinburgh.

FROTHINGHAM, E.H. (1909).
Douglas fir. A study of the Pacific coast and Rocky Mountain forms. USDA Forest Service, Circular 150. Washington DC.

GALOUX, A. (1956).
Le sapin de douglas et la phytogeographie. *Trav. Sta. Rech. Eaux et Forets, Groenendaal,* Ser. B., No 20, pp 131.

GILL, J.G.S. (1987).
Juvenile-Mature correlations and the trends in genetic variances in Sitka spruce in Britain. *Silvae Genetica* **36(5–6)**, 189–195.

HULME, M. (2002).
The changing climate of the UK: Now and in the future. In: M.S.J. Broadmeadow ed.

Climate change: Impact on UK forests.. Forestry Commission Bulletin 125. Forestry Commission, Edinburgh. pp 9–26.

JENKINS, G.J., PERRY, M.C. and PRIOR, M.J.O. (2007).
The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, UK.

KLEINSCHMIT, J., SVOLBA, J., WEISGERBER, H., DIMPFLMEIER, R., RUETZ, W. and WIDMAIER, T. (1987).
Results of IUFRO Douglas fir provenance experiment in the Federal Republic of Germany at age 14. In: Proceedings of the IUFRO Working Party on Douglas Fir S.2.02.05, (Vienna, Austria, 1985). Schriftenreihe der Forstlichen Bundesversuchsanstalt. **21**, 67–75.

KLEINSCHMIT, J., SVOLBA, J., WEISGERBER, H., RAU, H.M. and FRANKE, A. (1995).
22 year results of the 2nd stage IUFRO Douglas fir provenance experiment in Germany. In: Proceedings of the Joint Meeting of the IUFRO Working Parties S2.02.05, 06, 12 and 14. (Limoges, France, 1995).

KRANENBORG, K.G. and DE VRIES, S.M.G. (1995).
Douglas fir provenance research in the Netherlands; 1966/67 IUFRO series. In: Proceedings of the Joint Meeting of the IUFRO Working Parties S2.02.05, 06, 12 and 14. (Limoges, France 1995).

KREIK, W. (1974).
Douglas fir IUFRO provenances in the Netherlands. 1966/67 series. *Nederlands Bosbouw Tijdschrift* **46(1)**, 1–14..

KREIK, W. (1980).
Further development of Douglas fir IUFRO provenances in the Netherlands 1966/67 series. In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

KREIK, W. (1983).
Results in Dutch field trials with Douglas fir IUFRO provenances and progenies of the 1968/1969 series. Rijksinstitutt voor Onderzoek in de Bos – En/Landschapsbouw "De Dorschamp", Wageninen, Report No 343. pp 40.

LAMBETH, C.C. (1980).
Juvenile-mature correlations in Pinaceae and implications for early selection. *Forest Science* **26(4)**, 571–580.

LARSEN, J.B. (1980).
Frost hardiness in Douglas fir. In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

LINES, R. (1987).
Choice of seed origins for the main forest species in Britain. Forestry Commission Bulletin 66. HMSO, London. pp 32–35.

LINES, R. and MITCHELL, A.F. (1968).
Provenance: Douglas fir. Report on Forest Research, Forestry Commission, 1968. HMSO, London. pp 71–73.

LINES, R. and MITCHELL, A.F. (1970).
Provenance: Douglas fir. Report on Forest Research, Forestry Commission, 1970. HMSO, London. pp 63–64.

LINES, R. and SAMUEL, C.J.A. (1987).
Results of the IUFRO Douglas fir experiments in Britain at 10 years. In: Proceedings of the IUFRO Working Party on Douglas Fir S.2.02.05 (Vienna, Austria, 1985). Schriftenreihe der Forstlichen Bundesversuchsanstalt. **21**, 31–48.

MACDONALD, J. (1952).
The place of north-western American conifers in British Forestry. Forestry Com-

mission Paper, Sixth British Commonwealth Forestry Conference, Canada. pp 21.

