The Redwoods and Red Cedar

Coast redwood (*Sequoia sempervirens*), giant redwood (*Sequoiadendron giganteum*) and western red cedar (*Thuja plicata*) – species, silviculture and utilisation potential

Scott McG. Wilson, **Bill Mason**, **Richard Jinks**, **David Gil-Moreno** and **Peter Savill** review the potential of these Pacific Northwest species.

Much thought is currently being given by foresters to alternative tree species that might be grown in Britain and Ireland if climatic change proceeds as predicted, and in the light of threats posed by novel tree pests and diseases, which have proliferated over the past decade. Recently the Wessex Silvicultural Group has considered the matter (Bladon and Evans, 2015), as have Forest Research (2016) and Wilson (2007, 2010, 2011). There is an on-line network that promotes novel species thought to have potential to grow well in the UK (SilviFuture, 2016), including nine high priority species and 20 medium priority species. Also Read et al. (2009) suggested a suite of 49 'emerging' species (24 conifers and 25 hardwoods) as a potential means of adapting British forests to climate change. Among these alternative conifer species are three productive members of the *Cupressaceae* family from western North America (a) coast redwood (*Sequoia sempervirens* (D. Don) Endl.), (b) giant redwood (*Sequoiadendron giganteum* (Lindl.) Buchholz) and (c) western red cedar (*Thuja plicata* Donn ex D. Don). These three species will be dealt with in this article. Much of the information we have used is drawn from Burns and Honkala (1990), Dallimore and Jackson (1948), Eckenwalder (2009), Farjon (1998, 2010, 2016), Macdonald et al. (1957) and Mitchell (1974).

Origin, taxonomy and introduction

All three of these species are now regarded as members of the broad family *Cupressaceae*, although the two Californian redwood species were formerly classified under *Taxodiaceae*. Other prominent forestry conifers in the *Cupressaceae* family include Lawson cypress (*Chamaecyparis lawsoniana*), Japanese red cedar (*Cryptomeria japonica*) (Savill, 2015), dawn redwood (*Metasequoia glyptostroboides*) and swamp cypress (*Taxodium distichum*). Conifer species of this type occurred commonly throughout the northern hemisphere during the Cretaceous and Tertiary periods, up to the beginning of the Quaternary glaciations 2-3 million years ago (Mai, 1989). The European and western Eurasian representatives were extinguished by the process of 'barrier compression' against east-west mountain chains (e.g. the Pyrenees, Alps, Carpathians and Caucasus) during the succeeding Pleistocene glacial episodes (Godwin, 1975; Ingrouille, 1995; West, 1970). However, the equivalent species have survived in eastern Asia and North America, where mountain chains run mainly north-south.

Coast redwood, the world's tallest tree, is a large, long-lived evergreen conifer, capable of exceeding 2,000 years in age and 110m in height. Trees with heights exceeding 60m

are abundant and 90m frequent. Early height growth is rapid, with 45m achievable by 50 years and 67m by 100 years. Young trees generally have a conical crown, becoming columnar and more open with age. Bark in young trees is orange-brown and stringy, becoming darker, drier and more fissured with age. The mature foliage is deep green, hard and slightly prickly, with both scale and normal leaves, the latter pectinate, oblong, pointed and 10-15mm in length. White stomata occur on the upper side of leaves, and pale blue-white or green bands beneath. Terminal buds are slender, pointed and incurving with pinkish-green loose scales. The species is confined to a 450 mile long coastal belt in central and northern California, with a minor northward incursion into southern Oregon, and it is rarely found more than 45 miles inland (Figure 1a). Coast redwood typically grows from sea level up to 750m asl, only locally extending up to 900m. It can form pure stands naturally, elsewhere growing in natural mixtures with Douglas fir, Sitka spruce, grand fir, western hemlock or Lawson cypress. Some 80,000ha of protected old-growth coast redwood forest still survive, although there are a further 260,000ha of commercially-managed (largely second rotation) redwood-dominated forest. A further 300,000ha of forest land falls within the natural occurrence range of this species.

Giant redwood (also known as Wellingtonia in Britain), the only surviving member of the genus *Sequoiadendron*, is now found naturally exclusively on the western face of the Sierra Nevada mountains of central California (Figure 1a). Giant redwood can be found growing from 830-2700m asl, the typical elevational range being 1400-2200m. There are 75 remnant natural populations, totalling some 14,000ha, in a belt running for 260 miles north to south, but only 15 miles

