RESEARCH INTO ACTION

KEY POINTS FOR FORESTRY PRACTITIONERS

Forestry in Great Britain is under threat from the changing climate. In particular, the species of trees that we have used in the past for establishing and regenerating forests may no longer be suitable due to the changing conditions and new pests and diseases. Therefore, there has been an increased interest in alternative species of trees that are currently rarely utilised in British forestry.

A key question is which of the species being considered for future planting can produce construction-grade timber for use alongside Sitka spruce, Scots pine and larch. We tested the wood properties of eight species from a limited number of sites across Scotland and England. These were European silver fir, grand fir, Caucasian fir, Pacific silver fir, Japanese red cedar, Serbian spruce, sycamore and silver birch. The tests were conducted on small clear samples and complement earlier studies on structural-size timber cut from trees at the same sites.

All the species except for Japanese red cedar had wood properties that suggest they would be suitable for construction-grade timber. Japanese red cedar had lower wood density, wood stiffness and wood strength than all the other species. Sycamore and silver birch had the best properties. Of the conifers, European silver fir, Caucasian fir and Serbian spruce had the best density, wood stiffness and wood strength.

These measurements on the wood properties of alternative species and other recent work on their establishment is a starting point for directing decisions on the choice of tree species to plant in the future. It also helps make decisions on future research investment in tree breeding, silviculture and methods for timber grading.

Physical and mechanical properties of wood from species with potential for wider planting in Great Britain

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Abstract

This paper reports on the physical and mechanical properties of small wood samples of eight species with potential for larger-scale planting in Great Britain. Six of these have been prioritised for future commercial production in Scotland and five have been prioritised in England. Measurements include wood density, Modulus of Rupture (MOR) and Modulus of Elasticity (MOE). The results are in line with recent studies on larger structural-sized timber samples from the same stands. Together they suggest the potential for a number of the species to be able to produce structural timber for the UK market, but identify at least one species that appears to be unsuitable based on these limited tests. We also report variations in wood properties with radial position within the tree, the difference in properties for two species planted on two sites widely separated by latitude, and we compare the results with previous measurements made in the UK and elsewhere. Though limited in scope, these measurements help in the development of our understanding of the wood properties of a range of tree species of interest for helping to increase the resilience of British forests and future wood supply in a changing climate.

Introduction

The changing climate is having an impact on tree health and growth in the forests of Great Britain and on the ecosystem services they can provide (Broadmeadow & Ray, 2005; Cannell et al., 1989; Ray et al., 2015; Yu et al., 2021). In particular, a number of species have recently been very badly affected by pests and diseases and are often no longer viable as commercial timber species in the UK. Examples include larch (*Larix spp.*) (Dun et al., 2022; Webber, 2022), ash (*Fraxinus excelsior* (L.)) (Combes et al., 2024; Mitchell et al., 2014) and Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) (Mullett et al., 2017).

A concern for timber production in the United Kingdom is that there is a heavy reliance on a small number of species (Gil-Moreno et al., 2016; Price et al., 2024). Amongst conifers these include Sitka spruce (*Picea sitchensis* (Bong.) Carr.) (54% by area, 55% by growing stock), Scots pine (*Pinus sylvestris* (L.)) (17% by area, 15% by growing stock), and larch (8% by area, 9% by growing stock), accounting in total for almost 80% of the conifer forest area and growing stock in Great Britain (Forest Research, 2025). Spruces (Sitka spruce and Norway spruce (*Picea abies* (L.) Karst)) represent 62% of the current forecast of softwood timber volume available, and this proportion is predicted to rise to 72% by 2040 (Forest Research, 2022). As a result of the spread of *Phytophthora ramorum*, the planting of larch has almost completely stopped and there is a major concern about future timber supplies if spruce or pine were to be similarly affected.

There are a number of alternative species that can be grown in the UK which could potentially provide structural-grade timber (Adams & Ridley-Ellis, 2021; Gil-Moreno et al., 2016). However, there is not always a lot of information on the growth and management of these trees in the UK (Mason et al., 2018; Malcolm, 1977; McG. Wilson et al., 2016; Meason & Mason, 2013).

To decide whether the species being considered are possible alternatives to those currently being used for timber in the UK (e.g. Willoughby et al., 2025), it is necessary to

determine the mechanical properties of their wood and their utilisation potential (Ridley-Ellis et al., 2016). To date, information on the wood mechanical properties of many potential species has been obtained from a very small sample, and often in only one part of the UK. Lavers (2002) presented important information on a wide variety of species growing both in and outside the UK, but often the number of samples is small. Gil-Moreno et al. (2016) and Gil-Moreno et al. (2023) present results for noble fir (*Abies procera* Rehder), Norway spruce, western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western red cedar (*Thuja plicata* Donn ex D. Don.) growing in the UK, based on the doctoral work of Gil-Moreno (2018).

In this paper we present wood physical and mechanical properties of European silver fir (*Abies alba* Mill.), grand fir (*Abies grandis* (Douglas ex D.Don) Lindl.), Caucasian fir (*Abies nordmanniana* (Steven) Spach; sometimes known as Nordmann fir), Pacific silver fir (*Abies amabilis* Douglas ex J.Forbes), Serbian spruce (*Picea omorika* (Pančić) Purk.), Japanese red cedar/ Sugi (*Cryptomeria japonica* (Thunb. ex L.f.) D.Don), sycamore (*Acer pseudoplatanus* L.) and silver birch (*Betula pendula* Roth). The sample material for this study was obtained from trees from which structural battens were destructively tested for strength class estimation, as reported in Price et al. (2024), and the measurements reported here are a complement to that study. We report the results from three-point bending tests on small defect-free samples that were undertaken to measure Modulus of Elasticity (kN mm^{-2}; MOE), Modulus of Rupture (N mm^{-2}; MOR) and wood density (kg m^{-3}; ρ). We compare our results with other measurements made on small clearwood samples in the UK and elsewhere.