MCKAY, H.M. and HOWES, R. (1996). *Recommended plant type and lifting dates for direct planting and cold storage of bare-root Douglas fir in Britain.* Forestry Commission Research Information Note 284. Forestry Commission, Edinburgh.

MCKAY, H.M. and MASON, W.L. (1991). Physiological indicators of tolerance to cold storage in Sitka spruce and Douglas fir. *Canadian Journal of Forest Research* **21**, 890–891.

MENZIES, A. (1923). *Menzies Journal of Vancouver's Voyage, April–October, 1792.* Memoir V, Archives of British Columbia, Victoria, Canada.

MICHAUD, D. (1987). *First results of American Douglas fir provenance trials in France.* In: Proceedings of the IUFRO Working Party on Douglas Fir S2.02.05, Vienna, Austria, 1985. Schriftenreihe der Forstlichen Bundesversuchsanstalt. **21**, 3–24.

MICHAUD, D., PERMINGEAT, J. and BOUVET, A. (1995). *Douglas fir provenances from natural areas: Results after 15 years in France.* In: Proceedings of the Joint Meeting of the IUFRO Working Parties S2.02, 05, 06, 12 and 14. (Limoges, France, 1995).

NANSON, A. (1973). *International Douglas fir provenance experiments in Belgium.* IUFRO S2.02.05 Working Party Meeting on Douglas fir provenances, (Gottingen, Germany, 1973).

NANSON, A. (1980). *Belgian provenance experiments with Douglas fir, grand fir and Sitka spruce.* In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

O'DRISCOLL, J. (1980). *Six-year phenological study of thirty two IUFRO provenances of Douglas fir.* In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

PEACE, T.R. (1948). The variation of Douglas fir in its native habitat. *Forestry* **22**, 45–61.

PEARCE, M.L. (1980). *The IUFRO experiments with Douglas fir in England and Wales.* In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

PFEIFER, A. (1988). *Douglas fir provenance research in Ireland.* Forest and Wildlife Service, Internal Report.

PYATT, D.G., RAY, D. and FLETCHER, J. (2001). *An Ecological Site Classification for Forestry in Great Britain.* Forestry Commission Bulletin 124. Forestry Commission, Edinburgh.

RAY, D., PYATT, D.G. and BROADMEADOW M.S.J. (2002). Modelling the future climatic suitability of plantation forest tree species. In: .S.J.Broadmeadow ed. *Climate change: Impacts on UK forests.* Forestry Commission Bulletin 125. Forestry Commission, Edinburgh. pp 151–167.

RECK, S.G. (1980). *Height growth and frost resistance in Douglas fir provenances tested in the northern part of Germany.* In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

SAMUEL, C.J.A., FLETCHER, A.M. and LINES, R. (2007).
Choice of Sitka Spruce Seed Origin for Use in British Forests. Forestry Commission Bulletin 127. Forestry Commission, Edinburgh.

ST CLAIR, J.B. (2006).
Genetic variation in fall cold hardiness in coastal Douglas-fir in western Oregon and Washington. *Canadian Journal of Botany.* 84, 1110–1121.

THOMPSON, D.G. and PFEIFER, A.R. (1995).
IUFRO Douglas fir provenance trial – 24 year Irish results. In: Proceedings of Joint Meeting of the IUFRO Working Parties S2.02.05, 06, 12 and 14, (Limoges, France, 1995).

WEISGERBER, H. (1980).
Height growth development and damage by spring frost of the IUFRO Douglas fir provenance trial of 1970 in Hesse, Federal Republic of Germany. In: Proceedings of the IUFRO Joint Meeting of Working Parties, (Vancouver, 1978). Ministry of Forests, Province of British Columbia, Canada.

WOOD, R.F. (1955).
Studies of north-west American forests in relation to silviculture in Great Britain. Forestry Commission Bulletin 25. HMSO, London.

