Properties of UK-Grown Sitka Spruce: Extent and Sources of Variation

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Summary

Structural timber produced from Sitka spruce plantations in the UK typically achieves the requirements for the C16 strength class. However, very little is known about the variability of this plantation resource, or the factors that contribute to this variability. A study to benchmark the properties of the current resource found that there was a considerable amount of variation in wood properties between sites as well as between trees within a site. This benchmarking study has been complemented by studies which have investigated the impacts of genetics, pre-commercial thinning and rotation length on timber properties. In these studies, measurements of stress wave velocity have been made on standing trees, freshly-felled logs and sawn timber. Knowledge gained should assist in better utilisation of the current resource as well as identifying management practices that will lead to an improved future resource for structural applications.

1 Introduction

Sitka spruce (*Picea sitchensis*), a species native to the west coast of North America, is the most widely planted coniferous tree in the United Kingdom, with the total area in this species being approximately 692,000 ha [8]. At present, approximately one third of the logs harvested are converted into structural timber, with the remainder being processed into fencing, pallets and packaging. However, the markets for non-structural end uses are either saturated or likely to become saturated in the future. It is therefore important that UK grown Sitka spruce gain increasing acceptance as a structural timber, as less than 30 percent of this market in the UK is currently supplied by timber from UK forests (Forestry Commission, 2007). However, there is concern about the suitability of locally-produced timber for use in timber frame construction, particularly around its stiffness, dimensional stability and knottiness.

It is known that there is considerable variation in the physical and mechanical properties of Sitka spruce timber. However, what are not well known are the sources and extent of this variation. Previous research in a range of species has indicated that factors including genetics, silviculture (i.e., initial planting spacing, timing and intensity of thinning, pruning, rotation length, fertiliser application), and site conditions (i.e., exposure, temperature, rainfall, and soil type) can affect the wood properties of a tree and thus the performance of timber produced from a tree (e.g., [7,13]). This information is important for wood processors when selecting stands for purchase, as certain combinations of site, genetics, and silviculture could yield timber with substantially poorer physical and mechanical properties leading to higher rates of strength grading rejects. Similarly, this information is of use to forest managers seeking to grow stands for timber production, as it allows them to manage for improved timber quality.

This paper presents an overview of the research being undertaken in the UK to identify the sources and extent of variation in certain physical (density, microfibril angle) and mechanical (bending strength and stiffness) properties of Sitka spruce timber. A benchmarking survey to identify the variation in wood properties from Sitka spruce stands of different structures growing on a range of different sites is described, along with studies which have focused on quantifying the effects of pre-commercial thinning, genetics and rotation length on these properties.

2 Methods and Materials

2.1 Benchmarking Survey

In this survey, 64 sites were selected on the basis of elevation, latitude, longitude, yield class (a measure of site productivity), initial planting spacing and whether or not the stand had been thinned. The survey follows a fractional factorial design with two levels of each factor. At each site, a fixed area plot was installed and the diameter of each tree measured. A random sample of ten trees per plot were selected and the dynamic modulus of elasticity of the wood was predicted using measurements made with a portable stress wave timer (IML Hammer – Instrumenta Mechanik Labor, Germany) on the standing tree. This time-of-flight tool measures the time taken for a stress wave to travel a fixed distance (normally 1 m centred around breast height) along the stem and from this the stress wave velocity (V) was calculated. The dynamic modulus of elasticity (E_{dyn}) was estimated using the following one-dimensional wave equation:

$$E_{dyn} = \rho V^2 \qquad [1]$$

where: ρ is the density of fresh (i.e., green) wood. For standing trees and freshly-felled logs, this density is assumed to be 1000 kg m^{-3} and constant within and between trees. Pith-to-bark core samples were also collected from these trees for subsequent analysis to determine density and microfibril angle.

A variance components analysis was used to determine the relative magnitudes of between site and within site variation in predicted E_{dyn}, while ANOVA was also used to determine whether E_{dyn} was related to any of the selected site and stand factors, or combinations of these factors.