In addition, we report variations in wood properties for species between sites when we have data from more than one site, and we model the radial variation in MOE, MOR and wood density for all species as a direct comparison with the work of Gil-Moreno et al. (2023). Finally, we report on the correlation between the MOE values obtained from the bending tests and values obtained from measurements of acoustic velocity on the standing trees as a method for non-destructive estimation of MOE.

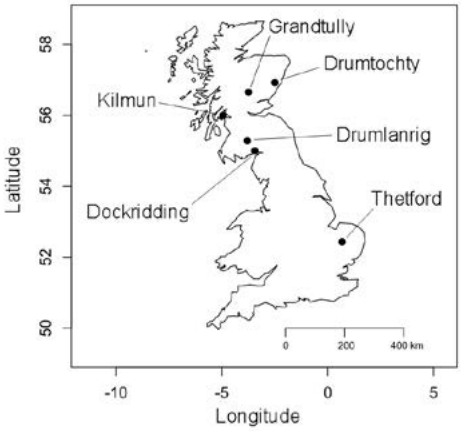


Figure 1: Map showing locations of study sites.

Materials and methods

Study sites

For each species included in this study, a sample stand was sought of at least 0.1ha, with a minimum age of 30 years, demonstrating good vigour and stem form and with reasonable access for collection of timber samples. The sample sites selected comprised a mixture of formal experimental trials, demonstration plots and regular forest stands (Table 1, Figure 1). Assessments and sampling took place between 2014 and 2016.

Material from two different provenances of European silver fir and a single provenance of grand fir were sourced from a provenance demonstration site planted in 1965 at Drumtochty Forest. Additional sample material for both species was obtained from a provenance trial planted in 1966 at Thetford Forest, which included three further provenances of European silver fir, in addition to those planted at Drumtochty, together with the same single provenance of grand fir. The Thetford trial also included a single provenance of Caucasian fir, which was included in this study. Further details of both trials and the measurements of survival, growth and stem form were reported by Kerr et al. (2015).

Kilmun Forest Garden in Argyll (Mason et al., 2018) provided Pacific silver fir and Japanese red cedar sample material. The Pacific silver fir was planted in 1958 in a plot of approximately 0.3ha and was unthinned (Plot number 267). The Japanese red cedar was planted in 1954 in a plot that was also approximately 0.3ha in area, and at the time of assessment had a variable stocking density and a wide diameter distribution.

A Serbian spruce stand growing close to the Solway Firth was provided by James Jones & Sons Ltd. Tree age was estimated from growth ring counts as 50 years. The stand had been thinned and demonstrated good growth and stem form.

A stand of managed sycamore, approximately 50 years old and growing at Drumlanrig Castle, was made available by Buccleuch Estates. Silver birch was sourced from a stand growing at Grandtully in Perthshire; tree age was estimated as 40 years from discs cut between 2.0 and 2.8m.

Stand measurements and selection of sample trees

As a result of the diversity of sample stand characteristics, it was not possible to use identical measurement and sampling procedures at each site. In the replicated experimental trials, all live trees in the treatment plots were measured. In forest stands and the demonstration plots in Kilmun Forest Garden, circular sample plots were used to assess stand attributes. The number of trees measured at each site is shown in Table 2.

Diameter at breast height (dbh; cm) and total tree height (m) were measured in accordance with standard mensuration procedures. Estimates of stand stocking density, mean dbh, top height, mean tree volume, stand volume and stand General Yield Class were derived from these measurements (Matthews & Mackie, 2006; Matthews et al., 2016) and are presented in Table 4 of Price et al. (2024).

Acoustic velocity (AV, m s^{-1}) was measured at breast height on the south side of the stem of each tree, using the Treesonic instrument (Fakopp KFT, Fenyo, Hungary), following the manufacturer's instructions and standard procedures (e.g. Mochan et al., 2009).

Sample trees for testing of wood properties were selected randomly from each of the three upper quartiles of the diameter distribution at each site and felled, with the number of trees varying between sites according to availability and practical considerations (Table 2).

One 3.1m sawlog was cut from each sample tree, the base of the log being just above 1.3m above ground level. These logs were later converted to structural-sized battens for mechanical testing, as reported by Price et al. (2024). Two short logs (1.3m) for the preparation of the clearwood test samples used in this study were cut, one above the 3.1m log and one at the base of the live crown.

Sample preparation and testing

A full-diameter board of 25–30mm thickness, oriented in the north–south axis and centred on the pith, was sawn longitudinally from each 1.3m log.

Growth rings, counted radially from the pith, were identified and marked on the ends of logs and traced along the boards. Defect-free test specimens, with dimensions of 300 x 20 x 20mm in the longitudinal, radial and tangential directions respectively, were then cut from the boards.