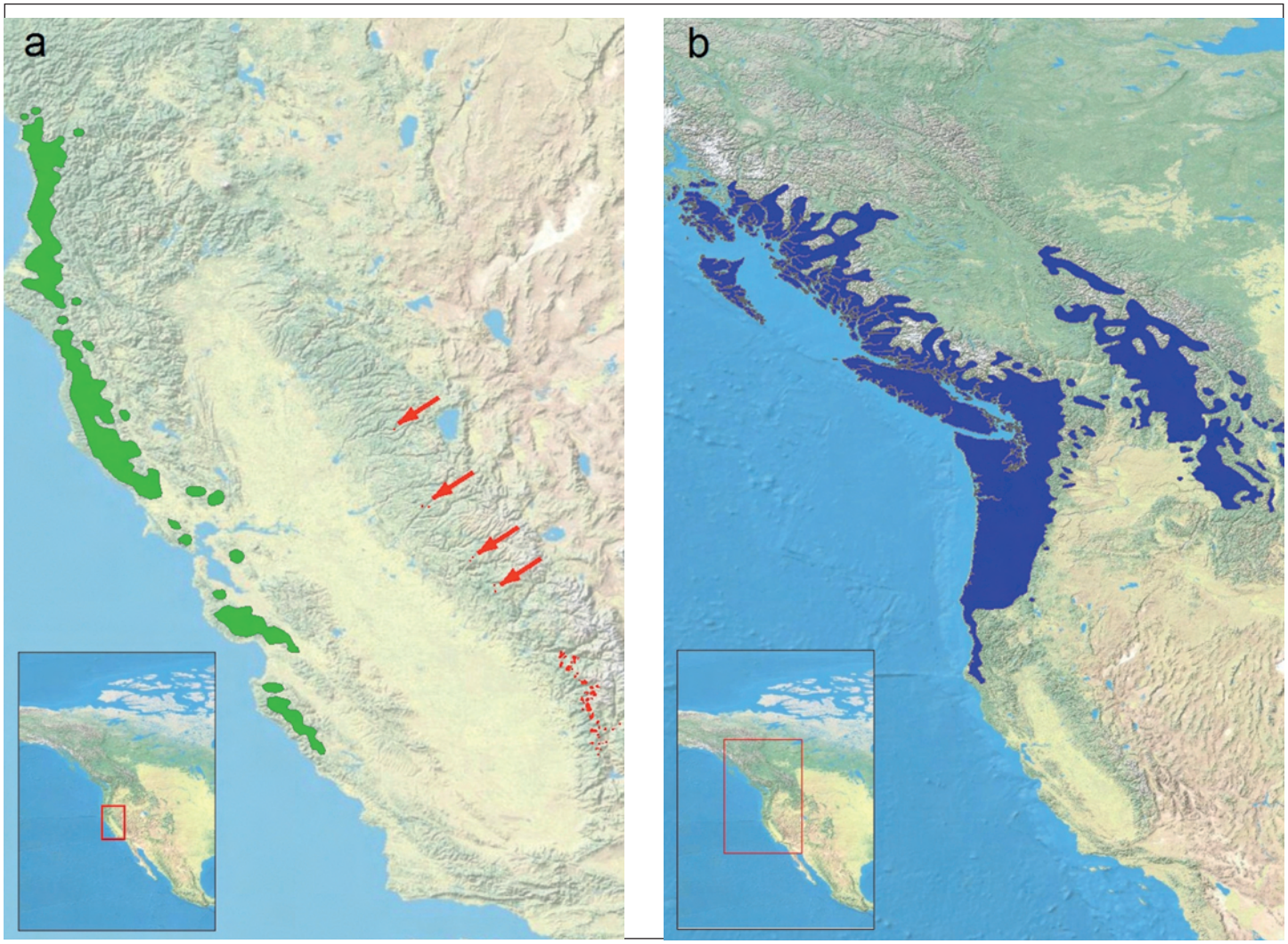

Figure 1. Natural ranges of a) coast redwood (Sequoia sempervirens) shaded green and giant redwood (Sequoiadendron giganteum) shaded red with the locations of small northerly populations indicated by arrows, and b) western red cedar (Thuja plicata) shaded blue. (Source: U.S. Geological Survey, 1999).

east to west. Giant redwood is the world's most massive individual tree, with one specimen, the General Sherman Tree, achieving nearly 1500m^3 stem volume / 2100 tonnes biomass. The tallest reaches 94.5m and mature specimens can reach a dbh of 8-9m, though more commonly 3-6m, with a more typical top-height of 75m. Many living specimens are believed to be over 2,000 years old, with occasional examples exceeding 3,000 years. The crown profile is conical, typically rather concave and with a wide sweeping basal skirt. The lower bark of mature specimens is thick, soft and deeply fissured with a red-brown colour. The aniseed-scented foliage consists of hard, greyish-green scale-leaves, 4-7mm in length, triangular, forward pointing and incurving. This species rarely forms extensive pure stands and occurs in natural mixture with a range of other tree species including: Low's white fir, California red fir, incense cedar, sugar pine, Ponderosa pine and California black oak.

