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Original Article

The influence of age on the timber properties and grading of Scots pine and larch in Ireland

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Abstract

Scots pine (*Pinus sylvestris* L.) and larch (*Larix* spp.) are two species that could contribute to diversifying Ireland's timber supply. However, there is little knowledge about their properties as well as their variation with age. The aim of this study is to investigate the structural properties (modulus of elasticity, strength and density) of Irish-grown Scots pine and larch and the effect of cambial age on timber grading. Structural-sized pieces were used for this purpose, and the timber properties, knots and ring width were measured on 158 and 250 pieces of Scots pine and larch, respectively. Characteristic values of the properties and indicative yields for different strength classes were calculated. The age effect was assessed using an empirical approach, and a novel modelling approach that disaggregates the timber properties at the annual growth ring level. Yields above 90 per cent of C20 were achieved for Scots pine, whereas larch achieved a 100 per cent yield of C24 strength class. The effect of cambial age in the grading properties indicated that older boards increased the characteristic values of a timber population. In Scots pine, the empirical approach showed that the yields increased by up to 26 per cent when using pieces up to 50 years old compared with pieces up to 30 years old. In larch, the use of pieces up to 40 years old increased the yields by up to 16 per cent compared with using pieces up to 30 years old. The results of the modelling approach were consistent with the values obtained in the empirical analysis and can help to make informed decisions regarding rotation lengths for the production of structural timber. Our results found that cambial ages of 40 years in Scots pine produce high yields of structural timber, whereas 30 years are enough for larch.

Keywords: Scots pine, Larch, Strength grading, Cambial age, Wood properties, Structural timber

Introduction

In forestry, the optimal rotation age in an even-aged stand is typically determined based on its growth in volume (Edwards, 1981; Maclaren, 2004; Bettinger *et al.*, 2017). However, when the management objective is not to optimize volume but instead to improve the structural properties, understanding how these vary with age becomes key in the determination of optimal rotation lengths. The key structural properties for timber grading are the modulus of elasticity (E), strength (f) and density (ρ), which are referred to as grade determining properties (GDPs) in the European standard EN14081-2 (CEN, 2022). These properties can be strongly affected by the rotation lengths (Cown and McConchie, 1982; Macdonald and Hubert, 2002; Barnett and Jeronimidis, 2003), with longer rotations generally resulting in improved properties (Kliger *et al.*, 1998; Duchesne, 2006; Moore *et al.*, 2012). This effect relates to the larger proportion of juvenile wood (wood near the pith) in shorter rotations. Juvenile wood tends to be less suitable than mature wood for structural applications (Walker *et al.*, 1993; Butterfield, 2003; Clark *et al.*, 2008; Moya *et al.*, 2013; Simic *et al.*, 2019) due to changes in the microfibril angle, spiral grain, cell wall and tracheids from the pith outwards (Lachenbruch *et al.*, 2011; Zobel and Sprague, 2012).

The forestry sector in Ireland heavily relies on Sitka spruce (*Picea sitchensis* (Bong.) Carr.), where the species occupies more than 50 per cent of the forest area (Forest Service, 2020). In recent years, work has been carried out in Ireland to diversify the timber supply (Gil-Moreno *et al.*, 2019a; Fátharta *et al.*, 2020; Gil-Moreno *et al.*, 2022) due to concerns about the over-reliance of the forest industry on a single species. Although this recent research focused on structural properties, little attention was given to the influence of age. In this article, we focus on both aspects for two species in Ireland: Scots pine (*Pinus sylvestris* L.) and larch (*Larix* spp.).

Scots pine is a native minor species in Ireland (McGeever and Mitchell, 2016; Roche, 2019). The species represents 1.1 per cent of the forest area (Forest Service, 2020), but it was the main conifer grown in Ireland until about 1950 when other faster-growing species were chosen for planting (Mooney, 1986). Although the species is broadly used in Europe in construction (Mason and Alía, 2000; Ranta-Maunus, 2007; Esteban *et al.*, 2009) the available information on the structural properties of Irish-grown material is limited. Larch is the second largest timber conifer species in terms of forest area in Ireland, with 4.7 per cent of the total forest area (Forest Service, 2016; Coillte, 2019), mostly in mixed stands. The most commonly planted species is Japanese larch (*Larix kaempferi* (*Lamb.*) Carrière), with smaller proportions of European (*Larix decidua* Mill.) and hybrid larch (*Larix* × *eurolepis*). These three larch species have similar wood properties, and thus

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sawmills in Ireland process the logs and sell the timber of all three species as if they are one single species. Again, there is limited information available on the structural properties of Irish-grown larch.

The overarching aim of this study is to investigate the GDPs of Irish-grown Scots pine and larch and the influence of cambial age. Structural timber was used for this purpose, as opposed to the more common approach where small clear wood specimens obtained from the pith outwards are favoured (Alteyrac *et al.*, 2006; Auty and Achim, 2008; Antony *et al.*, 2012; Auty *et al.*, 2016; McLean *et al.*, 2016). Dealing with the effect of age on the properties of structural timber does not come without its challenges. For instance, the number of rings varies from piece to piece, more so than in small clears, and therefore it is difficult to assign a timber piece to a specific age group. Because of this, the influence of cambial age on structural properties is investigated here using two different approaches. First, an empirical approach will address the age effect on grading by progressively including pieces within a varying age threshold. For the second approach, a trial modelling method will disaggregate the GDPs by age and taking into consideration ring width. This second approach will, in turn, allow the reconstruction of the population of GDPs up to any desired age, by reaggregating the predicted GDPs at the ring level. The results will help in the understanding of the variation of properties with age and will allow informed decisions to be made by the forestry sector regarding silvicultural management for the production of timber taking age into account as well as to improve sorting for different end uses according to structural quality. In addition, the development of the new modelling method will provide the theoretical bases from which more refined calculations on the effect of age on strength grading could be produced.

Materials and methods

Data

The trees were obtained as part of larger-scale forestry operations carried out in 2019. The selection of trees responded exclusively to harvesting criteria. The Scots pine came from a mixed forest plantation with beech (*Fagus sylvatica* L.) and Norway spruce (*Picea abies* (L.) Karst.), in County Laois (53°06′04.9″N 7°09′20.3″W). The stand was 77 years of age at the time of felling and had a yield class (YC) of 10 m^3 ha^{-1} $year^{-1}$. The YC is an estimation of the potential productivity of an even-aged forest plantation based on the maximum mean annual increment of cumulative timber volume (Matthews *et al.*, 2016). Based on a survey in 2014, the stand had a density of 397 trees ha^{-1}, a mean diameter at breast height (d.b.h.) of 36 cm and a top height of 23.0 m. A total of 20 sawlogs, 3.7 m long, were used. Up to two sawlogs were obtained per tree, but information on their position in the tree (top or bottom log) was not available. This study focuses on radial variation, and while the authors acknowledge that there is also longitudinal variation, this effect on the structural properties is small relative to radial variation (Jyske *et al.*, 2008; Moore *et al.*, 2013; Auty *et al.*, 2016) and therefore it is not considered detrimental to the study.

The larch came from a mixed forest plantation with Sitka spruce and Noble Fir (*Abies procera* Rehd.) in County Wicklow (52°55′33.2″N 6°24′21.8″W). The stand was 46 years of age and had a YC of 14 m^3 ha^{-1} $year^{-1}$. In a survey in 2016, the tree density was estimated as 572 trees ha^{-1} with a mean d.b.h. of 24 cm and a top height of 22.6 m. A total of 35 sawlogs, 4.9 m long, were used, with only one log per tree.