Before testing, samples were conditioned to constant mass using a TAS Environmental Chamber (TAS Ltd, Worthing, UK) at 65% relative humidity and 20°C, resulting in a nominal sample moisture content (MC) of 12%. Samples were weighed using a Sartorius laboratory balance (Sartorius UK Ltd, Epsom, UK) and dimensions measured using a steel rule for length and Mitutoyo digital callipers (Mitutoyo (UK) Ltd, Andover, UK) for depth and width. Sample wood density was calculated by dividing sample mass by volume. The cambial age of the youngest and oldest growth rings (previously marked) was recorded for each sample and a mean sample cambial age determined.

Samples were tested using a Tinius Olsen H5K-S benchtop three-point bending machine (Tinius Olsen Ltd, Redhill, UK), with a span of 280mm. MOR and MOE were calculated by Tinius Olsen QMAT operating software, using the maximum tested load and the linear load-displacement response region of the data respectively.

Samples were weighed again immediately after testing and then again after drying at 102°C to constant weight, in order to calculate the actual MC at the time of testing. Subsequently all MOE, MOR and wood density values were corrected to 12% MC using the formulations given in EN384 (CEN, 2018).

The dynamic MOE of each sample tree was estimated from acoustic velocity (AV) measurements by multiplying the square of AV by the measured wood density of the clearwood sample closest to the outside of the tree. The measured density at 12% was first converted to the density at the Fibre Saturation Point (FSP) (nominal 30% MC) using EN384 (CEN, 2018) and then the dynamic MOE was converted from the green wood value (30% MC) to the value at 12% MC (Unterwieser & Schickhofer, 2011).

Model fitting

The form of the model equations used for predicting MOE, MOR and wood density (ρ) were the same as those used in Gil-Moreno et al. (2023) and are given in Equations 1 to 3. Unlike Gil-Moreno et al. (2023), each species was modelled separately because there was only one site for most species, and therefore it was not possible to investigate the interaction between species and the fixed parameters. There is also no plot interaction in the models because all samples were taken from trees in single plots.

$$MOE_{jlm}=\alpha_1 . e^{\alpha_2 . Age_{jlm}}+\alpha_3+\beta_{1,j}+\beta_{3,jl}+\varepsilon_{jlm} \quad (1)$$

where MOE_{jlm} is the MOE of the clearwood specimen m from the lth tree from the jth site, the Age is the cambial age of the specimen, α_1 is the difference between the maximum value and the baseline, α_2 is the rate of change, and α_3 is the asymptotic value; $\beta_{1,j}$ and $\beta_{3,jl}$ are the random effects of site (if more than one site) and tree, respectively, and ϵ_{jlm} is the residual variance.

$$MOR_{jlm}=\alpha_4 . Age_{jlm}+\alpha_5+\beta_{4,j}+\beta_{6,jl}+\varepsilon_{jlm} \quad (2)$$

where MOR_{jlm} is the MOR of the clearwood specimen m from the lth tree from the jth site, α_4 is the slope and α_5 is the intercept; $\beta_{4,j}$ and $\beta_{6,jl}$ are the random effects of site and tree, respectively, and ϵ_{jlm} is the residual variance.

$$\rho_{jlm}=\alpha_6 \times e^{\alpha_7 . Age_{jlm}+\frac{(\alpha_8+\beta_{7,j}+\beta_{9,jl}) . Age_{jlm}}{\alpha_9+Age_{jlm}}}+\varepsilon_{jlm} \quad (3)$$

where ρ_{jlm} is the wood density (ρ) at 12% MC of the clearwood specimen m from the lth tree at the jth site, α_6 is the initial value of wood density as cambial age approaches zero, α_7 is the rate parameter of the initial decrease in density from the pith, α_8 is the asymptotic value of the density as the outerwood is approached, and α_9 is the rate of increase between the minimum value and the asymptote. $\beta_{7,j}$, and $\beta_{9,jl}$ are the random effects of site and tree, respectively, and ϵ_{jlm} is the residual variance.

Statistical analyses

Data summaries, Pearson correlation analyses, and pairwise t-tests were all performed using 'R' software, version 4.4.2 (R Core Team, 2024). Model fitting was carried out using the *nlme* library (version 3.1–163, Pinheiro et al., 2020).

Results

Table 2 provides a summary of the area-averaged values of density (kg m^{-3}), stiffness (MOE) (kN mm^{-2}) and strength (MOR) (N mm^{-2}) for the eight species, taking all the samples together and averaging based on the radial position of each clearwood sample. For comparison, values of these properties for the same species from the literature are provided in Table 4.

European silver fir, Caucasian fir and Serbian spruce are not significantly different from each other in terms of area-averaged density. This is also true for the area-averaged density of grand fir, Pacific silver fir and Japanese red cedar. Otherwise, the differences are all significant. Silver birch and sycamore have densities significantly different from all other species tested. Silver birch has the highest area-averaged density, and Japanese cedar has the lowest value.

The pattern is similar but more complicated for the area-averaged MOE values. European silver fir, Caucasian fir, Pacific silver fir and sycamore; European silver fir, Caucasian fir, Pacific silver fir and Serbian spruce; grand fir, Pacific silver fir and Serbian spruce; and silver birch and sycamore; are not significantly different from each other respectively. Japanese red cedar has an MOE significantly different from all other species. Silver birch has the highest value of MOE (stiffest wood) and Japanese red cedar has the lowest value of MOE (least stiff wood).