Western red cedar naturally occupies an extensive territory running from northern California to south-eastern Alaska (Figure 1b). About 80% of the standing volume is considered to be in Canada (British Columbia), with the remaining 20% within the United States (Alaska, Montana, Idaho, Washington, Oregon and California). This species occurs in both maritime areas of the Coastal, Cascade and Olympic Mountains and further inland in the central Rocky Mountains. Coastal populations of western red cedar occur from sea level up to 1200m asl, whereas interior populations typically occur from 320m to 2300m asl, a wide elevational range. Western red cedar is another long-lived tree, often achieving 800-1,000 years in nature. Top-heights in the range 50-60m are frequent and diameter can reach 5-6m in older specimens. Younger trees have an acutely conical crown, but this acquires a characteristic rounded apex once 25-30m top height is exceeded. Foliage (with a sweet, fruity scent) consists of flat sprays of scale-leaves, deep glossy green above but paler below, pointed and incurving. Bark is reddish brown and stringy, which can cause processing challenges. Although there are small areas of pure western red cedar forests, the species typically occurs in mixtures with a range of conifers including western hemlock, Douglas fir, Sitka spruce, Pacific silver fir and grand fir. Bigleaf maple and black cottonwood are hardwood associates.

All three species covered in this article have been heavily exploited within their native ranges for the production of naturally durable construction timber from old-growth trees. This exploitation took place primarily during the century after 1850, particularly during the period of the California gold-rush and subsequent development of San Francisco and associated railroads. In the case of the two redwood species, this resulted in very significant losses of natural populations. The IUCN regard coast redwood as 'Endangered' and giant redwood as 'Vulnerable' (the latter species, although much less widespread, is now very strongly protected). In the case of western red cedar, reduction in natural occurrence has been much less severe, and the species is regarded by IUCN as being of 'Lower Risk / Least Concern' overall. However, much of the more accessible old-growth western red cedar forest has already been harvested at least once. These impressive conifer species attracted the attention of the early Victorian plant hunters with first noted introductions to the British Isles occurring during the 1840s (for coast redwood) and the 1850s (for giant redwood and western red cedar). Coast redwood and western red cedar have since been used as plantation species in several parts of the temperate world, including Europe and New Zealand (coast redwood).

Climatic, site and soil requirements

Generally, these species will be most productive in regions with a warm moist, temperate climate, avoiding extremes of wind exposure, summer drought or winter cold. Optimum soils are deep, moist but freely draining brown earths of poor to moderate fertility. There is, therefore, a marked overlap with the favourable 'lower slope' site conditions normally regarded as being most suitable for productive growth of Douglas fir and grand fir in Britain. However, there is some differentiation between the three species that should allow for selective deployment in lowland areas with a drier climate and on selected upland site types.

Coast redwood is normally regarded as being the most demanding of these three species. Despite coming from a Pacific coastal region, it is intolerant of wind and salt exposure. The species naturally occurs in a mild, humid climate with frequent summer fogs, which mitigate most risks of growing season moisture deficit. Annual precipitation ranges from 640mm to 3100mm, but this is significantly augmented by summer occult precipitation, hence the species is not considered drought tolerant. Mean annual temperatures are typically 10-16^{o}C with winter minimum temperature rarely falling below -9^{o}C, hence the species should not be regarded as particularly cold hardy and is certainly sensitive to late spring frosts in Britain. Forest Research (2016) advise that coast redwood is most suitable for mild, moist climates with more than 1250mm of rainfall, such as those found in Argyll, Wales and southwest England.

It can also perform well in eastern Britain where rainfall is only 600-1200mm, given suitable, moisture retentive soils. The Ecological Site Classification (ESC) (Pyatt et al. 2001) indicates that the preferred soils are brown earths of 'Poor' to 'Medium' ESC Soil Nutrient Regime (SNR) and 'Fresh' to 'Moist' ESC Soil Moisture Regime (SMR). Gleys, peats and infertile dry sand and gravel soils are inherently unsuitable for growth of this species.

Giant redwood is significantly less site demanding, with greater tolerance of wind exposure, frost, climatic drought and less moisture retentive soils. The species naturally occurs in a montane climate, but unlike the coast redwood, this typically has significant summer moisture deficits, with most of the winter precipitation as snow, which can reach 2m in depth in the California redwood groves. Annual equivalent precipitation is typically 900-1400mm, with less than 30mm between June and September. Frost tolerance is somewhat greater than for coast redwood, but critical minimum temperatures still may only be -12°C. Forest Research (2016) advise that the species is most suitable for intermediate climates with 800-1750mm of rainfall, which would encompass a wide range of British growing conditions away from very high rainfall upland areas in the west and very dry lowland areas in the east. Some stands in wetter areas of western Britain (e.g. at Kilmun and Crarae, both in Argyll), can appear unhealthy, with sparse foliage. Preferred soils are brown earths and some better podzols of 'Poor' to 'Medium' ESC Soil Nutrient Regime (SNR) and 'Slightly Dry' to 'Fresh' ESC Soil Moisture Regime (SMR) (Pyatt et al. 2001). As with coast redwood, gleys, peats and very infertile dry sand and gravel soils are inherently unsuitable for growth of this species.