The annual rings were marked on the small ends of the logs to record the cambial age of the structural pieces to be processed. The sawlogs were processed following standard cutting patterns aimed at maximizing the volume recovery of pieces. A total of 158 pieces of Scots pine of cross-section of 100 × 50 mm^2 were obtained and 250 pieces of larch of different cross-section size: 150 × 75 mm^2 (94 pieces), 100 × 50 mm^2 (60 pieces) and 75 × 35 mm^2 (96 pieces). All the pieces were X-ray scanned with a GoldenEye 702 (MiCROTEC GmbH) at Murray Timber Group, in Ballygar, Ireland, and kiln-dried to 18 per cent moisture content (mc). Subsequently, the pieces were non-destructively assessed with a Viscan (MiCROTEC GmbH, Brixen, Italy), a device that measures the natural frequency produced by the impact of a hammer in the longitudinal direction and allows for the calculation of the dynamic modulus of elasticity (E_{dyn}, $N\ mm^{-2}$), using equation (1):

$$E_{dyn} = \rho_{board} V^2 = \rho_{board} \times \left(2 \times Frequency \times Length\right)^2 \quad (1)$$

where ρ_{board} is the density of the entire board (kg m^{-3}) and V is the acoustic velocity (m s^{-1}) of the natural frequency of the first mode resonance (Hz) propagated along the length of the board (m).

The knot index TKAR (total knot area ratio) of each board was then determined as defined in IS127 (NSAI, 2015). The software Web Knot Calculator v2.2 (MiCROTEC GmbH), where the operator enters the dimensions and position of knots in relation to the cross-section of the board, was used to calculate the index. The average width of the growth rings in a timber piece was then measured, at the small end of the log, as the length in millimetres of a straight line normal to the growth rings covering as many rings as possible divided by the number of rings.

The pieces were then tested destructively in four-point bending according to the standard EN408 (CEN, 2012) to determine the bending properties (E and f). The expected weakest position under mechanical loading, located at the centre of the test span, was determined from the information on density and knot characteristics obtained from the Goldeneye 702, and confirmed by visual inspection in the laboratory. Both global (E_G) and local modulus of elasticity (E_L) were measured simultaneously. Finally, a defect-free sample spanning the full cross-section of the test piece was sawn from near the failure point to calculate its density and mc using the oven-dry method (CEN, 2002). More details on the determination of GDPs are provided in the appendix.

Data analysis

The statistical analysis was conducted separately for each species using the open-source statistical environment R (R Core Team, 2019). The values of E_{dyn} were adjusted to 12 per cent mc following EN14081-2 (CEN, 2022). The values of E_G, E_L and density were corrected to 12 per cent mc, strength was adjusted to a 150 mm depth and E_G was adapted to pure bending (E_{PB}) following EN384 (CEN, 2018). This E_{PB} is used in the grading calculations and to assess the effect of age in grading. To assign an age to a board, the oldest ring within a cross-section, rather than the middle ring, was used. This decision was intended to capture the influence of the oldest ring within a piece. To determine whether this decision may influence the results for larch, which had three cross-section sizes, the distributions of the oldest ring and the middle ring in a cross-section were examined (results not shown), and it was observed that the differences between cross-sections were more significant when the middle ring was used. The variation of the GDPs with age was then studied by grouping the timber pieces into age classes. By age class, this study refers to the intervals into which a range of ring numbers are grouped for further analysis. It must be noted that the age marking on 10 pieces of Scots pine and one of larch were damaged and could not be read. To determine whether there were any statistically significant differences between the means of the properties by age class, one-way analysis of variance (ANOVA) type III followed by Tukey tests (HSD) with a level of significance α of 0.05 were carried out. Linear regression was used to examine the relationships between GDPs, ring width and TKAR knot index. The characteristic values of strength and density were calculated using the non-parametric (ranking) method at a 95 per cent confidence level before grading to strength classes given in EN338 (CEN, 2016) for different ages. The effect of cambial age on the GDPs was assessed using an empirical approach and a modelling approach described in the next section.

Modelling developments for assessing the effect of age in grading

A modelling exercise was conducted to disaggregate the different GDPs by any custom-defined age class (i.e. range of rings from the pith) using the measured information from the dataset (section Disaggregation of GDPs at a piece level and aggregation by age classes). This then allowed to simulate a population of timber pieces of different cambial ages by re-aggregating the timber properties up to any age of interest (section Simulation of GDPs at a tree level at different ages). The characteristic values for these cambial ages can then be calculated from those populations, thus unfolding the effect of age in grading. Because the rings farthest from the pith represent a larger percentage of the cross-sectional area of a tree, the simulation of the populations requires weighting of the predictions from the disaggregation model by age class area (sum of several ring areas). This is effectively an upscaling of the predictions, which incurs a sampling error (i.e. we are making the assumption that our prediction is valid for the whole ring) and needs to be considered in the simulation itself.

Disaggregation of GDPs at a piece level and aggregation by age classes

The disaggregation model takes into account the cambial age of the rings contained within a piece, the number of rings and the weight that each ring bears on the overall GDPs of the piece. Using this approach, the influence of each age class (i.e. group of rings) on the GDPs of a timber piece was estimated.

For these purposes, the rings were first grouped into age classes within each piece. Ten-year age classes were chosen, resulting in seven age classes for pine and five for larch. Then, it was assumed that the value of any GDP for a given piece can be defined as the weighted average of the GDP of the age classes that form the piece (Figure 1). This can be expressed by means of the following model:

$$y_i = \sum_{j}^{n_i} y_j \, \hat{w}_{ij} + \varepsilon_i \tag{2}$$

where y_i is the measured GDP for piece i, y_j is the unknown mean GDP for age class j to be ascertained, $\hat{w}_{ij}$ is the weight factor for age class j in piece i and ε_i is the error term, which is assumed normally distributed such that $\varepsilon_i \sim N(0, \sigma^2)$, with σ^2 being the residual variance. In order to determine $\hat{w}_{ij}$, it is first necessary to know the mean ring width in a piece and then extrapolate to an age class.

The mean ring width within a given piece ($\overline{\Delta r_i}$) is available across the whole measured dataset, and the cambial age of the rings is known. Therefore, it is possible to infer a rough estimate of the mean ring width for each age class as

$$\hat{\Delta r}_j = \frac{\sum_i^N \overline{\Delta r_i}\, n_{ij}}{\sum_i^N n_{ij}} \tag{3}$$

where n_{ij} is the number of rings within piece i that belong to age class j and N is the total number of pieces in the dataset.

The area of a ring contained within a piece can be further assumed to be proportional to ring width. Under this assumption, an estimate of the weight that each age class bears in a piece can be defined as

$$\hat{w}_{ij} = \frac{\hat{\Delta r}_j n_{ij}}{\sum_j^{n_i} \hat{\Delta r}_j n_{ij}} \tag{4}$$

where n_i is the number of age classes within a piece. This weighing is necessary because the pieces will rarely include only a single age class (Figure 1).

Equation (2) can be redefined for each GDP in the more familiar terms of linear regression as

$$E_i = \beta_0 + \beta_1 \hat{w}_{i,2} + \cdots + \beta_{n_i-1} \hat{w}_{i,n_i} + \varepsilon_{E,i} \tag{5a}$$

$$f_i = \gamma_0 + \gamma_1 \hat{w}_{i,2} + \cdots + \gamma_{n_i-1} \hat{w}_{i,n_i} + \varepsilon_{f,i} \tag{5b}$$

$$\rho_i = \theta_0 + \theta_1 \hat{w}_{i,2} + \cdots + \theta_{n_i-1} \hat{w}_{i,n_i} + \varepsilon_{\rho,i} \tag{5c}$$

where E_i, f_i and ρ_i are the responses at the piece level for modulus of elasticity, strength and density, respectively, and β, γ and θ are vectors of estimable parameters that represent the mean value of E_j, f_j and ρ_j in age class j for the dataset studied, which are the quantities of interest for the next steps of the approach. The model can straightforwardly be fitted by least squares to obtain those parameter estimates. It must be recalled that the piece i can cover any range of rings and does not necessarily have to include a specific age class.