Appendices

Appendix 1

Details of seed origins used in IUFRO and Manning Bonded seedlots experiments.

Identity number	Origin	Region	North American seed zone	Latitude °N	Longitude °W	Altitude (m)	Map[1]
IUFRO series							
Interior types							
1006	Tatla	BCIN	5020	51.7	124.7	950	6
1013	Revelstoke		3030	51.0	118.0	610	8
1014	Eagle Bay		2040	50.9	119.2	440	9
1004	Stuie		5060	52.4	126.0	230	4
Coast Range							
[illegible]	Klina Klini	BCCO	1040	51.1	125.6	3	7
1023	Jeune Landing		1010	50.5	127.5	168	10
1027	Alta		1050	50.2	122.9	640	11
1029	Thasis		1010	49.8	126.6	16	12
1030	Squamish		1050	49.1	123.0	15	13
1031	Gold River		1010	49.8	126.1	90	14
1043	San Juan River		1010	48.6	124.1	215	15
1062	Forks	WACO	012	48.0	124.4	120	26
1086	Naselle		041	46.4	123.7	50	25
1089	Cathlamet		041	46.3	123.3	200	21
66(7975)8R	Elma		030/241	47.0	123.5	80	46
1094	Vernonia	NOCO	052	45.8	123.2	250	28
1098	Hebo		053	45.2	123.9	150	29
1101	Waldport		061	44.4	123.9	65	31
1103	Coquille	SOCO	072	43.2	124.2	30	34
1104	Brookings		082	42.1	124.2	325	36
East of Coast Range							
1050	Marblemount	NWCA	402	48.6	121.4	110	16
1051	Sedro Woolley		202	48.5	122.3	65	17
1053	Darrington		403	48.3	121.6	160	18
1054	Arlington		202	48.2	122.1	120	19
1056	Sloan Creek		403	48.1	121.3	650	20
1063	Gold Bar	SWCA	411	47.9	121.7	120	22
1075	Enumclaw		412	47.3	121.3	280	27
1081	Alder Lake		422	46.8	122.3	420	24
1083	Packwood		430	46.6	121.7	620	23
1124	Wolf Creek	DONC	511	42.7	123.4	500	37
1126	Ashland		511	42.1	122.7	1650	38
1130	Hawkinsville		321	41.8	123.7	1150	42
1135	Sawyers Bar		311	41.3	123.2	1400	33
1144	Covelo		340	39.9	123.3	1000	39
1146	Alder Springs		371	39.7	122.8	1500	40
Manning Bonded seedlots							
50/3	Shuswap Lake	BCIN	2040	50.9	119.2	440	R
51/233	Elma	WACO	030/241	47.0	123.5	80	J
51/225	Sappho, Forks		011	48.1	124.4	122	A
51/226	Hoquiam		030	47.0	123.8	91	B
51/238	Vernonia	NOCO	052	45.8	123.2	244	P
51/230	Darrington	NWCA	403	48.3	121.6	152	F
51/231	Enumclaw - low	SWCA	412	47.3	123.9	152	G
51/232	Enumclaw - high		412	47.3	123.8	457	H
51/236	Ashford		430	46.6	122.0	457	M
51/237	Castle Rock		430	46.3	123.0	152	N
51/234	Tenino		232	46.8	122.7	91	K
51/235	Graham		232	47.1	122.3	183	L

[1] Code number or letter used to identify location on map in Figure 5a.

Appendix 2

Details of test sites and experimental design used in Great Britain.