Western red cedar is less climatically demanding than coast redwood in terms of frost and drought tolerance, although it remains intolerant of exposure, which causes leaf scorch. Use of western red cedar on sites with a DAMS score in excess of 15 is not advised within Britain. Within the natural range, a wide spectrum of climates are encountered, ranging

from a minimum of 700mm annual rainfall in the interior to an extreme of 6600mm in some hyper-oceanic areas. Minimum winter temperatures are much lower than for the redwoods, reaching -30°C in coastal areas and -47°C in the interior. Although relatively cold tolerant, the species is susceptible to damage, especially from aseasonal late spring frosts. Western red cedar occurs naturally on a very wide range of soils, including some gleys and peats. Forest Research (2016) advise that the species is most suitable for intermediate climates with in excess of 800mm rainfall, which would encompass most of mainland Britain away from very dry lowland areas in the east. Optimum soils are brown earths of 'Medium' to 'Very Rich' ESC Soil Nutrient Regime (SNR) and 'Fresh' to 'Moist' ESC Soil Moisture Regime (SMR) (Pyatt et al. 2001). However this species will tolerate a wider range of non-optimal soil conditions including gleys, calcareous soils and potentially, some better shallow peats. Very infertile and very dry soils remain inherently unsuitable for growth of this species.

Natural regeneration

Coast redwood and western red cedar are considered shade-tolerant late-successional species, producing copious advance seedling regeneration under a forest canopy, whereas giant redwood is a more light-demanding species, requiring maintenance of open and varied stand conditions, usually by wildfire, in order to regenerate naturally. All three species, unusually for conifers, are capable of some degree of vegetative reproduction. In the case of giant redwood, this is believed only to be commonplace up to 20 years of age, whereas for the other two species it can derive from sprouting of old cut stumps (mainly in the case of coast redwood) or layering of fallen logs of more mature specimens. These means of vegetative reproduction can form a very significant component of overall natural regeneration. In Britain abundant advance natural seedling regeneration of western red cedar can be recruited, with appropriate silviculture, in semi-mature stands from around 50 years of age. Natural regeneration of coast redwood can also be secured from similar stands, but this may well include a significant component of root-crown and stump sprouts. There is little evidence to date of natural regeneration of giant redwood in Britain and it may prove very difficult to secure because of inherent lack of fire and natural insect and small mammal associates.

Seed production and nursery conditions

Seed production in coast redwood begins from 5-15 years of age but viability is regarded as being very low from trees up to 20 years of age. After this trees produce abundant seed in most years. Optimum viability is reached by 250 years, declining to a minimum after 1200 years. Germination rates are often low at <15% before sorting, but can be above 80% after sorting. The seed is regarded as being very difficult to store successfully and is small and light (265,000/kg). Pre-treatment is not generally necessary for germination, but an overnight soak can assist. Standard nursery practice with a mineral soil seedbed is generally suitable. Plants can be expected to take longer in the nursery than spruce, with higher resulting plant costs. Frost sensitivity in the nursery has proven a particular issue with this species in Britain. Some attempts have been made with vegetative nursery propagation by cuttings, using a misting approach, and more recently micro-propagation techniques have also been developed.

Seed production in giant redwood begins from ten years of age but prolific coning only begins from age 150-200

years. Unlike coast redwood, there is little evidence of senescence in seed production. Cones are serotinous, and can remain on the tree, retaining viable seed, for 20 years. Eventual release of seed is by fire or by the action of *Phymatodes nitidus* (a cone-boring beetle) or the Douglas squirrel / chickaree (*Tamiasciurus douglasi*). Absence of these agents in Britain may limit scope for natural regeneration. Germination rates are usually 40-60%. There is no dormancy, germination is immediate and the seedbed must therefore be suitable, often prepared by wildfire. The seed is small and light (200,000/kg), winged and suitable for wind dispersal. There is limited experience with commercial nursery propagation, but standard nursery practice with a mineral soil seedbed is potentially suitable. Cuttings can be propagated, with a higher strike rate from donors less than 30 years old, but there has been little success from old-growth material. Stump sprouts become less prevalent after 20 years.

In western red cedar seed production begins from ten years of age and often has a marked biennial oscillation. The seed is very small and light (up to 1,300,000/kg) but, surprisingly, does not travel as far as that of hemlock, spruce or Douglas fir. Dry, refrigerated storage for at least seven years is possible without loss of viability. Germination is typically strong without the need for stratification. In the nursery, spring sowing is recommended, with partial seedbed shading. Seed may need to be pelleted for compatibility with automated sowing equipment designed for larger-seeded species. Containerised stock can be produced in less than one year, but two-year bare-root stock is preferred in the coastal range, partly on economic grounds. From British nursery experience, the species is more sensitive than spruce and pine and may require a longer period of development before it is ready to plant out, generating higher plant costs. Attack by the fungal pathogen *Didymascella thujina* causes Keithia leaf blight in the nursery, which can restrict planting stock availability. It is possible to produce large volumes of red cedar clones from stem cuttings, which may root untreated.