Simulation of GDPs at a tree level at different ages

The parameter estimates resulting from equation (5) were used to calculate the characteristic values of the population of pieces for different cambial ages for each species. As mentioned earlier, this implies simulating these populations. In the first step, for each observed age class mean area-based weights were calculated, as opposed to ring width-based weights which were used in the aggregation by age classes. This step is illustrated in Figure 1. These weights are defined as

$$\overline{w}_{j\equiv l} = \frac{\left(\sum_{j=1}^{l} \hat{\Delta r}_j n_j\right)^2 - \left(\sum_{j=1}^{l-1} \hat{\Delta r}_j n_j\right)^2}{\left(\sum_{j=1}^{l} \hat{\Delta r}_j n_j\right)^2} \tag{6}$$

where l is the target age class and n_j is the nominal number of rings of any age class j.

Second, the area-based wood properties were simulated by substituting in equation (5) the mean area-based weights ($\overline{w}_j$)for the vector of ring width-based weights ($\hat{w}_{ij}$), and the parameter estimates of the models ($\beta_0, \ldots, \beta_n, \gamma_0, \ldots, \gamma_n, \theta_0, \ldots, \theta_n$) for the vector of parameters. This simulation was done stochastically, i.e. taking into account the uncertainty due to the parameters of the models and the residual term, through Monte Carlo simulation. The result of this simulation was an empirical area-weighted population of the GDPs across the age classes investigated. This empirical timber population is, however, not the simulated population from which to grade timber. It is important to note that the predictions from models in equation (5) were explicitly weighted by ring width, not by ring area. By using area-based weights, the model predictions are implicitly upscaled and therefore incur a sampling error. This is because the predictions in equation (5),

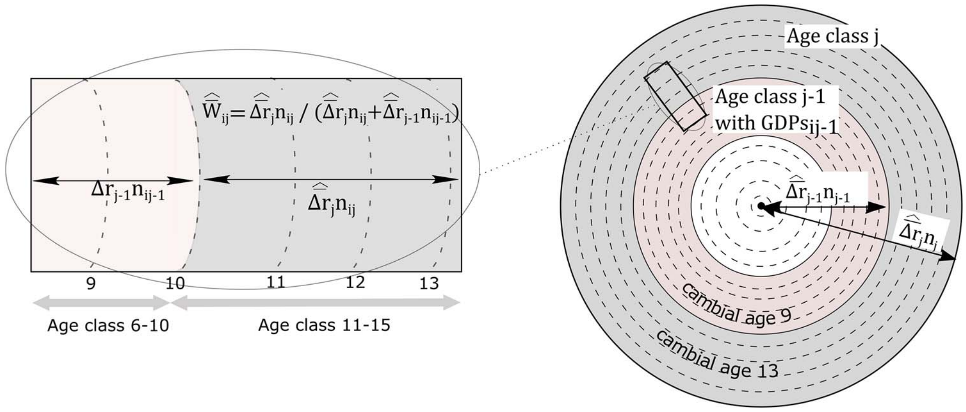

Figure 1. Left: piece i that falls between two hypothetical age classes with weights w_{ij-1} and w_{ij}; Right: hypothetical section of a log with demarcation of age classes from which piece i was obtained.

which are valid for a part of the cross-section of the tree (i.e. a piece), are extrapolated to the totality of the cross-section of a tree. This error cannot be ignored, as it contributes to the distribution of the GDPs, which are in turn necessary for grading. The third step deals with estimating the variance of this sampling error. If each of the Monte Carlo simulations from equation (5) is seen as an observation of the GDPs for each age class – plus a random realization at the piece level (residual error) – then these predictions could be seen as observations in a stratified sampling scheme where the strata are the age classes. The variance of the estimator of the mean for this type of sample is

$$s^2_{str.sampling} = \sum_h^L \left(\frac{N_h}{N_T}\right)^2 \left(\frac{N_h - n_h}{N_h}\right) \frac{s_h^2}{n_h} \quad (7)$$

where h is the index for the stratum (age class), L is the number of strata, N_h is the size of each stratum, n_h is the number of observations in each stratum, N_T is the total size of all strata and $s^2{}_h$ is the variance within each stratum. Given that in the study $n_h = 1$ and substituting equation (6) for N_h/N, equation (7) can be simplified as

$$s^2_{str.sampling} = \sum_j \left(\overline{w}_j\right)^2 \left(1 - \frac{1}{N_j}\right) \hat{\sigma}_j{}^2 \quad (8)$$

where $\hat{\sigma}_j{}^2$ is the variance of each parameter estimate from the model. Further, $1/N_j \rightarrow 0$, and therefore the central term in equation (8) can be approximated as 1. Equation (8) can then be rearranged in matrix form as

$$s^2_{str.sampling} = \overline{w}\Omega\overline{w}^T \quad (9)$$

where Ω is the variance–covariance matrix of the parameter estimates, which takes into account the fact that the errors between age classes are correlated.

The residual error is constant across age classes, as it applies at the piece level and it was therefore not included in equations (7), (8) and (9). This error, however, forms part of the predictions and still needs to be propagated. The sample variance in a random sample is calculated as the variance of the sample divided by the number of observations (i.e. $n_{ij} = 1$). Consequently, equation (9) can straightforwardly be modified to account for this additional source of error:

$$s^2_{sampling} = s^2_{str\ sampling} + \hat{\sigma_\varepsilon^2} \quad (10)$$

The fourth step consisted in combining the uncertainty due to the process, the realized variance between Monte Carlo simulations, and the uncertainty due to the implicit sampling structure just described ($s^2{}_{sampling}$, the variance within each Monte Carlo simulation) into a single term (s^2) through a simplification of the law of total variance:

$$s^2 = E\left[Var(Y)\right] + Var\left(E\left[Y\right]\right) \quad (11a)$$

where Y is a random variable that simply represents here the value of the GDP of interest. The first term can be interpreted as the mean of all the variances due to the sampling related to each Monte Carlo simulation. The second term represents the variance of all the Monte Carlo predictions, which indeed amounts to the variability inherent to each of the GDPs. In the current case,

$$s^2 \equiv Var(y) = E\left[Var\left(y_l|\beta,\gamma,\theta,\Omega,\hat{\sigma_\varepsilon}^2,\overline{w}\right)\right] + Var\left(E\left[y_l|\beta,\gamma,\theta,\Omega,\hat{\sigma_\varepsilon}^2,\overline{w}\right]\right) \quad (11b)$$

where l is the index for the Monte Carlo realization and, again, y is the GDP of interest. For the purpose of this simulation, 50 000 Monte Carlo simulations were run. The variance–covariance matrix of the parameter estimates and the residual variance of the model were considered.

The final step was to create a theoretical distribution for the population of the three GDPs. It was assumed that these populations were normally distributed with a mean equal to the mean of the stochastic outputs for each property, and variance equal to the solution of equation (10). This assumption seems reasonable in the light of the empirical distributions of the GDPs for the pieces tested in this study. The theoretical distributions can then be straightforwardly used to grade timber up to virtually any age included in the studied dataset. In order to do so, the aforementioned steps were followed for each species using first all the age classes and then sequentially removing the outermost age class to simulate different growing ages.