2.2 Effects of genetics, thinning and rotation length

Three processing studies have also been undertaken to investigate the effects of specific factors on wood properties and timber performance. These factors were: (1) genetics; (2) pre-commercial thinning, and; (3) rotation length. A common approach was used in each of these studies. Once the sample trees were identified, their outer-wood stress wave velocity was measured using either the IML Hammer or ST-300 (Fibre-gen, New Zealand), and E_{dyn} was predicted using Eq. [1]. Trees were then felled and processed into commercial-length logs (typically 3.0 to 3.7 m in length) and 0.5-m billets. The stress wave velocity of the commercial-length logs was measured using the HM-200 resonance-based acoustic instrument (Fibre-gen, New Zealand). This tool measures the fundamental resonant frequency of oscillation (f) of a stress wave and from this the stress wave velocity is calculated from the following equation:

$$V = 2lf \qquad [2]$$

where: l is the length of the log or piece of timber. E_{dyn} was estimated from these velocity measurements using Eq. [1]. These logs were then processed into structural-dimensioned timber (nominally 100 mm by 47 mm), which was then kiln dried and conditioned at 21ºC and 65% relative humidity. Once the timber reached equilibrium moisture content, the stress wave velocity was measured using the HM-200, while the actual dimensions and mass of each piece were measured so that it wood density could be determined. E_{dyn} was calculated from both density and stress wave velocity using Eq. [1]. All timber samples were labelled so that the log, tree and treatment they originated from could be identified.

The timber was then destructively tested using four-point bending tests conducted with a Zwick Z050 universal testing machine (Zwick Roell, Ulm, Germany) according to EN408 [4] to determine static global modulus of elasticity (E_{s}) and bending strength (f_{m}). Samples were taken from each broken piece of timber and used to determine specific gravity and moisture content. E_{stat} was adjusted to a 12 percent moisture content basis according to EN384 [3]. Characteristic values for f_m and E_s were calculated according to the approach described in EN384 and the results compared with the requirements for structural timber grades as outlined in EN338 [5]. Values of E_{dyn} calculated from measurements of stress wave velocity made on standing trees, freshly felled logs and sawn boards were compared with E_{stat} obtained from the four-point bending tests. Variance components analyses were used to determine the relative magnitudes of between treatment, between tree and within tree variation in E_{stat}, f_m and basis density, while ANOVA was also used to determine whether these properties differed between the genotype and spacing treatments examined.

2.2.1 Genetics

This study compared the wood properties of four different Sitka spruce genotypes. Three of these genotypes contained the progeny of "plus trees" (i.e., trees that were identified as having superior characteristics) while the fourth contained trees grown from unimproved seed collected from the Queen Charlotte Islands off the coast of British Columbia, Canada. The experiment consisted of three replications of each genotype in a randomised complete block design and the trees were 37 years of age when felled. Twelve trees were sampled in each plot, i.e., 144 trees were sampled in total [12].

2.2.2 Pre-commercial thinning

This study compared the properties of timber from five different re-spacing treatments growing at a single site. The stand was planted in 1949 at a spacing of 1.9 m by 1.9 m [9] and was pre-commercially thinned in 1960 when the trees were approximately 4 m tall. An un-thinned treatment was retained as a control, while the approximate square spacings in the thinned plots were 2.6 m, 3.7 m, 4.6 m and 5.6 m. Each treatment was replicated five times in a Latin square design. The experiment was felled when the stand was 57 years old and three trees were sampled from each plot.

2.2.3 Rotation length

Typical rotation lengths for commercial Sitka spruce stands in the UK are between 40 and 50 years. At this age, core-wood (often referred to as juvenile wood) comprises a significant proportion of the volume of harvested log. Core-wood is normally produced when the cambium is less than 12-15 years old and generally has poorer mechanical properties than wood formed when the cambium is older [1]. It also has poorer dimensional stability, with a high propensity to twist. In this study, 30 trees from an 83-year-old stand were sampled and the properties of timber cut from consecutive radial positions within a log (i.e., representing increasing cambial age) were compared.

3 Results and discussion

3.1.1 Benchmarking study

Across the 640 individual trees assessed in the benchmarking study, predicted E_{dyn} ranged from 3.81 kN/mm^2 up to 12.29 kN/mm^2, with a mean value of 7.71 kN/mm^2. The majority of this variation (55%) was due to differences between individual trees within a site, while 36 percent was due to differences between sites. The remaining nine percent was due to differences within a tree. At a site level, the mean value of E_{dyn} ranged from 6.09 kN/mm^2 up to 9.74 kN/mm^2. Preliminary analyses of these site-level data indicate that E_{dyn} is significantly influenced by yield class, elevation and initial spacing, as well as by the interactions between elevation, latitude and longitude, and yield class, elevation and initial spacing ($p<0.05$). More in-depth analyses of the data are currently being undertaken and a linear regression model is being developed using actual values for each of these variables, rather than treating them as factors with two levels.