Provenance issues

Very limited studies have been undertaken of provenance variation in these species within the British Isles. The ultimate geographical origin of older planted specimens in Britain is frequently unknown or cannot be reliably established from surviving records. The only comprehensive trial of western red cedar was a series of six experiments with 13 seed sources that was established in the early 1960s. The seed sources tested ranged from northern British Columbia to Oregon and results at 15-25 years provided the basis for Forest Research's current (2016) recommendation for the use of western Washington or Vancouver Island provenances of this species. For coast redwood, the performance of 18 seed sources collected from along the natural range was tested at two sites in Devon and Hampshire in the 1960s. Early survival and growth were significantly poorer for southerly seed origins compared with origins from the middle and northern parts of the natural range. Northern California and Oregon provenances of coast redwood are expected to be more frost-hardy based on observations within the native range. There may be a case for first generation selective breeding in these species, drawing upon the existing resource of mature 'plus tree' specimens of superior form within British forest stands, provided that the first generation stands have been well thinned and contain at least 200 trees to limit any risk of inbreeding. Alternatively, a programme of clonal selection in coast redwood has been underway in New Zealand for over a decade (Low et al., 2008) and a similar approach could be attempted in Britain.

Establishment practice

Silviculture of these species within their native ranges has traditionally been by exploitation of naturally-established old-growth stands. Only in recent years has rotational management of second-growth stands, also usually naturally regenerated, become a significant factor.

In Britain and Ireland western red cedar and coast redwood should be seen as shade-tolerant, late-successional species, best suited to established forest conditions. Optimum conditions for establishment will be as enrichment interplanting or underplanting within mature conifer stands of open structure (e.g. of pine, larch, spruce or Douglas fir). Establishment in small felling coupes on more sheltered sites, with adjoining retained stands, should also be possible. While single species stands may be created under such conditions, preference should be given to establishment of silvicultural mixtures including these species – either nursing mixtures with oak, beech and sycamore or rotational mixtures with Douglas fir, western hemlock and *Abies* firs. Western red cedar is regarded as a particularly compatible nurse for quality oak stands. Western red cedar and coast redwood are unsuitable for establishment on exposed upland or clearfell sites without side shelter and, preferably, top shelter. It may be possible to create suitable conditions for their establishment by using 'nurse stands' comprising faster-growing broadleaves (e.g. birch, aspen). In some pure stands, red cedar has previously been established at 1.5-1.7m spacing (3,500-4,000 stems/ha), whereas current advice and grant requirements are typically for productive conifers to be established at 2.0m spacing (2,500 stems/ha). These are highly palatable conifers and deer fencing will usually be necessary to protect them. Good weeding is also considered beneficial, at least to avoid over-topping.

Growth and productivity

There have been fewer than 30 sample plots established with these species, mostly in the southern half of England and Wales. Selected data from some of these plots (Table 1) indicate the very high productivity that can be obtained from coast redwood, the lower production and more variable performance of giant redwood, and the acceptable performance achieved with western red cedar over a wide spread of climatic zones, ranging from south-east England to north of the Moray Firth in Scotland. Operational experience also suggests that yields of these species on suitable sites are generally high, ranging from GYC 12-26 or more, but typically GYC 18-22.

Yield models for western red cedar are presented in FC Booklet 48 (Edwards and Christie, 1981) and a similar regime

Table 1. Selected data from Forest Research sample plots in Britain with coast redwood, giant redwood, and western red cedar.

Species	Coast redwood (seven plots established)							
Site	**Age (years)**	**Trees ha^{-1}**	**Top height (m)**	**Mean dbh (cm)**	**Basal area (m^{2}ha^{-1})**	**Standing volume (m^{3}ha^{-1})**	**Cumulative volume (m^{3}ha^{-1})**	**General yield class**
Brechfa, Wales	53	215	30.1	66.1	73.8	865	1785	30
Forest of Dean	56	266	37.7	55.1	63.4	865	1757	28
Leighton Park (1)	77	162	41.2	88.2	99.0	1489	2554	26
Leighton Park (2)	149	196	37.3	128.2	253.1		3312	24
	Giant redwood (three plots established)							
Brechfa, Wales	40	701	21.4	37.7	78.4	563	868	18
Bedgebury	38	541	22.0	39.6	66.5	594	1062	18
Leighton Park	120	54	40.7	124.0	65.2		622	20
	Red cedar (eighteen plots established)							
Haldon, Exeter	53	398	29.9	40.9	52.3	499	689	26
Alice Holt	65	437	24.8	37.6	48.7	439	875	16
Forest of Dean	95	309	40.5	64.2	100.1	1273	2028	22
Friston	68	556	-	33.8	50.0		808	14
Gwydyr, North Wales	73	303	34.6	64.3	98.4	1020	1740	20
Corris, Mid-Wales	67	284	35.8	64.3	92.3	990	1937	26
Novar, Highland	44	648	24.2	31.1	49.1	422	1083	24

Notes:
1. The older coast redwood plot at Leighton Park and the giant redwood stand at the same location were never thinned;
2. The red cedar plot at Haldon was established by underplanting under European larch.