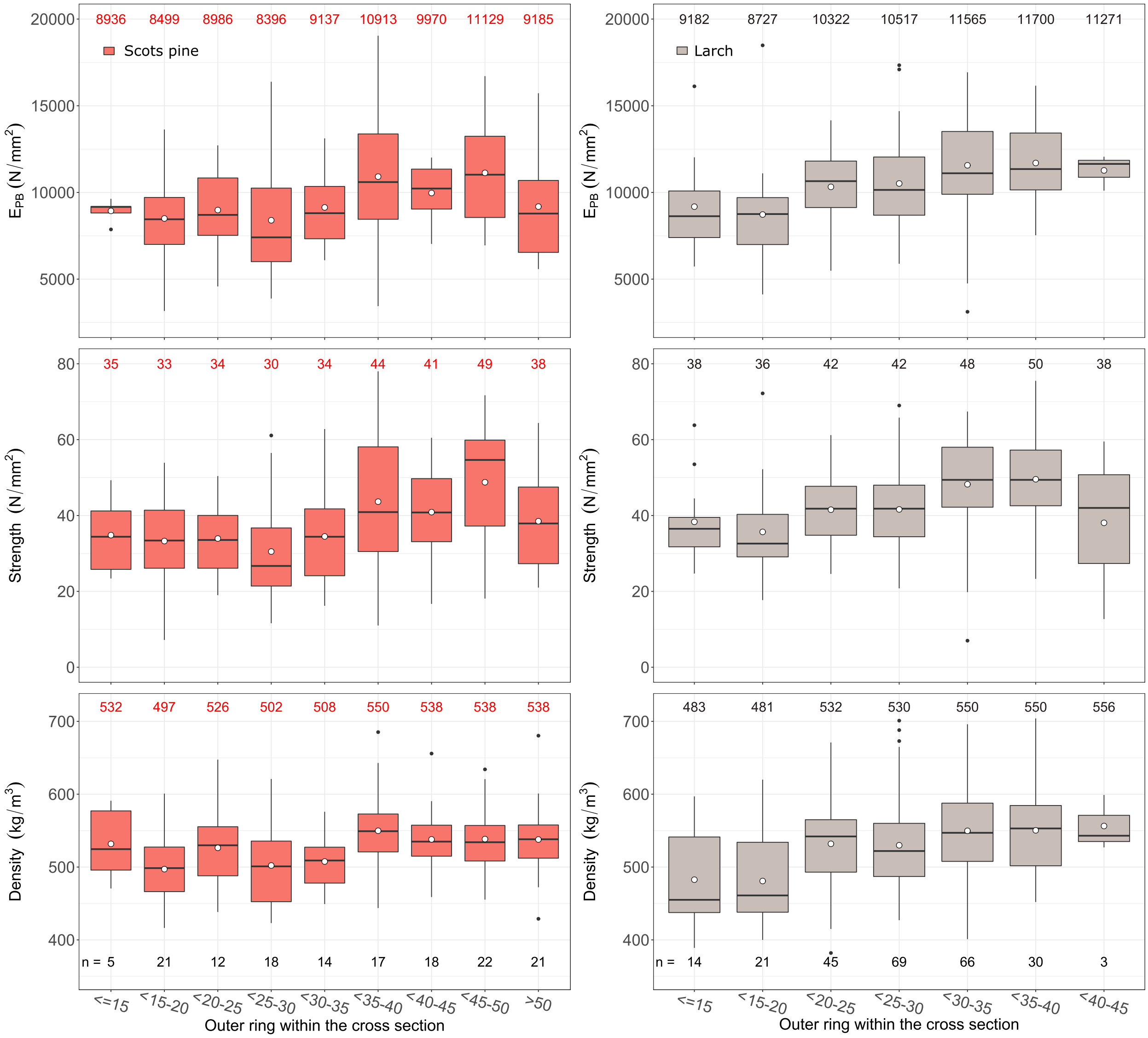

Figure 2. Variation of GDPs with age. Means as white dot and values on top, n = number of pieces.

Results

Descriptive summary of timber properties

The variation and range of GDPs (E_{PB}, strength and density) with cambial age are shown in Figure 2. The values of E_{PB} ranged from 3.17 to 19.0 kN mm^{-2} in Scots pine and from 3.12 to 20.3 kN mm^{-2} in larch. In the case of strength, the range was 7.2 to 78.0 kN mm^{-2} in Scots pine and 7.0 to 75.5 kN mm^{-2} in larch. Density ranged from 416 to 685 kg m^{-3}, and from 382 to 734 kg m^{-3}, in Scots pine and in larch, respectively.

Typically, the GDP values increased with age. In larch, an increase of 39 per cent and 37 per cent in the strength and E_{PB} values, respectively, was observed in the age classes 35–40 compared with the age classes 15–20, which had the lowest GDP values in both species. While this pattern was uniform in larch, the increase was only evident in the older age classes for Scots pine where an increase of 47 per cent and 31 per cent in the strength and E_{PB} values, respectively, was observed in the age classes 45–50 compared with the age classes 15–20. A more moderate increase was observed in density in both species. Despite the upward trend in both species, most of the boards in the age classes 25–30 and in the oldest age classes of each species (>50 for Scots pine and 40–45 for larch) reached lower GDP values than the predecessor classes.

A one-way ANOVA type III found a significant difference in strength between age classes in Scots pine ([$F(8, 139) = 3.21$, $P = 0.002$]) and larch ([$F(6, 242) = 6.49$, $P < 0.001$]). Similar trends were found for E_{PB} ([$F(8, 139) = 2.63$, $P < 0.01$]) and ([$F(6, 242) = 5.80$, $P < 0.001$], respectively) and density ([$F(8, 139) = 2.49$, $P < 0.015$]) and ([$F(6, 242) = 5.72$, $P < 0.001$], respectively). The post hoc Tukey test indicated that there were statistically significant differences in the strength and E_{PB} of Scots pine for the pairs 45–50, 15–20 and 45–50, 25–30, and in the density for the pair 35–40, 15–20. More differences were found in the strength of larch between all pairs containing the age classes 30–35 or 35–40 except between themselves. Differences were also found in the E_{PB} and density for four pairs, between the age classes ≤15, 15–20 and 30–35, 35–40. Plots of the normalized residuals versus fitted values and the explanatory variables selected did not show any clear trend. Table 1 shows that the values of the GDPs of larch were higher than those of Scots pine, regardless of age, except for ρ_k.

Table 1. Characteristic GDP values (CoV%) for different cambial age ranges

	Scots pine					Larch	
	Cambial age					Cambial age	
	≤30	≤40	≤50	>50	Overall	≤30	Overall
Pieces	56	87	127	21	158[1]	149	250[1]
E_G	8.69 (22)	9.10 (24)	9.46 (23)	9.13 (23)	9.38 (22)	9.82 (19)	10.3 (20)
E_L	8.68 (27)	9.10 (30)	9.45 (29)	9.41 (24)	9.42 (28)	9.90 (23)	10.5 (23)
E_{dyn}	10.1 (22)	10.7 (23)	11.1 (22)	11.5 (23)	11.1 (22)	11.3 (22)	11.9 (22)
E_{PB}	8.61 (29)	9.14 (31)	9.61 (29)	9.19 (30)	9.50 (29)	10.1 (25)	10.7 (25)
f_m	32.7 (36)	35.1 (41)	38.3 (40)	38.5 (34)	38.2 (39)	40.4 (26)	43.6 (27)
f_k	14.1	15.1	16.4	21.0	17.2	25.5	25.7
ρ	508 (10)	516 (11)	523 (10)	538 (10)	524 (10)	519 (12)	532 (12)
ρ_k	424	436	441	431	443	417	427

Moduli of elasticity, kN mm^{-2}; strength, N mm^{-2}; density, kg m^{-3}. The overall and ≤40 values (not shown) of larch are essentially the same. [1]Age could not be read on 10 pieces of Scots pine and one of larch.