The level of variation encountered indicates that there is an opportunity for segregation which would identify those stands (and possibly trees) which are unlikely to produce an economically acceptable outturn of structural-quality timber. The effectiveness of standing tree acoustic tools as a means of segregating stands will be examined in the future through a processing study. A sample of 10-12 of these sites, which span the range of E_{dyn}, will be selected and the trees converted into structural timber. The grade recovery and mechanical properties of the timber from the different sites will be compared and related back to predicted values of E_{dyn}.

3.1.2 Variation due to genetics

Values of E_{stat} for sawn timber ranged from 4.0 kN/mm² up to 12.0 kN/mm², with a mean of 7.9 kN/mm² (Table 1) and did not differ between the four genotypes investigated ($F_{3,6}$=2.0, p=0.216). The variance components analysis revealed that only a small amount of the variation in E_{stat} was attributable to differences between genotypes (0.6%), while most of the variation was attributable to differences between individual trees within a genotype (38.4%) and individual pieces of timber within a log (50.5%). The bending strength of the timber ranged from 16.7 N/mm² up to 65.4 N/mm², with a mean value of 35.5 N/mm² and a 5th percentile value of 21.5 N/mm^2. There was no difference in f_m between genotypes ($F_{3,6}$=2.81, p=0.130), but as expected a moderate correlation was found with E_{stat} (R^2 = 0.41). Based on the characteristic bending strength and stiffness values, this timber met the requirements for the C16 grade. The lack of any significant differences in mechanical properties between the four genotypes investigated is due to the high degree of within- and between-tree variation. If this study was repeated using clonal material (i.e., vegetatively propagated trees) and the radial position of the timber within a log was accounted for, it is possible that differences in timber properties between the same genotypes could be found.

Table 1. Summary stress wave measurements and mechanical properties of Sitka spruce. E_{dyn} and E_{stat} are the dynamic and static modulus of elasticity, respectively of structural timber.

Study	Mean Stress Wave Velocity (km/s)		Mean Modulus of Elasticity (kN/mm^2)		5th Percentile Bending Strength (N/mm^2)
	Standing tree	Log	E_{dyn}	E_{stat}	f_m
Genotype	-	-	8.87	7.94	21.5
Pre-commercial thinning	3.72	3.49	8.73	7.83	16.5
Rotation length	3.74	3.71	10.90	9.18	26.0
OVERALL	3.71	3.58	9.45	7.98	18.9

3.1.3 Effect of pre-commercial thinning

Across the five pre-commercial thinning treatments, E_{stat} ranged from 4.1 kN/mm^2 up to 13.7 kN/mm^2, with a mean of 7.8 kN/mm^2. The corresponding range for f_m was 5.4 N/mm^2 up to 62.8 N/mm^2, with a mean of 31.3 N/mm^2 and a 5th percentile value of 16.5 N/mm^2. Despite considerable inter and intra-tree variation in timber properties, significant differences in E_{stat} and f_m were found between thinning treatments ($F_{4,11}$=6.517, p=0.006; and $F_{4,11}$=5.877, p=0.009, respectively). Both E_{stat} and f_m decreased with increased spacing (Figure 1), with timber from the widest spacing (5.6 m) having characteristic strength and stiffness values of 13.1 N/mm^2 and 7.2 kN/mm^2, respectively. In comparison, timber from the un-thinned control treatment (1.9 m spacing) had characteristic strength and stiffness values of 21.0 N/mm^2 and 9.0 kN/mm^2, respectively. These characteristic values were sufficient for timber from this treatment to satisfy the requirements for the C18 strength class, while timber from those treatments where the spacing following thinning was greater than or equal to 3.7 m was unable to satisfy the requirements for the C16 class. Results from this study generally agree with those obtained by Brazier and Mobbs [2] who found that at spacings above 2.0 m, the yields of timber meeting the requirements for the C16 strength class were too low to be economically viable. Based on the results from this study, it appears that this limit of 2.0 m may be a little pessimistic. However, this result should be treated with a degree of caution as it is based on material obtained from a single site.