Figure 2. Western red cedar study site, Forest of Dean. (Photo: David Gil-Moreno)

is likely to be relevant to coast redwood. Optimum rotation length for premium logs would be longer than for spruce, and more akin to that for premium Douglas fir (60-90 years). Red cedar was also considered in a review of a range of alternative conifers (Aldhous and Low, 1974), where it was found to be capable of outgrowing Sitka spruce on more sheltered sites in southern Britain. Thinning practice in British regular stands of western red cedar has typically been deficient due to the previous greater difficulty in selling smaller dimension material and a perception of slow response by retained trees. The traditional aim was to produce a dense stand of uniform straight material with minimum marketable dbh of 30cm as quickly as possible. With improved outlets for the smaller diameter material and decorative foliage, consideration should be given to earlier thinning to develop a more varied, irregular structure. Many stands containing these species will now be managed under continuous-cover systems. Buttressing and 'bell bottom' are typical stem defects in western red cedar, especially once diameter exceeds 60cm, but processors can still make effective use of such material by 'sawing around' the defects to recover boards.

The limited experience with giant redwood in Britain means that much less can be said about the most appropriate silviculture for use with this species. There are few plantation stands from which GYC could sensibly be derived, but these suggest somewhat lower productivity than for coast redwood (e.g. the two species can be compared side-by-side at Kilmun in Argyll, with coast redwood achieving GYC of 22 and giant redwood GYC of 12 at similar ages, based on use of yield class tables developed for comparable species, including western red cedar). There is also some evidence of poor performance of giant redwood in closed stands (Table 1) and it may be better to grow it in structurally-diverse mixture with other species, in a similar way to the pattern within stands in its native range. Most giant redwood growing in Britain was originally established as specimen trees (as individuals and in avenues) and hence has been more exposed in its earlier years. Hence there may be somewhat greater tolerance to establishment on open sites, particularly in the east of the country.

Pests and diseases

The major pest and disease issues with these species affect western red cedar. Attack by the fungal pathogen *Didymascella thujina* causes Keithia leaf blight under nursery conditions, which can restrict planting stock availability. Growing trees are susceptible to honey fungus (*Armillaria*) decay and Fomes (*Heterobasidion annosum*) root and butt rot, especially on sites of higher soil base status, with a record of pre-existing hardwood or conifer crops. The cypress aphid (*Cinara cupressivora*) can cause foliage browning, confusable with scorch. Recently, a specimen of western red cedar in central Scotland was found to be suffering from infection by *Phytophthora lateralis*, more commonly seen in Lawson cypress.

Coast redwood is generally regarded as free of major pathogens, with some superficial foliage damage by *Phytophthora ramorum* reported from California. As with western red cedar, giant redwood is susceptible to honey fungus (*Armillaria*) decay and Fomes (*Heterobasidion annosum*) root and butt rot, but with lesser severity (Forest Research, 2016).

Table 2. Location and mean values of stiffness (MoE), density and bending strength (MoR) of structural sized pieces for sites studied compared with other (UK-grown) common species.

Site	Age (yrs)	Pieces (no.)	Grid Ref.	MoE[1] (kN/mm²) (st. dev)	Density[2] (kg/m³) (st. dev)	MoR[3] (N/mm²) (st. dev)
Western red cedar						
Southern	35	32	SO 646098	7.9 (1.2)	366 (31)	31.2 (5.6)
Central	61	39	SJ 064549	8.2 (1.7)	365 (34)	34.3 (8.0)
Northern	78	67	NS 489982	7.0 (1.7)	361 (34)	28.1(8.0)
Overall[a]	45	115		7.4 (1.7)	365 (30)	30.1 (8.0)
Sitka spruce[b]	35-45	955	———	8.3	387	32.7
Douglas fir[c]	42-58	188	———	9.1 (2.4)	455 (47)	34.1 (11.9)

[1]MoE corresponding to the shear free MoE, calculated according to EN384:2016 (CEN, 2016a); [2]At 12% moisture content; [3]Adjusted to a depth of 150mm;
[a]Gil-Moreno et al. (2016, in press); [b]Moore et al., 2013; [c]Drewett, 2015.

Figure 3a. Western red cedar logs, Cornwall. (Photo: Scott McG Wilson)

Figure 3b. Processing western red cedar for cladding boards, Cornwall. (Photo: Scott McG Wilson)

Figure 3c. Processing western red cedar for cladding boards, Cornwall. (Photo: Scott McG Wilson)

Timber properties and uses

The timbers of these species are moderately naturally durable, strongly reddish in colour, of rather low density and mechanically relatively weak. Ramsay and Macdonald (2013) cite specific gravities of 0.30-0.35 and Patterson (1988) and Savill (2013) report them as having densities in the range 390-420 kg/m^3 at 15% moisture content. For western red cedar there is some evidence that natural durability is higher in old-growth material from the native range than in much younger plantation-grown material from Britain. There is often strong visual differentiation between heartwood and sapwood, especially in coast redwood and western red cedar, which have an outer layer of paler, and almost certainly less durable, sapwood. Some processors will discard this material, favouring heartwood on visual and durability criteria.

There is currently a serious lack of information about the wood properties of these three species when grown under British conditions. Research at Edinburgh Napier University is assessing the mechanical properties and density of western red cedar. The study is using material from three pure even-aged stands, located at southern (Forest of Dean, England) (see Figure 2), central (Clocaenog Forest, Wales) and northern (Loch Ard Forest, Scotland) latitudes in Great Britain. Unfortunately, provenance details for these three stands are unavailable. Nine trees, covering the span of merchantable diameters, were felled from within each study stand. The resultant mean values are shown in Table 2.