Site	Latitude (N)	Longitude (W)	Altitude (m)	Rainfall[1] (mm)	Growing season (days)[2]	ATS[3] (° days)	Design of trial[4] Small plots	Large plots
Manning Bonded series (1954)								
Laiken	57° 33'	03° 50'	110	700	203	1151		169 x 3(16)
Sunart	56° 41'	05° 38'	60	2000	221	1315		64 x 4(13)
Glentress	55° 38'	03° 12'	213	1000	168	1197	36 x 3(20)	
Shouldham	52° 41'	-00° 31'	10	610	237	1796	9 x 10(16)	36 x 5(16)
Rheidol	52° 26'	04° 01'	125	1100	225	1653	36 x 5(17)	
IUFRO series								
Inchnacardoch (1972)	57° 08'	04° 42'	50	1270	182	1272	36 x 4(7)	
Craigvinean (1970)[5]	56° 36'	03° 38'	135	960	169	1216	36 x 5(20)	144 x 3(17)
Radnor (1972)	52° 15'	03° 01'	226	1000	177	1471	25 x 3(34)	196 x 2(34)
Dean (1972)	51° 49'	02° 40'	60	900	239	1831	25 x 3(34)	196 x 2(34)
Quantock (1972)	51° 07'	03° 12'	229	900	179	1566	25 x 3(27)	196 x 2(27)
Charmouth (1972)	50° 47'	02° 57'	137	1000	231	1786	25 x 3(34)	196 x 2(34)
Bodmin (1972)	50° 29'	04° 41'	90	1397	268	1930	4 x 9(34)	
Seed orchard comparison trials (1993)								
Kintyre	55° 22'	5° 38'	70	1500	219	1453	8 x 5(22)	
Mortimer	52° 21'	2° 46'	310	800	152	1433	8 x 5(29)	
North York Moors	54° 10'	1° 04'	140	760	198	1432	25 x 3(24)	
European stands and seed orchards (1998)								
Mortimer	52° 16'	2° 16'	230	900	169	1425		100 x 3(16)
Gwent	51° 39'	2° 50'	245	1100	183	1465		100 x 3(16)

[1] Annual mean rainfall
[2] Growing season calculated using the methods of Fairbairn (1968).
[3] Column ATS indicates accumulated degree-days above 5 degrees Celsius.
[4] Design of trial is indicated as plot size x replicates e.g. 36 x 4 indicates 36 tree plots with 4 replications. The figure in brackets is the number of provenances present. On many sites, trials were duplicated in small plot and large plot designs.
[5] At Craigvinean, a further set of the same 7 origins as at Inchnacardoch was planted in 1972 in 2 replicates of 36 plant plots.

Appendix 3

Details of seed lots from North America, the UK and Europe.

Identity	Location	Type[1]	Seed Zones[2]	Region[3]
North American seed orchards – 1993 planting				
DF83(711)Lot900	Pacific (Id.9553)	SO	1010, 1020, 1040	BCCO
DF83(711)Lot901	Saanichton (Id.9556)	SO	1010, 1020, 1040	
DF83(711)Lot902	Saanichton (Id.9558)	SO	1010, 1020, 1040	
DF83(711)Lot903	Saanichton (Id.9560)	SO	1010, 1020, 1040	
DF86(7972)900	Twin Harbours	SO	030(041,241)	WACO
DF85(7972)904	Commercial collection	WS	030	
DF87(7953)901	Vernonia Elite	SO	041, 052	NOCO
DF86(7952)900	Coos Bay	SO	071	SOCO
DF85(7974)902	Darrington	WS	403	NWCA
DF86(7973)900	Everett	SO	411,412	SWCA
DF86(7974)900	Cascade	SO	232,242,421,422	
DF86(7972)902	Longview	SO	041,042,430,440	
DF87(7951)900	Molalla	SO	261, poss452	NOCA
DF86(7953)900	Springfield	SO	262,471,481,482	MOCA
UK seed stands – 1993 and 1998 (*) planting				
DF87(1007)Lot900	Inverinate*	ST	RoP10	
DF87(2015)Lot900	Inchnacardoch	ST	RoP20	
DF87(2019)Lot900	Port Clair	ST	RoP20	
DF87(2020)Lot900	Port Clair	ST	RoP20	
DF87(2021)Lot900	Monaughty*	ST	RoP20	
DF87(2022)Lot900	Balmoral	ST	RoP20	
DF87(2024)Lot900	Fort Augustus*	ST	RoP20	
DF87(2026)Lot900	Fort Augustus	ST	RoP20	
European seed stands and orchards – 1998 planting[4]				
DF90(430)Lot900	Bremerhofer (seedlings)	SO	Unknown	Germany
DF90(430)Lot902	Bremerhofer (grafts)	SO	Humptulips	Germany
DF90(430)Lot903	Nonnenholz	SO		Germany
DF90(430)Lot904	Cloppenburg	ST		Germany
DF92/552C	Fenffe	SO		Belgium
DF95/087C	Cedrogne	ST		Belgium
DF95/088C	Huqueny	ST		Belgium
DFR960600	Couze	SO		Netherlands
DF96(44)Lot900	Vayrieres	SO	Darrington, ex DK	France
DF96(44)Lot901	Bout 24	SO	Unknown	France
DF96(44)Lot902	Luzette	SO	Washington	France
DF76(797)IUFRO1053	Darrington	WS	403	NWCA
DF76(797)IUFRO1073	Humptulips	WS	030	WACO