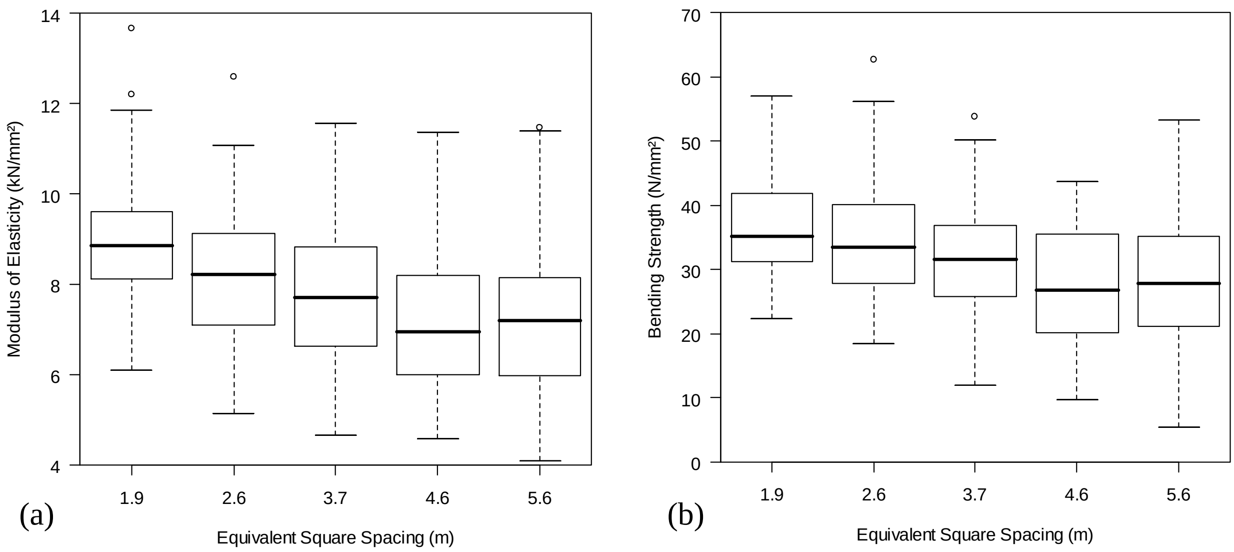

Fig. 1 Comparison of (a) modulus of elasticity and (b) bending strength between different tree spacing levels following a pre-commercial thinning.

3.1.4 Effect of increasing rotation length

The range in values of E_{stat} across all 300 pieces of timber was 4.9 kN/mm^2 up to 13.9 kN/mm^2, with a mean value of 9.2 kN/mm^2. The corresponding range for f_m was 12.8 N/mm^2 up to 81.1 N/mm^2, with a mean of 44.6 N/mm^2 and a 5th percentile value of 26.0 N/mm^2. There was a substantial increase in both E_{stat} and f_m with increasing distance from the pith of the tree (Figure 2). Timber cut from near the centre of the log (radial position 1) had characteristic values of strength and stiffness of 17.5 N/mm^2 and 7.6 kN/mm^2, respectively, while the corresponding values for radial position 4 (outermost position) were 27.5 N/mm^2 and 10.1 kN/mm^2, respectively. Therefore, timber sawn from near the outsides of logs is able to meet the requirements for the C22 strength class, while timber from radial position 1 can only satisfy the requirements for C14. If the core-wood was sent to non-structural uses, then the overall mean value of E_{stat} would increase from 9.2 kN/mm^2 up to 9.6 kN/mm^2. In addition to having lower strength and stiffness, timber sawn from near the pith generally has a greater propensity to twist under changing moisture content due to the higher level of spiral grain found in this region of the log [10]. The site that this stand was growing on was quite wind exposed and it is possible that similar-aged trees growing on a more sheltered site may yield some timber that is able to satisfy the requirements for the C24 strength class. C24 grade timber is being increasingly demanded by end-users in the UK and longer rotations may be one means of achieving economic yields of this material from Sitka spruce plantations.