The pattern is similar for MOR (wood strength) with European silver fir, Caucasian fir and Serbian spruce; grand fir, Pacific silver fir, and Japanese red cedar; grand fir, Pacific silver fir and Serbian spruce; and silver birch and sycamore; not significantly different from each other respectively. Silver birch has the highest value of area-averaged strength, although not significantly different from sycamore, and Japanese red cedar has the lowest strength.

The ranking of density, stiffness and strength are very similar with Japanese red cedar, grand fir and Pacific silver fir occupying the lowest three places and sycamore and silver birch occupying the highest two places. European silver fir, Caucasian fir and Serbian spruce occupy the middle ranks with some variation in position according to density, MOE or MOR. Overall, this shows the strong relationship and correlation between wood density and wood stiffness and strength. Of all the conifers tested, European silver fir and Caucasian fir have the best mechanical properties and Serbian spruce has the highest wood density, although none of the property differences were significant between the three species.

For European silver fir and grand fir, we compared the wood density and mechanical properties for the two species between trees of the same provenances grown at both Drumtochty

Table 1: Sites used in this study. A * against planting year indicates that the age is estimated. Accumulated temperature and DAMS windiness were obtained from the Forest Research Ecological Site Classification (ESC) online Decision Support Tool (www.forestdss.org.uk/geoforestdss/).

Study site Type of stand	Species	Stand planting year (age at sampling)	National Grid Reference (NGR)	Coordinates (Lat, Lon)	Elevation (m asl)	Accumulated temperature (day-degrees >5.0°C annum^{-1})	DAMS windiness score	Soil type
Drumtochty Forest, Aberdeenshire Experimental trial	European silver fir	1965 (50)	NO700810	56° 55'N 2° 29.5'W	350	982	14	Podzol
	Grand fir							
Grandtully Wood, Perthshire Forest stand	Silver birch	1974* (40)	NN931523	56° 39'N 3° 44.5'W	130	1102	8	Brown earth
Kilmun Forest Garden, Argyll Demonstration plots	Pacific silver fir	1958 (56)	NS161827	56° 00'N 4° 57'W	110	1351	12	Upland brown earth, podzolised
	Japanese red cedar	1954 (60)	NS164823	56^{0} 00'N 4° 57'W	30	1387	11	
Drumlanrig Castle, Dumfries & Galloway Forest stand	Sycamore	1965* (50)	NS859000	55° 17'N 3° 48'W	90	1437	10	Brown earth
Dockridding Wood, Dumfries & Galloway Forest stand	Serbian spruce	1964* (50)	NY073680	55° 00'N 3° 27'W	10	1565	14	Flushed basin bog (juncus)
Thetford Forest, Suffolk Experimental trial	European silver fir	1966 (50)	TL823851	52° 26'N 0° 41.5'E	40	1764	12	Podzolic brown earth
	Grand fir							
	Caucasian fir							

Table 2: Summary statistics for cambial age, MOE, MOR and wood density determined on clearwood samples and area-averaged values based on radial position. If the superscript letter next to a value (MOE, MOR or density) is the same for two species then there is no statistically significant difference between the measurements for the two species, and if the letters are different then there is a significant difference at the p = 0.05 level. Values in brackets are standard deviation (s.d.).

Species	No. of trees measured for DBH, height and AV	No. of sample trees	No. of samples	Mean sample age (years)	Area-averaged MOE (kN mm^{-2})	Area-averaged MOR (N mm^{-2})	Area-averaged density (kg m^{-3})
European silver fir	202	57	722	11.97 (7.49)	8.44 (1.30)$^{a, b}$	75.72 (12.76)^{a}	424.60 (39.94)^{a}
Grand fir	89	18	363	11.46 (7.70)	6.89 (1.17)^{c}	60.22 (10.01)$^{b, c}$	375.54 (31.79)^{b}
Caucasian fir	21	9	95	11.07 (6.91)	9.03 (1.65)$^{a, b}$	80.34 (17.38)^{a}	437.60 (48.98)^{a}
Pacific silver fir	56	11	207	15.50 (10.31)	7.41 (1.34)$^{b, c}$	60.88 (11.18)$^{b, c}$	376.61 (35.59)^{b}
Japanese red cedar	50	12	199	17.5 (12.86)	4.57 (1.23)^{d}	51.38 (11.94)^{b}	344.47 (44.38)^{b}
Serbian spruce	52	12	225	15.18 (9.39)	7.83 (0.98)$^{b, c}$	72.83 (8.74)$^{a, c}$	458.82 (30.60)^{a}
Sycamore	71	12	249	18.60 (10.97)	9.56 (0.60)$^{a, e}$	99.81 (7.95)^{d}	565.85 (32.76)^{c}
Silver birch	101	13	180	14.24 (8.97)	11.01 (1.12)^{e}	101.03 (10.58)^{d}	617.96 (32.47)^{d}

and at Thetford. All properties are significantly different at the p<0.001 level except for the density of grand fir, which is only significant at the p<0.05 level (Table 3). In all cases, the mechanical properties are superior for the trees grown at Thetford.

In comparison to other studies on the same species growing in the UK (Table 4), as reported in Lavers (2002), the values are similar, though with some interesting exceptions. For example, the European silver fir in this study has an MOE quite a bit lower than in Lavers; the Serbian spruce in this study has a higher density than Lavers; and the silver birch measured by Lavers has slightly higher values of all properties. For species with properties not measured previously in the UK, and in comparison with measurements

Table 3: Site mean values of measured wood properties for grand fir and European silver fir. All values adjusted to 12% moisture content. Values in brackets are standard deviation (s.d.) and n is the number of samples.