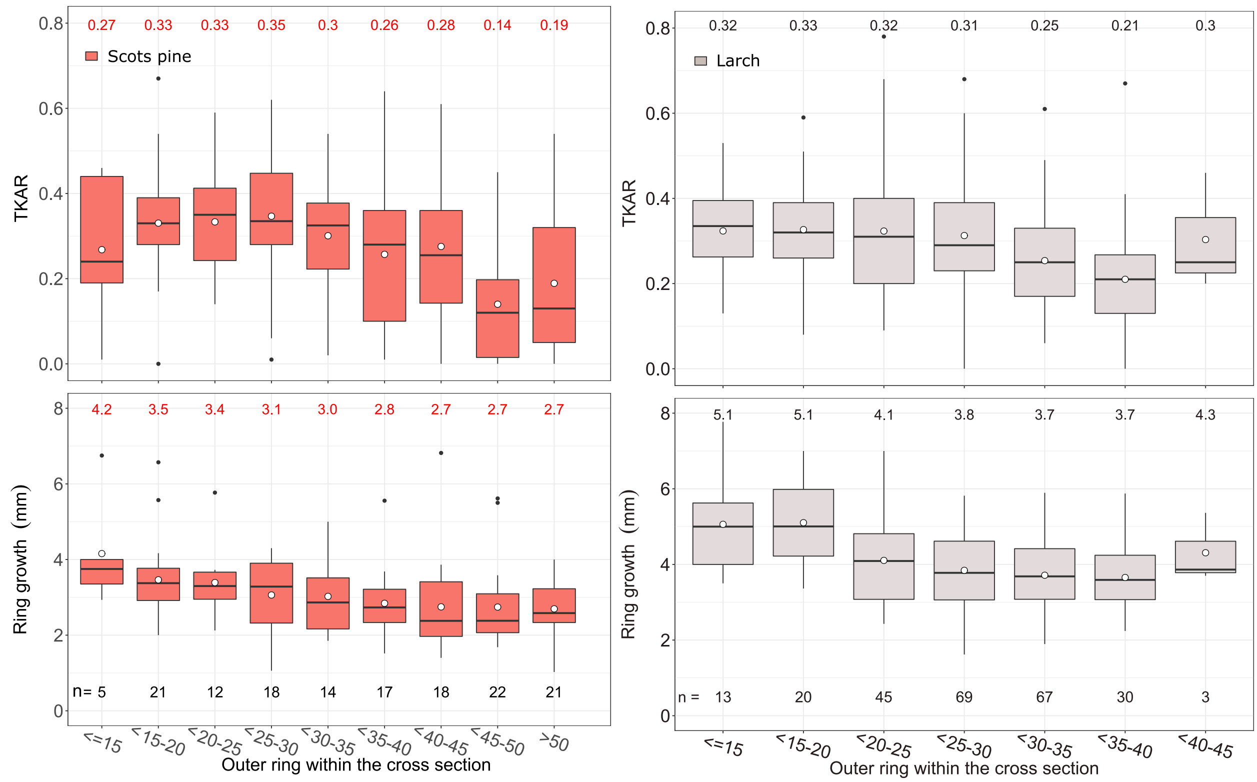

Figure 3. TKAR and ring growth with age. Means as white dot and values on top, n = number of pieces.

The two visual features, TKAR and ring width, described opposite trends compared with the GDPs throughout all the age classes, typically decreasing with age (Figure 3), although TKAR of Scots pine showed a slight increase in the first 25 years. The increment in the GDPs after the age classes 25–30, therefore, coincided with a decrease in TKAR and ring width. The ring width in Scots pine was smaller than in larch across all the age classes, more noticeably in the first 20 years. The values of TKAR ranged from 0 to 0.67 in Scots pine and from 0 to 0.78 in larch. The average growth ring in a board ranged from 1.1 to 6.8 mm/ring in Scots pine and 1.6 to 8.5 mm/ring in larch.

TKAR was able to explain a larger variation of the mechanical properties of Scots pine (R^2 = 0.61 with strength and R^2 = 0.31 with E_{PB}) than of larch (R^2 = 0.22 and R^2 = 0.07, respectively), with a very weak relationship between TKAR and density in Scots pine (R^2 = 0.14), which was non-significant in larch (R^2 = 0.01). There was no relationship between ring width and the GDPs in Scots pine (R^2 = 0.04, R^2 = 0.01 and R^2 = 0.01 with E_{PB}, strength and density, respectively) and a very weak relationship in larch (R^2 = 0.14, R^2 = 0.03 and R^2 = 0.21).

The effect of age in the grading: empirical assessment

The strength class achieved by 100 per cent of the population was C16 for Scots pine and C24 for larch (Table 2). Strength limited the grade in Scots pine up to the C22 strength class, while from C24 the limiting property was E_{mean}. Larch was limited by E_{mean} in all strength classes.

When considering the influence of age, the differences in the yields of Scots pine grown after 50 years compared with 30 years were relatively small when grading to the C22 strength

Table 2. Characteristic values for E_{PB} (kN mm^{-2}), f (N mm^{-2}) and ρ (kg m^{-3}), and yields (over a total of 158 pieces for Scots pine and 250 for larch) for different strength classes

Strength class	Required			Scots pine				Larch			
	f_k	E_{mean} [1]	ρ_k	f_k	E_{mean}	ρ_k	Yield[2]	f_k	E_{mean}	ρ_k	Yield[2]
C16	16	7.60	310	17.2	9.50	443	100%	25.7	10.7	427	100%
C18	18	8.55	320	18.0	9.54	445	99%	25.7	10.7	427	100%
C20	20	9.03	330	20.0	9.70	450	96%	25.7	10.7	427	100%
C22	22	9.50	340	22.0	9.77	445	90%	25.7	10.7	427	100%
C24[3]/C16	24/16	10.5/7.60	350/310	24.7/16.1	10.5/7.61	457/420	74%/16%	25.7/NA	10.7/NA	427/NA	100%/NA
C27[3]/C16	27/16	10.9/7.60	360/310	28.3/16.0	10.9/7.63	466/430	63%/27%	27.0/19.8	10.9/7.71	427/452	95%/2%
C30	30	11.4	380	30.9	11.4	467	53%	30.4	11.4	443	84%
C35	35	12.4	390	36.2	12.4	488	35%	36.2	12.4	476	58%
C40	40	13.3	400	42.1	13.3	491	22%	41.6	13.3	492	38%

[1]The 0.95 factor is applied to the required characteristic value E_{PB} (E_{mean}). [2]Rejects add the rest up to 100%. [3]The value of the higher strength class also applies as a single strength class.

Table 3. Yields and rejects (R) achieved for species for different ages

			Yields (%)			
	Age	N pieces	C18/R	C22/R	C24[2]/C16/R	C27/R
Scots pine	30	56	96/4	75/25	52/23/25	39/61
	40	87	96/4	84/16	66/18/16	54/46
	50	127	98/2	87/13	76/18/6	65/35
Larch	30	149	100/0	100/0	91/0/9	79/21
	40	246	100/0	100/0	100/0/0	95/5
	45[1]	249	100/0	100/0	100/0/0	95/5

[1]The oldest ring age for larch was 45. [2]The value of the higher strength class also applies as a single strength class.