3.1.5 Relationship between E_{dyn} and E_{stat}

There was a moderately strong relationship between E_{dyn} for an individual piece of timber and the predicted E_{dyn} for the log it was cut from ($R^2 = 0.40$, $p < 0.0001$; Figure 3). The remaining 60 percent of the variation that is not explained represents the radial and circumferential variation in wood properties within a log as well as log-to-log variation in green density. There was a similar relationship between E_{dyn} (log) and E_{stat} of the timber cut from these logs ($R^2 = 0.31$, $p < 0.001$). In the rotation length study, E_{dyn} predicted from standing tree time-of-flight velocity measurements made with the IML Hammer only explained approximately 13 percent of the variation in E_{dyn} of the sawn timber. However, an initial trial of the ST-300 instrument indicated that standing tree stress wave velocity measurements could explain approximately 25% of the variation in E_{dyn} of individual pieces of sawn timber (Forest Research, unpublished data). This degree of association is at the lower end of the range of values presented by Chauhan and Walker [6]. Measurements made on standing trees only estimate E_{dyn} for the outermost wood in the stem, while structural timber is often produced from the near the centre of the tree. Because wood stiffness exhibits strong radial variation, it is not surprising that these spatially separated measurements don't exhibit such a high degree of correlation. However, further research will be undertaken to investigate this relationship when a sample of sites from the benchmarking study are selected for more in-depth study.

For sawn timber there was a very strong relationship between E_{stat} and E_{dyn} ($R^2 = 0.84$, $p<0.001$) (Figure 3). As expected, the E_{dyn} was higher than static MOE, with the degree of over-prediction being approximately 14%.

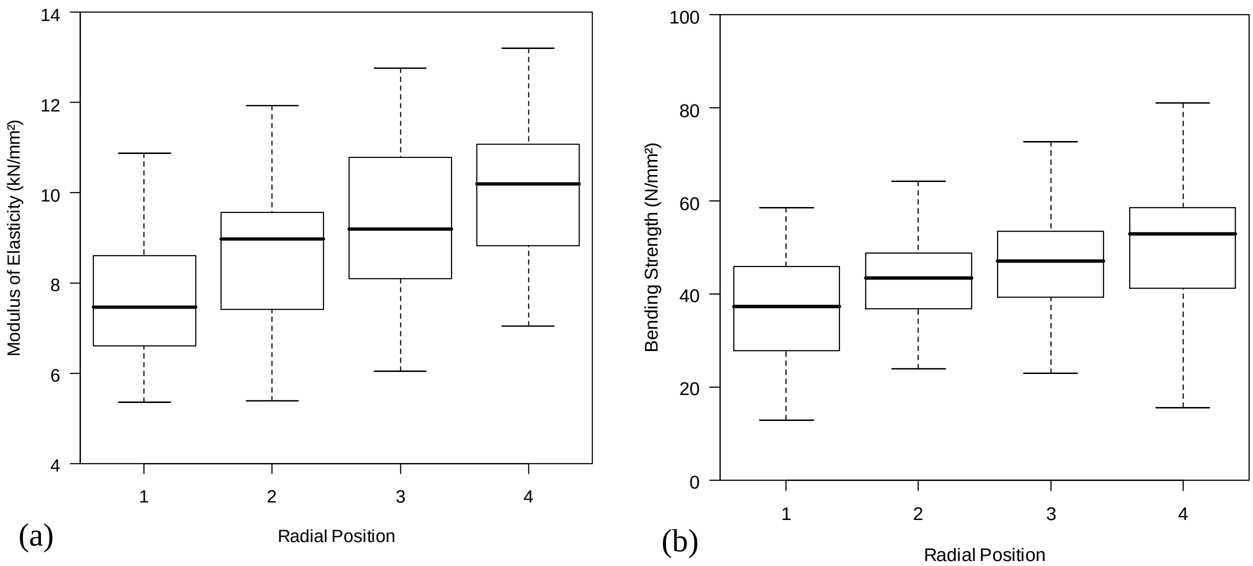

Fig. 2 Effect of radial position within a log on (a) modulus of elasticity and (b) bending strength of sawn timber