Species	Site	Mean MOE (kN mm^{-2})	Mean MOR (N mm^{-2})	Density (kg m^{-3})
Grand fir	Drumtochty n = 274	6.38*** (1.85)	56.7*** (12.4)	370.4* (42.0)
	Thetford n = 89	7.62*** (2.22)	65.4*** (19.3)	385.9* (53.5)
European silver fir	Drumtochty n = 236	7.07*** (1.42)	63.3*** (10.0)	403.7*** (30.1)
	Thetford n = 164	9.04*** (2.49)	83.4*** (18.5)	455.4*** (54.0)

Comparisons of property mean values between sites within a species: p value: *** < 0.001, ** <0.01, * <0.05.

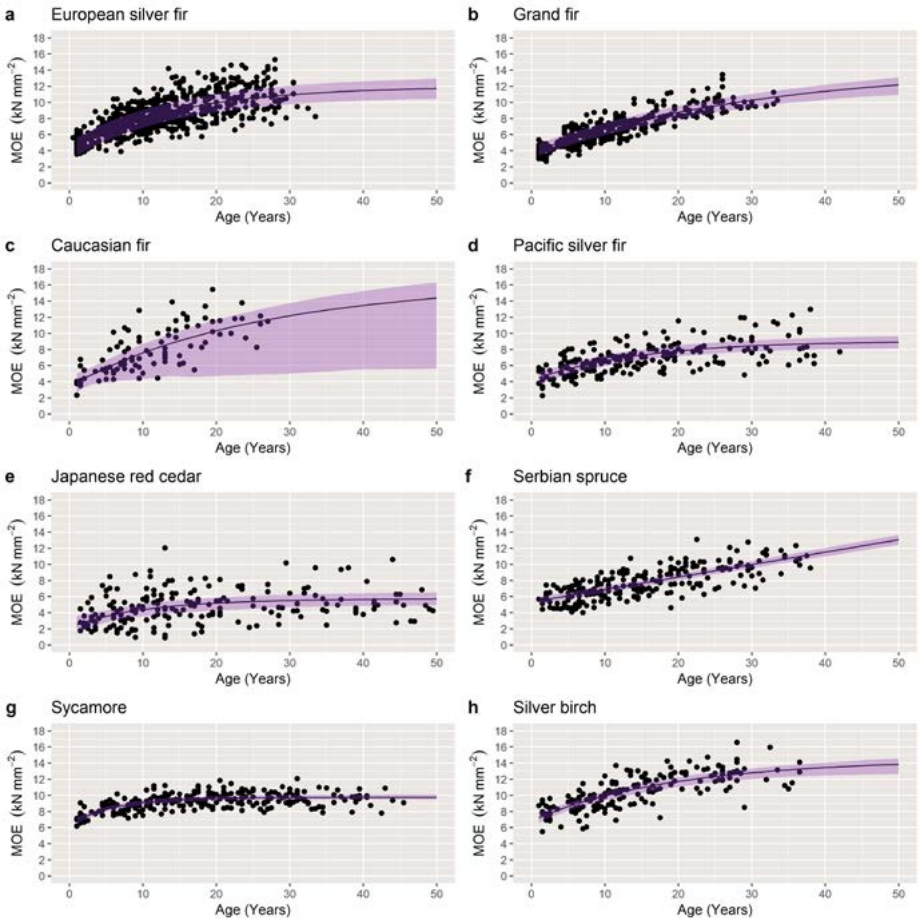
Table 4: Values for clearwood samples for stiffness (MOE), strength (MOR) and wood density from the literature. Values in brackets are standard deviation (s.d.).

Species	No. of samples density/MOE/MOR	Literature source	Sample origin and type	MOE (kN mm^{-2})	MOR (N mm^{-2})	Density (kg m^{-3})
European silver fir	381/61/61	Lavers (2002)	UK: Clearwood samples cut from 15 trees	9.8 (1.3)	79.0 (10.0)	449 (52.8)
	169/149/149	Lavers (2002)	Yugoslavia: Clearwood samples cut from 28 joists	8.8 (1.5)	77.0 (12.7)	433 (44.4)
Grand fir	435/226/226	Lavers (2002)	UK: Clearwood samples cut from 20 joists and 11 trees	7.00 (1.2)	57.0 (10.3)	352 (47.3)
Caucasian fir	NA	Özkan et al. (2017)	Turkey: Sample types and numbers not specified	7.38 (0.68)	60.1 (4.4)	NA
	7/7/10	Vurdu et al. (2013)	Turkey: Clearwood samples (just 7 for density and MOE; 10 for MOR)	7.22 (0.75)	64.6 (5.7)	438 (27)
Pacific silver fir	186	Forest Products Laboratory (2021)	USA: Clearwood samples	12.1 (2.7)	75.8 (12.1)	498.5 (49.8)
Japanese cedar	187	Zhu et al (2005)	Japan: Clearwood samples (from 78-year-old trees) at 1.2 m	8.43 (1.43)	66.0 (7.9)	371.0 (30.4)
		Takahashi et al (2021)	Japan: Clearwood samples (from 20-year-old trees)	3.28 (0.68)	54.1 (8.7)	391.0 (41.0)
Serbian spruce	52/6/6	Lavers (2002)	UK: Clearwood samples cut from 5 trees	7.60 (1.34)	72.0 (7.5)	400 (26.7)
Sycamore	455/61/61	Lavers (2002)	UK: Clearwood samples cut from 16 trees	9.4 (1.16)	99.0 (11.0)	561 (30.8)
Silver birch	76/5/5	Lavers (2002) 'European' birch	UK: Clearwood samples cut from 8 trees	13.3 (0.8)	123.0 (7.6)	673 (41.5)

Table 5: Pearson's correlation values (r) between different wood properties for each species.