Table 4. Age classes used in this study and mean and standard deviation (SD) of ring width within each class for Scots pine and larch

Class	Cambial age		Mean ring width (SD), mm	
	Lower limit	Upper limit[1]	Scots pine	Larch
1	1	10	3.45 (8.90)	4.39 (11.8)
2	11	20	3.09 (7.37)	3.99 (9.68)
3	21	30	2.79 (6.84)	3.71 (7.65)
4	31	40	2.75 (6.84)	3.59 (9.43)
5	41	50	2.79 (8.99)	3.86 (41.6)
6	51	60	2.77 (11.3)	
7	61	70	2.63 (15.8)	

[1]The oldest ring age recorded was 66 in Scots pine and 45 in larch.

class, but they increased by 46 per cent and 66 per cent when grading to C24 and C27, respectively. Larch improved considerably when grown for 40 years compared with 30 years. The differences were not important for strength classes below C22 and became larger as the requirements increased, improving by 10 per cent and 20 per cent when grading to C24 and C27, respectively, when grown for 40 years compared with 30 years (Table 3).

The effect of age in the grading: disaggregation of GDPs by age class

The 10-year interval that was chosen for the age classes resulted in a good compromise between a sufficient number of observations per class and a reasonable number of classes for disaggregation. Details on the age classes for both species are provided in Table 4.

The parameter estimates from the models in equations (5a), (5b) and (5c) for Scots pine are shown in Table 5. The estimated value of any GDPs for a given age class should be calculated as the sum of the estimate for the intercept (age classes 1–10, the reference) and that of the parameter for the said age class. This is as a result of the constraints that apply in linear regression to guarantee parameter estimability. The maximum value for E_{PB} and strength is reached in age classes 31–40. In the case of density, that maximum spans age classes 31–40 and 41–50. This is preceded by a slight drop in all GDPs in the age classes 21–30 with respect to the age classes 11–20. After the maximum, a certain decrease is evident. The uncertainty of the predictions remains relatively constant across age classes, except for age classes 61–70, where only four observations exist. The predictions of strength are the most uncertain, followed by those of E_{PB} and density.

The same information is summarized in Table 6 for larch, which also reaches the maximum value for the three GDPs between 31 and 40 years of age. It must be recalled that only three pieces of larch contained a ring of cambial age older than 40, hence the large standard deviation (SD). The variation of the GDPs over age classes and their uncertainty are comparable with those of Scots pine (Table 5). A graphical comparison with Scots pine is presented in Figure 4.

The characteristic values calculated by applying the models and methods described earlier to different growing ages are shown in Tables 7 and 8. All metrics seem to be within realistic limits and are comparable with the performance shown in Table 1 using the measured values in the laboratory. In the case of larch, negative values were obtained for E_{PB} and strength, and a very unrealistic value for density, when considering the longer rotation length (i.e. >41 years). Again, this was a consequence of the limited sample size, which led to a large uncertainty for that age class, and the results are therefore not shown.

Table 5. Parameter estimates and variance terms of the disaggregation models of Scots pine in an age class

	E_{PB}, kN mm^{-2}			Strength (f), N mm^{-2}			Density (ρ), kg m^{-3}		
Age class	Param.	Estimate	Std. error	Param	Estimate	Std. error	Param	Estimate	Std. error
1–10	β_0	7.70	1.25	γ_0	26.0	6.57	θ_0	486	15.9
11–20	β_1	1.72	2.42	γ_1	14.3	12.7	θ_1	42.3	1.34
21–30	β_2	0.72	1.74	γ_2	-2.12	9.12	θ_2	8.29	0.36
31–40	β_3	6.31	2.48	γ_3	38.0	13.0	θ_3	70.3	2.38
41–50	β_4	1.00	2.35	γ_4	19.6	12.3	θ_4	74.5	2.44
51–60	β_5	-0.04	1.75	γ_5	3.05	9.20	θ_5	11.6	0.43
61–70	β_6	2.86	7.23	γ_6	33.2	37.9	θ_6	242	2.40
	$\sigma_{\varepsilon,E}$	2.62		$\sigma_{\varepsilon,f}$	13.7		$\sigma_{\varepsilon,\rho}$	47.9	

The estimate of the intercept is the expected value of the GDPs for age classes 1–10. The remaining parameter estimates correspond to the expected value of the GDPs for a given age class minus the estimate of the intercept.

Table 6. Parameter estimates and variance terms of the disaggregation models of larch in an age class

	E_{PB}, kN mm^{-2}			Strength (f), N mm^{-2}			Density (ρ), kg m^{-3}		
Age class	Param.	Estimate	Std. error	Param.	Estimate	Std. error	Param.	Estimate	Std. error
1–10	β_0	7.44	0.74	γ_0	34.9	3.19	θ_0	426	17.4
11–20	β_1	4.39	1.45	γ_1	7.88	6.26	θ_1	153	34.2
21–30	β_2	3.50	0.86	γ_2	10.9	3.71	θ_2	114	20.2
31–40	β_3	6.98	1.69	γ_3	29.7	7.26	θ_3	173	39.6
41–50	β_4	-41.9	95.3	γ_4	475	411	θ_4	189	2242
	$\sigma_{\varepsilon,E}$	2.48		$\sigma_{\varepsilon,f}$	10.7		$\sigma_{\varepsilon,\rho}$	58.4	

The estimate of the intercept is the expected value of the GDPs for age classes 1–10. The remaining parameter estimates correspond to the expected value of the GDPs for a given age class minus the estimate of the intercept.

Discussion

The paper examined the potential of two minor commercial species in Ireland, Scots pine and larch, for the production of structural timber. This is the first time that the characterization of these two species has been carried out in Ireland on datasets large enough to constitute a subsample for grading, i.e. more than 100 pieces according to the European standard EN14081-2. The paper also investigated the effect of age in strength grading through an empirical method and a novel modelling approach based on the disaggregation of GDPs by age class, which contributes to the originality of the work presented.

Timber properties

In general, the timber quality of larch was more suited for structural timber than that of Scots pine for every age class studied, except for density during the first 20 years. Overall, there was a positive trend between the GDPs and age. The trend found for larch is similar to that described in other studies (Keith and Chauret, 1988; Leban and Haines, 1999; Zhu *et al.*, 2000; Karlman *et al.*, 2005; Fujimoto *et al.*, 2006). Scots pine, on the other hand, showed a fluctuating pattern in the GDP values. This behaviour was not anticipated because previous studies described the typical radial pattern (Lachenbruch *et al.*, 2011) in the modulus of elasticity and strength in Scots pine with a uniform increase from the pith outwards (Auty and Achim, 2008; Auty *et al.*, 2014; Auty *et al.*, 2016). Scots pine is a 'hard pine' where density increases with ring age from the pith outwards (Sauter *et al.*, 1999; Auty *et al.*, 2014), but the dataset analysed showed the lowest density in the age classes 15–20. The difference could be largely influenced by the large range of rings contained within a timber piece where the age classes 15–20 still contains a large proportion of juvenile wood. Forest management may have also had an effect on the trend of the GDP values. After the initial drop in the age classes 15–20, the GDP values increased before dropping again in the age classes 25–30 to recover afterwards. The radial pattern described by Scots pine may have been the result of crown lifting, which is recommended for Scots pine in Ireland with a yield class of 10 m^3 ha^{-1} year^{-1} at between 23 and 27 years of age (Fitzsimons, 1989). Although the first thinning of Scots pine is expected to be carried out between 24 and 31 years (Dominic Joyce, 2020, personal communication, Coillte, Ireland), which may have also explained the reduction of TKAR, these thinnings would have led to an increase in ring width (Schneider *et al.*, 2008) and to a drop in the GDP values (Krajnc *et al.*, 2019; Mörling, 2002) that were not observed in the current study.