When interpreting these results, it should be remembered that the use of timber for structural purposes depends on mechanical properties under bending (stiffness and strength) and density. Stiffness measures the deflection of a beam under a given load and strength measures the resistance to

Figure 4. Mature western red cedar, Avondale Estate, Ireland. (Photo: Scott McG Wilson)

material failure. For use in construction, timber is graded in strength classes, and must attain required characteristic values of strength, density and stiffness. A common concern with British timber is that stiffness generally limits the grading to C16 (CEN, 2016b), a commonly specified strength class in the United Kingdom for construction. For C16 the required mean stiffness (MoE) of the graded timber must be at least 7.6 kN/mm^2.

The material studied in this research appears less desirable for structural applications than either home-grown Sitka spruce or Douglas fir, even when grown over a longer rotation length. Results indicate that stiffness is once again the property that limits the grading of western red cedar, with strength and density achieving values proper to higher grades. The material from the south and central growing sites achieves characteristic values of C16 for 100% grading yield, limited by the stiffness (the higher strength class, C18,

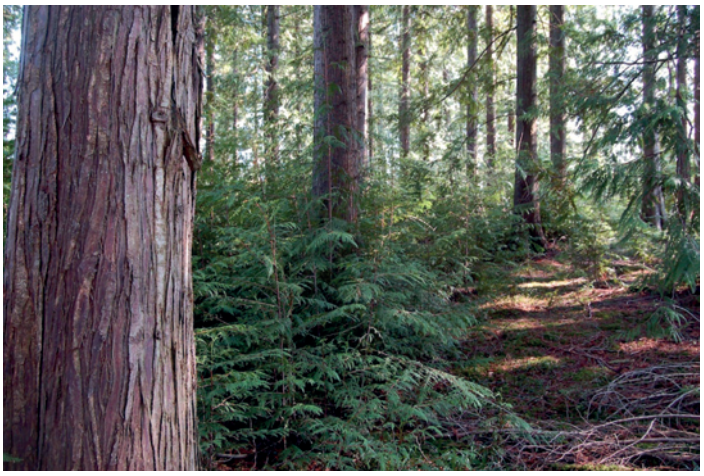

Figure 5. Western red cedar seed stand (p1914), Darnaway Estate, Moray. (Photo: Scott McG Wilson)

requires a mean stiffness of 8.55 kN/mm^2). However, the stand in the north, even though it is the oldest, only attains characteristic values of stiffness suitable for the C14 strength class for 100% yield (required mean stiffness of 6.65 kN/mm^2). The overall analysis of all the material up to 45 years old, would also grade as C14, although C16 could be graded with a lower yield.

While these results must be treated with caution due to the relatively small number of specimens tested, they suggest that when grown in Britain, these three species should essentially be seen as producing 'special purpose timbers'. These will primarily be used for exterior decorative carpentry, cladding and shingle roofing applications that exploit their visual appeal and natural durability (Morgan, 2008). They should therefore not be seen as substitute or competitor products for spruce, pine or Douglas fir. They should be processed in mills equipped to deal with their specific timber properties and bark characteristics. Another important consideration is that care is needed when kiln drying western red cedar to avoid the phenomenon of collapse. In Britain the limited amount of material available, mainly of western red cedar, tends to be sawn by mobile, estate or specialist small industrial processors for applications such as decking, cladding, glasshouse framing, shed and beehive manufacture (see Figure 3a-c). Financial values obtainable for larger logs (exceeding 30cm dbh) can be quite attractive. The colour and chemistry of these timbers makes them less suitable for industrial particle board and pulp manufacturing, although red cedar is a major supplier of feedstock for chemical pulping in North America (there is currently no such mill in the UK).

Figure 6a. Coast redwood, Longleat Estate, Wilts. (Photo: Scott McG Wilson)

Figure 6b. Premium coast redwood logs, Longleat Estate, Wilts. (Photo: Scott McG Wilson)

Place in British forestry

Western red cedar has been deployed fairly widely as a 'minor conifer' species in British and Irish forestry, since its introduction in the 1850s (Bothwell, 1988). There are no published figures for the overall stocked area, but this might amount to some 1,000-2,000ha overall. It is most commonly found within private estate and Forestry Commission woodlands in southwest England, Wales, the Marches and, to a much lesser extent, in Argyll. There is a notable stand at Avondale in Co. Wicklow, Ireland (Carey, 2004) (see Figure 4). There are more occasional deployments in eastern Britain, as at Darnaway (see Figure 5), Kyloe, Fulmodeston and Weasenham. The majority of these stands date from before the 1960s, with a reduced level of deployment since, until a recent noticeable revival since 2010 (e.g. to replace larch in Wales). There are some very fine pure, pre-WWII stands, for example at Gwydyr Forest in Snowdonia. A considerable proportion of the stocking is in mixed stands, most often with Douglas fir, western hemlock and oak (with which red cedar was quite often used as a nurse). A number of private forestry estates have, over time, developed a significant record of growing, processing and marketing western red cedar, particularly in southwest England and the Welsh Marches.