	European silver fir	Grand fir	Caucasian fir	Pacific silver fir	Japanese red cedar	Serbian spruce	Sycamore	Silver birch
Density-MOE	0.623***	0.652***	0.653***	0.369***	0.366***	0.192**	0.129*	0.732***
Density-MOR	0.783***	0.788***	0.828***	0.748***	0.778***	0.543***	0.570***	0.794***
MOE-MOR	0.901***	0.897***	0.887***	0.786***	0.802***	0.887***	0.683***	0.855***

p value: *** < 0.001, ** < 0.01, * < 0.05.



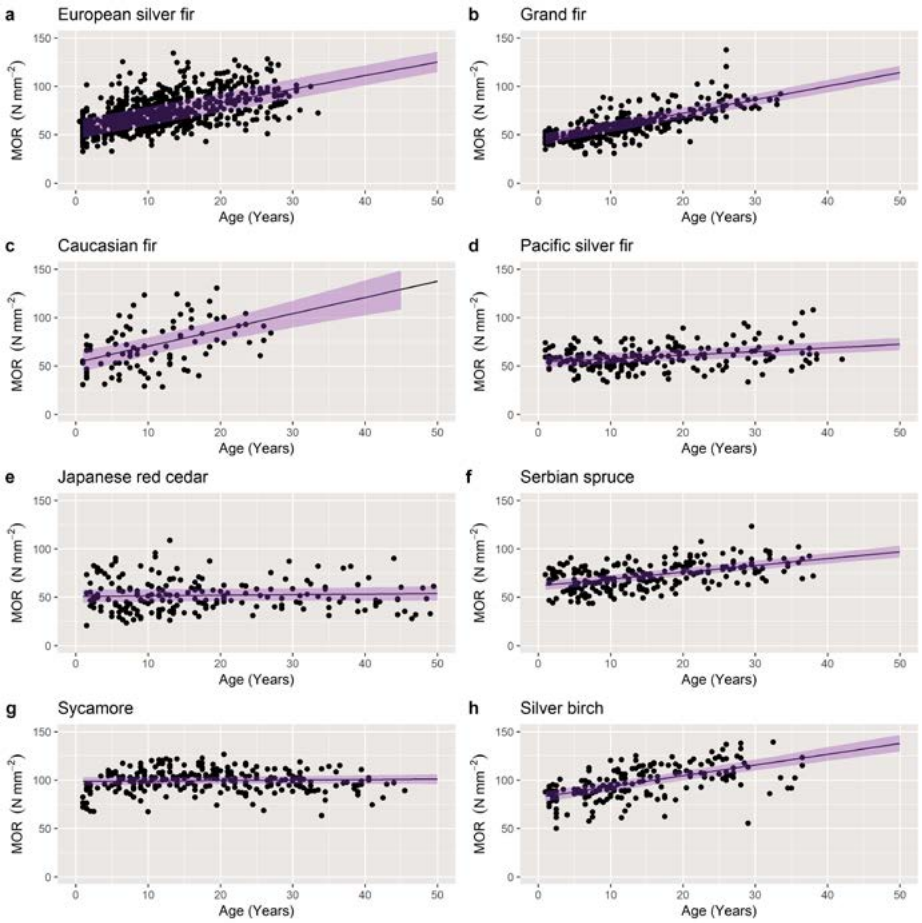


Figure 2, upper left: Measured (points) and modelled (grey line) radial variation of MOE. Model confidence limits at the 95% level are shown by the purple area.

Figure 3, lower left: Measured (points) and modelled (grey line) radial variation of MOR. Model confidence limits at the 95% level are shown by the purple area.

Figure 4, opposite page: Measured (points) and modelled (grey line) radial variation of wood density. Model confidence limits at the 95% level are shown by the purple area.

elsewhere in the world, the UK-grown Japanese red cedar has lower values of all properties when compared to 78-year-old trees measured in Japan, but similar values to those obtained from 20-year-old trees. The Caucasian fir grown in the UK has similar densities to Turkish-grown Caucasian fir but superior values of MOE and MOR. Finally, the UK-grown Pacific silver fir has uniformly inferior properties compared to the same species grown in the USA.

The correlation coefficients for all species between different wood properties are shown in Table 5. Almost all the correlations have p values <0.001, except for the correlation between wood density and MOE for sycamore (p<0.05) and for Serbian spruce (p<0.01).

The experimental data and the model fits for MOE, MOR and wood density are shown in Figure 2, Figure 3 and Figure 4 respectively. The parameters from the mixed models for MOE, MOR and wood density (Equations 1, 2 and 3) are given in Appendix A.

For all species except Serbian spruce, the trend in MOE with cambial age is very similar, with an increase in MOE that levels off towards the outer parts of the tree (Figure 2). For Serbian spruce, over the range of cambial ages measured, there is a linear relationship with no sign of a final value being reached.

There is a linear increase in MOR with age for all species except Japanese red cedar and sycamore (Figure 3), for which there is no obvious change in MOR value from pith to bark.