[1] Type of basic material: SO = seed orchard, ST = selected seed stand, WS = commercial collection from wild stand.
[2] Seed Zones – North American Seed Zone or British Region of Provenance (RoP).
[3] North American regions as in Table 1.
[4] In Figures 19 and 20 stands (ST) are shown in hatched bars on the charts.

Appendix 4

Predictive equations used in the development of origin suitability maps.

Dependant variable

Height at 10 years at the following sites in the IUFRO and Manning Bonded Lots series:

Craigvinean, Glentress, Rheidol, Radnor, Dean, Charmouth, Bodmin.

Independent variables

1. National grid northings (NO)
2. Accumulated temperature in day-degrees above 5°C (AT5)
3. Moisture deficit – accumulated monthly excess of evaporation over rainfall (mm) between March and October (MD)

Predictive equations

Washington coast (WACO)

HT = 0.2224 - 0.0225(NO) + 5.3512(AT5) - 0.1387(MD)
Percent variation accounted for: 55.8

South-west Cascades (SWCA)

HT = 2.6498 - 0.0411(NO) + 2.8176(AT5) + 0.0130(MD)
Percent variation accounted for: 79.3

Alan Fletcher worked in Forest Research from 1963 to 1997, leading the breeding programme for Sitka spruce. During the 1970s he made frequent visits to the Pacific Northwest to organise surveys and seed collections of important conifer species. In the 1980s he led teams of European Union specialists to survey and designate areas of Douglas fir which could provide seed for use in Western Europe. He was head of Tree Improvement Branch from 1992 to 1996.

Sam Samuel worked in Forest Research from 1970 to 2010, providing support in the analysis and interpretation of data from seed origin evaluation and tree breeding programmes. He was head of Tree Improvement Branch from 1996 to 2004.

Forest Research

Forest Research is an Agency of the Forestry Commission and is the leading UK organisation engaged in forestry and tree related research. The Agency aims to support and enhance forestry and its role in sustainable development by providing innovative, high-quality scientific research, technical support and consultancy services.

Douglas fir plays an important role in the production of quality timber and is also important for other multi-purpose forestry uses. Due to the extent of its natural range in Pacific Northwest America, a range of material from natural populations and tree improvement programmes has been evaluated in field trials to identify the most well-adapted sources for planting in Great Britain.

This Bulletin summarises the results from over half a century of research. The growth and production data have been used to produce suitability maps which can assist forest managers in their decisions on the choice of seed origin for planting. The Bulletin is recommended reading for forest managers, advisors and researchers alike – as well as readers interested in the development and use of species from the Pacific Northwest in British forestry.

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