These two features, TKAR and ring width, described patterns opposite to those of the GDP in their variation with age. TKAR had a stronger relationship with the GDPs than ring width in Scots pine. Both variables were, however, very weakly correlated with the GDPs of larch. Ring width, despite being a parameter often used to assess structural lumber quality, explained a low proportion of the variation in density, likely due to the abrupt transition from earlywood to latewood in the species (Saranpää, 2003). Other authors concluded that mean ring width also did not play a role in determining the mechanical properties of black spruce (*Picea mariana* (Mill.) B.S.P.) (Alteyrac *et al.*, 2006) and jack pine (*Pinus Banksiana* Lamb.) (Schneider *et al.*, 2008) once the effects of age and density were considered.

Timber grading

The entire population of Scots pine studied achieved a C16 strength class, with strength being the limiting GDP, and also obtaining very high yields of C20. Scots pine of similar age in Scotland achieved lower mean values of E_G and density than in the current study, but higher strength that determined a grade of C20 for the entire population (Macdonald *et al.*, 2009). The size

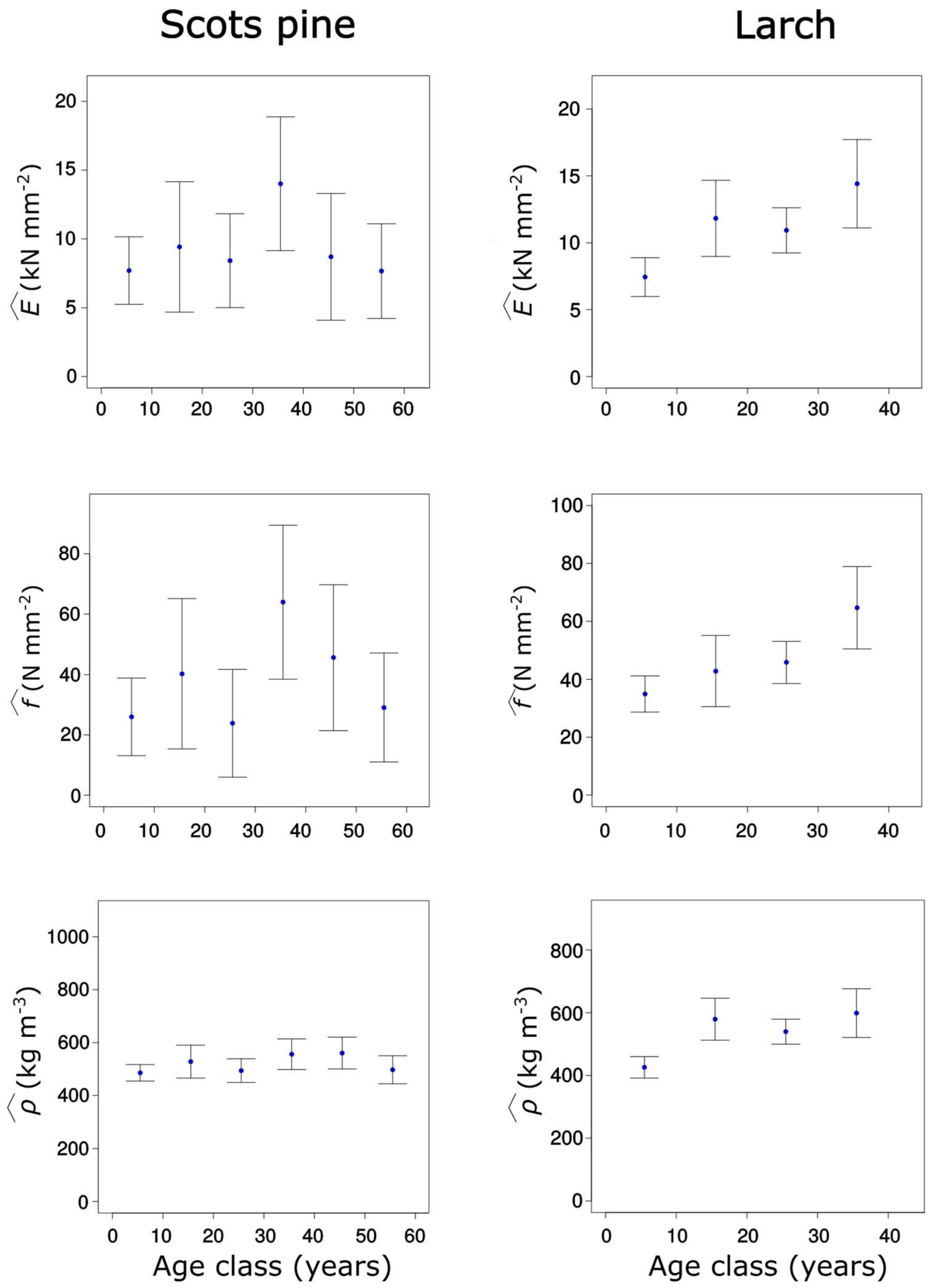

Figure 4. Variation of the GDPs with age classes using the disaggregation method for Scots pine and larch. The estimates for the last age class are omitted (non-meaningful as a result of their uncertainty).

of knots may have played a key role in reducing the strength and therefore determining the grades in the current study. In fact, silvicultural management aimed at reducing the size of branches through pruning is recommended for timber production of Scots pine in Ireland, although this recommendation can only be justified if the strength grade achieved pays the cost of the pruning. This being said, the Irish Scots pine studied here fell within the range of GDP values observed across Europe (Ranta-Maunus, 2009; Ranta-Maunus *et al.*, 2011; Stöd *et al.*, 2016; Burawska-Kupniewska *et al.*, 2020).

The whole population of larch achieved a C24 strength class. The limiting GDP was the E_{PB}, which is also limiting in British-grown larch (Ridley-Ellis *et al.*, 2016), Sitka spruce and other conifers in Ireland and the UK, which have similar growing conditions (Moore *et al.*, 2013; Gil-Moreno and Ridley-Ellis, 2015; Gil–Moreno et al., 2016a, b; Gil-Moreno *et al.*, 2019b). It may thus be of interest for grading to develop an empirical equation for larch to convert the measured E_G to E_{PB} as recommended for other species (Gil-Moreno *et al.*, 2016b; Gil-Moreno *et al.*, 2021) instead of using the generic equation in the standard EN384 (CEN, 2018). The characteristic values in the current study are comparable with those in the UK (Ridley-Ellis *et al.*, 2016, Ridley-Ellis *et al.*, 2022). For comparison with the main timber species in the two countries, Sitka spruce produces yields of C16 in excess of 90 per cent, and it is typically grown for 35–45 years (Moore, 2011; Moore *et al.*, 2013; Freer-Smith *et al.*, 2019). Therefore, the two studied species grown

Table 7. Characteristic values of simulatedGDPs for Scots pine at different rotation ages

	Rotation lengths, years				
	<21–30	31–40	41–50	51–60	>61
E_{mean}, kN mm^{-2}	9.98	12.1	11.4	10.7	11.0
f_k, N mm^{-2}	9.58	22.2	23.0	18.5	17.4
ρ_k, kg m^{-3}	440	459	471	459	494

Table 8. Characteristic values of simulated GDPs for larch at different rotation ages

	Rotation lengths, years	
	<21–30	31–40
E_{mean}, kN mm^{-2}	12.0	13.4
f_k, N mm^{-2}	29.1	36.7
ρ_k, kg m^{-3}	460	480

to similar ages as Sitka spruce could produce similar or higher yields of C16 graded timber.