The change in wood density with cambial age is similar for grand fir, Pacific silver fir and Serbian spruce, with an initial decrease away from the pith and then a gradual increase within the mature wood (Figure 4). Japanese red cedar has a similar initial decline in density, but then no subsequent change in density. European silver fir, Caucasian fir and silver birch have similar patterns, with a linear increase

in density with age, whereas sycamore shows no change in density with age.

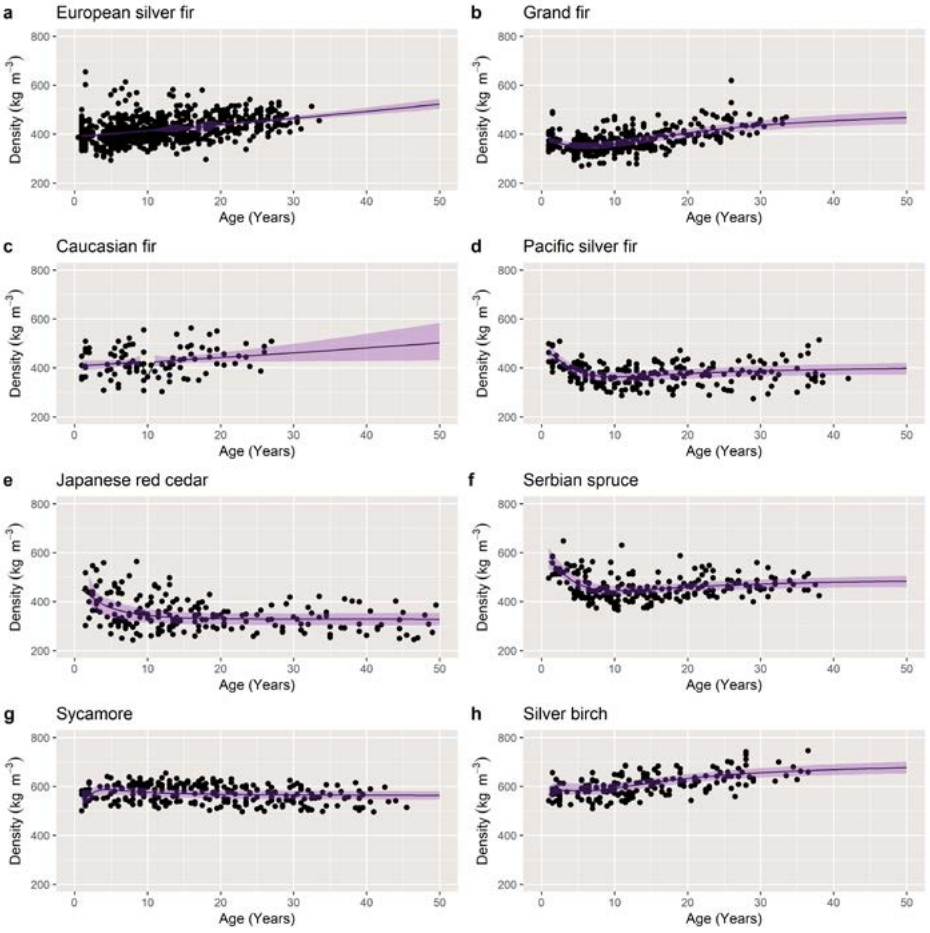
In Figure 5, the correlation between the measured MOE on the clearwood samples closest to the bark and an estimated MOE from the acoustic tool measurements on the trees is illustrated together for all species except Pacific silver fir (no data from standing trees). A regression line forced through zero is plotted, together with the uncertainty in the fit. The correlation was highly significant (p<0.001) and the adjusted R^2 value was 0.9646.

Discussion

In this paper we present information on the important physical and mechanical properties of the wood of eight timber species grown in Great Britain that have the potential to be planted and utilised more widely. The paper is a complement to the publication of Price et al. (2024), which investigated the mechanical properties of structural-sized battens from the same trees. It is also relevant to the recent publication by Willoughby et al. (2025), which looked at establishment of 17 species, including five of those in this study (grand fir, Pacific silver fir, European silver fir, Serbian spruce and Japanese red cedar) and the recommendations on future commercial species in Scotland (Edwards et al., 2024; Sellars & Edwards, 2025) and in England (Forestry England, 2026).

European silver fir and grand fir were the only species with data obtained from two locations, and the mechanical properties from the more southerly and warmer site (Thetford) were superior to the properties from the more northerly and cooler site (Drumtochty). This pattern has been observed in a number of studies both in the UK (Moore et al., 2009; Gil-Moreno et al., 2023) and in other countries (Watt et al., 2006). Watt et al. (2006) suggest that warmer autumn temperatures lead to greater latewood formation, with higher values of density, MOE and MOR.

Our area-averaged values of MOE, MOR and wood density are broadly consistent with the values obtained by Lavers (2002) for those species for which there are data from these trees growing in Great Britain (grand fir, European silver fir, Serbian spruce, silver birch, Pacific silver fir and sycamore). For species for which there are no previous published measurements from trees growing in Britain, comparison with measurements made in their countries of origin gives varying results. The Caucasian fir from the UK had similar density but superior values of MOE and MOR compared to the same species grown in Turkey. However, the properties of Japanese red cedar and Pacific silver fir were uniformly inferior to the values obtained from the same species grown in Japan and the western United States respectively.