Coast redwood was previously deployed on a much smaller scale, both by the Forestry Commission and private estates, often for silvicultural demonstration and landscape amenity purposes (Gale, 1962; Morgan, 2008). Again most examples date from the period 1840 to 1960, with many fewer younger stands in existence. Particularly fine stands of mature coast redwood can be found in private estate woodlands at Longleat (Wiltshire) (see Figure 6a&b),

Figure 7. Coast redwood (p1935), Crarae Forest Garden, Argyll. (Photo: Scott McG Wilson)

Figure 8. Giant redwood avenue, Younger Botanic Garden (Benmore), Cowal. (Photo: Scott McG Wilson)

Figure 9. Giant redwood plot (p1935), Crarae Forest Garden, Argyll. (Photo: Scott McG Wilson)

Dartington (Devon), Leighton (Powys), Huntley (Gloucestershire) and Kyloe (Northumberland) and in the National Trust for Scotland's Crarae Forest Garden (Argyll) (see Figure 7). Good examples in Forestry Commission woodlands include those in the Forest of Dean, Brechfa Forest Garden (Wales) (Danby and Mason, 1998) and Kilmun Forest Garden (Cowal, Argyll) (Mason et al., 1999). Research and operational studies in New Zealand (e.g. Jones et al., 2014; Meason, 2014) underline the high productivities that can be obtained with selected strains of coast redwood if good establishment silviculture is combined with correct site selection.

Most deployment of giant redwood in Britain has been as widespread specimen individuals in arboreta (e.g. at Scone Palace and at Bolderwood, New Forest) and avenues of trees in designed landscapes (e.g. Stratfield Saye, Benmore, Murthly, House of Dun, Drumlanrig) (see Figure 8). Stands of giant redwood are uncommon, although there is an example at Kyloe (apparently a mixture of the giant and coast species) and others in Kilmun Forest Garden (Cowal, Argyll) and Crarae Forest Garden (Argyll) (see Figure 9). As a result there is limited evidence of the likely performance of giant redwood within British forests.

Western red cedar and coast redwood are species that may find a significantly increased role in British forestry under predicted climate change. The most likely scenarios for deployment will be in mixed oceanic stands, managed under continuous-cover systems, also including Sitka spruce, Douglas fir, *Abies* firs and western hemlock (Wood, 1955). Pure stands and clearfell-restock silviculture may also remain relevant under some circumstances. The most favourable locations in terms of climate and site quality will be lower slope and valley bottom sites in Ireland and western Britain – southwest England, Wales, southwest Scotland and Argyll. Here, coast redwood is likely to be the highest yielding species and should be of considerable value for carbon sequestration. However, markets for the timber of western red cedar are currently better developed within Great Britain, which may influence commercial growers. Situations where larch crops are being diversified due to *Phytophthora ramorum* threats present an opportunity to deploy coast redwood and western red cedar where site conditions are suitable. However, these species should not be considered for establishment on exposed upland sites with peaty or very infertile soils, and hence are not suitable to replace failed larch crops growing on such sites at present. There may also be a role for giant redwood and western red cedar in mixture with pine and hardwoods, on drier lowland sites in southern and eastern Britain, such as at Thetford. Western red cedar is one of the few conifer species that is tolerant of calcareous soils which is of significance where such conditions apply.

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Dr Scott McG. Wilson is an independent Chartered Forester and Chartered Surveyor based in Aberdeen, Scotland whose applied research interests include selection of optimum species and silvicultural systems to realize multiple benefits from British forests. Correspondence address: 3 Thorngrove Crescent, Aberdeen AB15 7FH.
Email: scottmcgwilson@hotmail.com

Dr Bill Mason was a silvicultural researcher at the Northern Research Station near Edinburgh for three decades before retiring in 2012. He is now a Research Fellow of Forest Research, is involved in EU COST Actions on 'Mixed Forests' and 'Non-Native Species' and is the current Chair of the Continuous Cover Forestry Group (CCFG).

Dr Richard Jinks is a project leader in the Centre for Sustainable Forestry and Climate Change, Forest Research, and is based at the Alice Holt Research Station in Surrey. He works on several research projects, including investigating potential species and provenances that might be useful for helping forests adapt to climate change.

David Gil-Moreno is a PhD research student at Centre for Wood Science and Technology, Edinburgh Napier University, 42 Colinton Road, Edinburgh EH10 5BT, Scotland and Forest Research, Northern Research Station, Roslin, Midlothian, EH25 9SY.

Dr Peter Savill, since retiring from Oxford University in 2008, has been working as a trustee of three charities: Woodland Heritage, the Future Trees Trust and the Sylva Foundation. He has also written *The Silviculture of Trees used in British Forestry* (CABI, 2013) and edited *Wytham Woods - Oxford's Ecological Laboratory* (OUP, 2010).