The results showed that the characteristic values and yields increased significantly with age. The fact that structural timber improves with longer rotation lengths is mostly influenced by the decreasing proportion of juvenile wood within a tree (Butterfield, 2003; Duchesne, 2006; Ni Dhubháin *et al.*, 2006; Moore *et al.*, 2012), and this is confirmed here by the radial pattern observed for the GDPs. Comparing the GDPs for different age ranges, the largest difference was found for strength. In Scots pine, there was a 17 per cent and 16 per cent increase in the mean and in the characteristic value of bending strength, respectively, when using pieces up to 50 years of age compared with pieces up to 30 years of age, which translated to an increase of up to 26 per cent in the grading yields. In larch, the use of pieces up to 40 years old increased the characteristic value of bending strength by 8 per cent compared with pieces up to 30 years old, resulting in an increase of up to 16 per cent in the grading yields. The differences were larger as the requirements of the strength classes increased. These increases must be understood not only as an improvement in yield, but also as a reduction in the percentage of rejects, which do not usually find a place in the market except for biomass. Above 50 years, there was a drop in the mechanical properties of Scots pine, with mean values comparable with the age classes 30–35, while the TKAR values increased. The reasons for this drop could not be determined in the present study, but this decrease seemed to have been observed in other conifers as well (Duchesne, 2006; Auty *et al.*, 2016; Wilson *et al.*, 2016). The rotation lengths recommended in Ireland for Scots pine are 60–90 years, and for larch 45–60 years (Horgan *et al.*, 2003). Given the results, the lower age limit largely satisfies the requirements of structural timber quality, whereas growing overmature trees may be detrimental to the structural properties.

The data used in this work were obtained from planted mixed stands. How the GDPs would differ from those in a pure stand is currently unknown. While it seems that wood density is not affected by the type of forest, mixed or pure stands (Pretzsch and Rais, 2016; Russo *et al.*, 2019), the effect on the moduli of elasticity and strength remains largely unknown due to the limited studies available. This said, Rais *et al.* (2022) found higher characteristic values for beech in pure stands than in mixed stands, with light-demanding species in the mix with beech reducing E_{dyn} significantly (Rais *et al.*, 2020). More research is needed to understand what impact trees sampled from mixed forests may have on the GDPs.

Focusing on the methodological side of this work, the empirical approach used to examine the impact of age in strength grading is a straightforward way to produce estimates of the grading performance of structural timber across different cambial ages. However, the approach has limitations. For example, a piece (e.g. of cambial age 31–42) that is excluded when grading timber up to a given age (e.g. 31–40) includes rings that are within the range of ages being graded, which is in a way a sampling artefact. The modelling approach introduced in this study allowed the disaggregation of the GDPs by age class and simulation of populations up to any cambial age to determine the strength class. This method is advantageous over the direct empirical assessment in that there is no room for sampling artefacts. From a theoretical point of view, disaggregating the GDPs at a cambial age level is equivalent to reducing the problem to a small clear samples exercise, with the advantage of taking into account the impact of knots and other defects that occur in structural timber but do not appear, by definition, in clearwood. This absence of defects is a major drawback of any work on timber properties based on small clears to be representative of a batch of sawn timber and assign grading strength classes. The approach presented here could in this respect be an alternative, although it remains to be properly tested in a dedicated study. The work considered the uncertainty due to the sampling when upscaling (i.e. weighing by age class area) the disaggregated values of GDPs to the cross-section. This upscaling has so far been done in previous studies by simply assuming that the sampled GDPs for a given ring number is constant across the whole ring area (e.g. Ivković *et al.*, 2009). Whereas this may be true from a theoretical point of view, the natural growth of a tree determines changes within a ring that influence the wood properties to a certain degree. This influence needs to be incorporated into future studies of structural properties. The modelling approach relies on several assumptions that need to hold for the outcomes to be valid. These assumptions can be grouped into two main types: assumptions on the physical behaviour of timber and assumptions on the expansion of the variance of the predicted properties as a consequence of upscaling the results to the whole cross-section. One obvious assumption from the first group is that a weighted sum of the target GDP by age class within a board equals the actual value of that GDP for the whole board. It is the opinion of the authors in this paper that this is a reasonable assumption that has already been made in other studies (e.g. Psaltis *et al.*, 2021). The other major assumption in this group is that the ring area within a board is proportional to ring width when calculating the weights. This is possible if the ring section on boards is assimilated to trapezoids, and it is acknowledged that the impact of slight departures from this assumption is unknown.

On the side of uncertainty expansion, it is assumed in equation (7) that the number of potential sampling units in each class (N_h) is relatively high, effectively assuming that the population is infinite (i.e. the finite population correction is being disregarded). In other words, it is assumed that the sampling effort is low and equal across all age classes, but this is not so. The inner rings will always be naturally better represented in any set of boards than the outer rings. The effect of not taking that finite population correction into account is that the variance from the lower age classes has a bigger impact on the total variance than it should. Given that the variance around these age classes is less than that of older classes, the total variance could be slightly underestimated and therefore the 5th percentile overestimated, particularly for the strength property. This is exactly what the comparison between the values for the whole sample (Table 2) and the results from the simulation (Table 6) for Scots pine suggests. This is an issue that needs to be addressed in the future.

Despite the aforementioned, it is reassuring that the simulations were generally consistent with the values obtained in the empirical analysis and the approach was able to capture the changes in the values of the GDPs throughout the age range studied. This being said, caution needs to be observed when using these results because they could unfortunately not be validated. In this respect, a slight bias in the predicted GDPs may lead to the wrong strength class. As an example, the simulated E_{PB} for Scots pine across age classes seems somehow larger than it should be. In spite of that, it is the opinion of the authors that the developed approach for grading will still be valuable for decision making as the predicted strength classes for different cambial ages could be compared in relative terms. It is also important to acknowledge the difficulties to carry out a proper validation exercise to test the accuracy and precision of the approach. This would require stands of different ages in a given area to be harvested, their timber graded and the resulting strength classes compared with those of the predictions from the current approach for those ages using stands grown to the current nominal rotation age, which is hardly achievable without the agreement of researchers, forest managers and the industry.

The study showed that both Scots pine and larch can contribute to the diversification of the construction timber supply in Ireland. The two species could play an important role under continuous cover forestry management. This silvicultural regime could improve the timber quality of logs as the result of retaining trees to older ages that will also benefit from a reduction in the number of knots, particularly in the case of Scots pine and larch that lose branches easily by self-pruning (Macdonald *et al.*, 2010). Increasing the quality of the raw material will allow the Irish forest sector to provide material competing with imports from Scandinavia and central Europe for structural applications that require higher mechanical performance.

Conclusions

This paper provides new information on the potential of Scots pine and larch grown in Ireland for the production of structural timber to diversify the national timber resource. The results showed that timber from these two species meets the GDPs requirements for use in construction, achieving 100 per cent yields of the strength class most commonly used in Ireland. In the absence of more knowledge about the GDPs under different rotation lengths, this study based on the intra-tree variation in wood properties is a good approximation to inform forest managers and policy makers on the effects of different rotation lengths on the timber properties. Our results found that logs with cambial ages of 40 years for Scots pine produce high yields of structural timber up to C22, whereas 30 years is enough for larch up to C24 strength class. Given the relatively short growing period required, and the timber properties observed, both Scots pine and larch are species that could contribute to the diversification of the timber resources in Ireland. Results can be applied in the planning and management of these two species as well as sorting timber for different end uses.

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Supplementary data

The following supplementary material is available at *Forestry* online and contains a detailed description of the destructive tests carried out according to the standard EN408 (CEN, 2012) as well as the adjustments carried out to the reference conditions as given in EN384 (CEN, 2018) and the differences between single and grade combinations.

Supplementary data are available at *Forestry* online.

Conflict of interest statement

Non declared.

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Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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