The results suggest that most of the species have a similar pattern of radial variation of MOE to the previous study by Gil-Moreno et al. (2023), with a negative exponential increase with cambial age. The exception was Serbian spruce, which has a linear increase in MOE with cambial age, at least for the cambial ages measured in this paper.

The radial patterns obtained for MOR were also similar to those obtained by Gil-Moreno et al. (2023), with a linear increase with cambial age for all species except for Japanese red cedar and sycamore. These latter two species showed almost no change in MOR with cambial age.

The radial pattern of wood density is less straightforward. Pacific silver fir, Serbian spruce and grand fir have patterns similar to those reported by Gil-Moreno et al. (2023) and for Sitka spruce by McLean et al. (2015), with an initial decrease of density with cambial age (up to approximately eight to ten years) and then a gradual increase in the transition from juvenile wood to mature wood. These species fit the model proposed in Equation 3 best, which is Type 2 wood density variation as discussed in Schimleck et al. (2022). Japanese red cedar shows the same initial decrease but then doesn't show any change of wood density, with increasing cambial age over the ages measured here. European silver fir, Caucasian fir and silver birch show a different pattern, with no initial decrease in wood density but rather a steady increase in density with cambial age. This is similar to a Type 1 variation in wood density (Schimleck et al., 2022), but in our data we do not see a final levelling out of the wood density with increasing age, probably due to the relatively young age of the trees assessed in this study. Sycamore is completely different to all the other species and shows almost no change of wood density with cambial age.

One of the potential values of having information on the radial variation in wood properties for a species is that it might be possible to predict the internal wood properties of a species from measurements made at the outside of the tree, ideally in a non-destructive manner. The results shown in Figure 5 suggest that acoustic velocity measurements on standing trees provide a measure of the MOE of

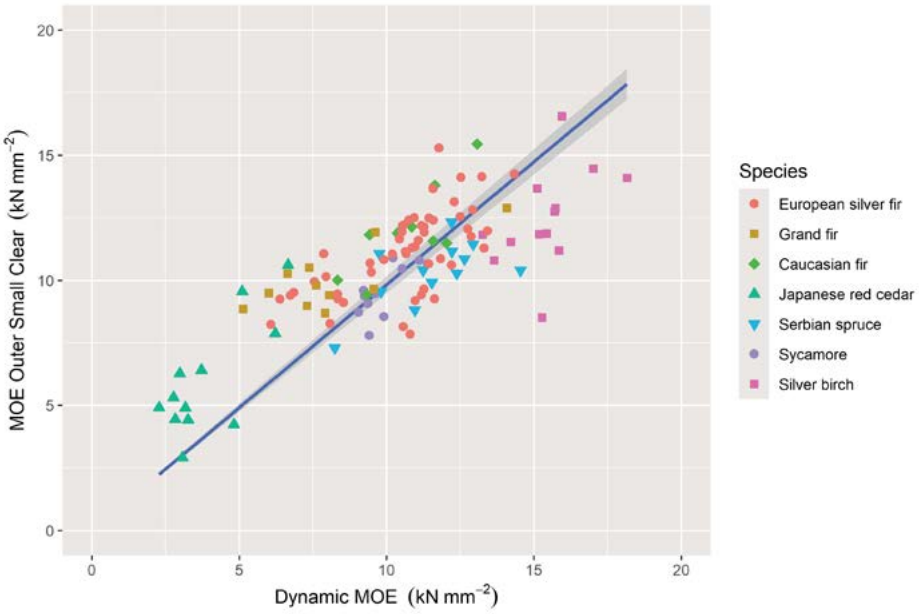


Figure 5, left: Comparison between MOE measured by three-point bending on the outside small clearwood samples and estimated from acoustic velocity (dynamic MOE) measured on the standing trees. Colours and symbols show data from different species. Blue line is fit to all data forced through zero and grey zone gives 95% confidence level.

the outer wood of trees, and – together with the model in Equation 1 and a knowledge of tree age – could be used to non-destructively predict the radial variation in MOE. Such information, when combined with models to predict batten performance and knowledge of the strong correlations between all wood mechanical properties (Table 5), could be a valuable approach for predicting the performance of the timber products likely to result from stands previously measured with acoustic tools prior to felling.

Conclusions and further work

All the species measured show potential for use as timber species in Great Britain (Ridley-Ellis et al., 2016), except for Japanese red cedar, which conforms with the assessment made in Price et al. (2024).

There were strong correlations between wood properties for all species, except for that between wood density and MOE for Serbian spruce and sycamore, and to a lesser extent for Pacific silver fir and Japanese red cedar (Table 5). Measurements of acoustic velocity on standing trees combined with the radial equations in Equations 1 to 3 and batten performance models have the potential to provide an initial assessment of the outturn of sawn timber.

The work reported in this paper was based on a limited number of trees, and for six of the species the trees came from only one site. To confirm our findings and to validate the results, further tests on a greater number of trees and from a wider range of sites is required. Initially it might be best to concentrate on those species showing both acceptable mechanical performance in this paper and in Price et al. (2024) and with good establishment and early growth (e.g. Willoughby et al., 2025). Such work would provide forest planners and forest owners with options to broaden the range of timber species grown, with the aim of developing greater resilience in UK forests to the changing climate.

Appendix A: Supplementary information

The parameters from the mixed models for MOE, MOR and wood density (Equations 1, 2 and 3) are available at bit.ly/wider-pl.

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