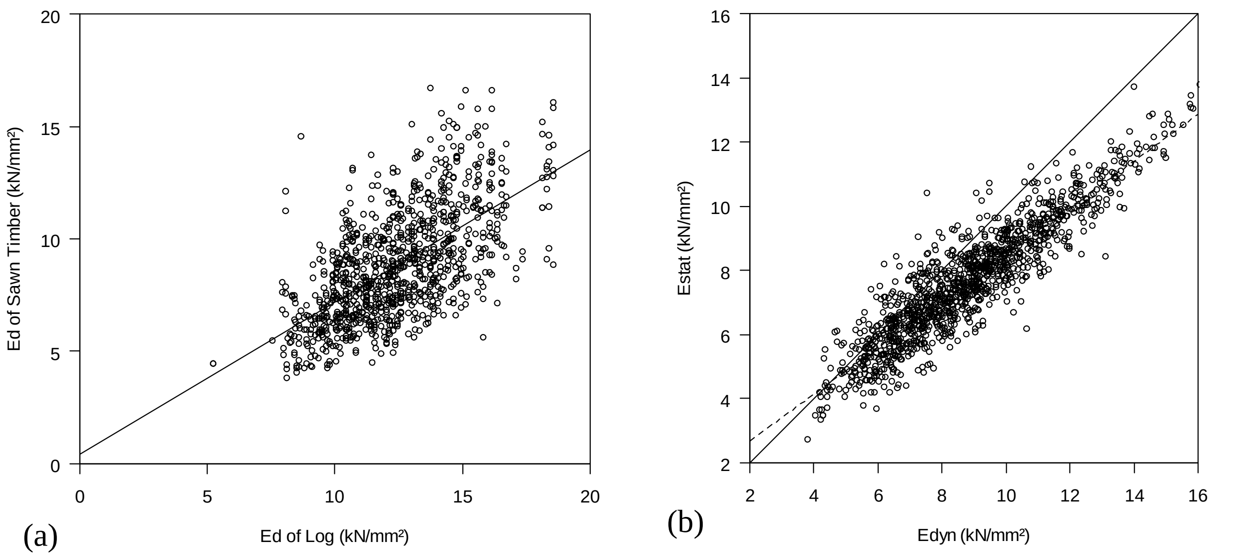

Fig. 3 Relationship between (a) predicted E_{dyn} for a log and E_{dyn} of timber cut from that log, and (b) E_{stat} and E_{dyn} for individual pieces of sawn timber. The solid line was fitted using ordinary least squares regression, while the dashed line indicates a 1:1 relationship.

4 Concluding remarks

Overall, plantation-grown Sitka spruce in the UK has mechanical properties that result in it satisfying the requirements of the C16 strength class. However, as the preliminary results from the benchmarking study indicate, there is potentially a large amount of variation in wood stiffness between stands that are approaching or are at harvesting age. There is also an even greater amount of variation in stiffness between trees within these sites. Results to date indicate that a significant amount of the stand-level variation can explained by site and stand characteristics. In order to better understand the influence of site characteristics on wood properties, a wider range of sites need to be examined. Initially, this could include more southerly latitudes within Great Britain and Ireland, but also other areas within Europe and North America where Sitka spruce is grown.

This variability in the current resource presents timber processors with an opportunity to improve the mechanical properties of sawn timber through segregating out the poorer quality material before it is processed. Measurements of stress-wave velocity made on standing trees and logs appear to offer a means for identifying stands and logs which will yield timber with poorer mechanical properties. Such material can either be directed towards non-structural uses, or still sent to a sawmill producing structural timber, but knowing that a higher proportion is likely to be rejected during machine strength grading.

In addition to making best use of the current resource, knowledge gained from this research can inform forest managers how to improve the wood properties of the future resource. This can be achieved through identifying the best sites for producing structural timber, deploying the best genotypes and applying the most appropriate silviculture. The ultimate aim of the benchmarking study is to be able to map the landscape so that sites which are highly suitable for producing structural timber can be readily identified. While there was no difference in timber mechanical properties between the genotypes that have been investigated to date, one of the genotypes yielded significantly more timber due to lower mortality and improved straightness. Given the high level of tree-to-tree variation in wood properties, there is a good opportunity to improve wood properties by selecting trees with higher wood stiffness; particularly as this trait has been shown to be moderately heritable [11]. Pre-commercial thinning appears to have a negative effect on timber strength and stiffness, and once the spacing following thinning exceeded 3.7 m, timber failed to meet the requirements for the C16 strength class. Conversely, increasing the rotation length beyond the current level of 45 years has the potential to substantially improve the mechanical properties and strength grade of timber. Through the right combination of site, genetics and silviculture it may be possible to meet end-users demands for C24-grade timber, however this would require an almost 40 percent increase in E_{stat}.

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