Juvenile wood in Irish grown Sitka spruce and the impact of rotation length

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Abstract
The impact of rotation length on the level of juvenile wood in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland was investigated. Mean density was 539 kg/m^3 at the first growth ring, rising to 558 kg/m^3 in the second, and thereafter declining to 384 kg/m^3. Demarcation between juvenile and mature wood was assumed to occur at growth ring 14, where the mean density was lowest. The proportion of juvenile wood was then estimated for Sitka spruce of yield class 24, and was found to substantially decline with age, from 30.3% at age 30 to 13.7% by age 46 (tabulated age of maximum mean annual increment). The implications of the results for rotation length policy are discussed.

Keywords: Juvenile wood, wood density, rotation length, timber quality, Sitka spruce.

Introduction
Introduced to Ireland in 1835 (Joyce and OCarroll 2002), Sitka spruce (*Picea sitchensis* (Bong.) Carr.) accounts for over 60% of the area of the forest estate. In Coillte (the commercial state forestry company) plantations, the species has a mean yield class of 17 m^{3}ha^{-1}an^{-1} (Horgan et al. 2003). The improvement in the quality of land afforested in Ireland since 1990 has meant that the predicted yield class of Sitka spruce planted since then exceeds 18 m^{3}ha^{-1}an^{-1} and sites more recently planted by Coillte have an average yield class of 20 m^{3}ha^{-1}an^{-1} (ibid). As it has proved to be a highly versatile and productive species, it is likely that Sitka spruce will remain the principal softwood species in Ireland.

The very fast rate of growth of Sitka spruce has lead to the species being grown to very short rotations. For example, it is the general practice within Coillte and most of the private sector to clearfell Sitka spruce at 80% of the age of maximum mean annual volume increment (MMAI). More recently forestry investment companies have advocated 30-year rotations which represent a further reduction in the age of MMAI (Anon. 2000).

The fast growth rate of the species, coupled with short rotations leads to high proportions of juvenile wood (Mitchell and Denne 1997). Juvenile wood, which is the wood located closest to the central part of a conifer stem, differs considerably from mature wood (Panshin and de Zeeuw 1980). The properties of juvenile wood are generally regarded as inferior to those of mature wood (Larson 1969; Harvald and Olesen 1987; Zobel and van Buijtenen 1989). These include large microfibril angles, short tracheids, high longitudinal shrinkage during drying (Zobel 1975) and, in some

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species, lower density (Walker and Nakada 1999). The combination of these properties means that juvenile wood usually has poor strength, with reductions of over 100% recorded in modulus of elasticity and modulus of rupture in juvenile compared with mature wood of loblolly pine (McAlister and Clark 1991). The large microfibril angle in juvenile wood coupled with its tendency to exhibit spiral grain also renders it unstable (Zobel and Sprague 1998).

The timber of Sitka spruce is suitable for a wide variety of end-uses such as structural material, fencing, palletwood and pulpwood and is the mainstay of the current wood processing industry in Ireland (DAFF 1996). There has been concern however, that the strength properties of much of this plantation-grown Sitka spruce may be on the borderline of acceptability for structural performance (Mitchell and Denne 1997).

This paper describes a study on juvenile wood in Irish grown Sitka spruce. The objectives of the study were to:

a) identify the juvenile wood zone in Sitka spruce;
b) use this information to determine the impact of rotation length on the proportion of juvenile wood in a final crop.

Background

Although juvenile wood is present in all trees, the extent of the juvenile wood zone varies, depending on species and environmental factors. Haygreen and Bowyer (1982) applied the term juvenile wood to the wood found in the first 5-25 growth rings. Walker and Nakada (1999) indicate that for radiata pine (*Pinus radiata*) and sugi (*Cryptomeria japonica*) from plantation forests, it is convenient to refer to the first 10 growth rings as juvenile wood. Cown (1992) also defined juvenile wood in radiata pine as the wood within 10 growth rings of the pith. The juvenile wood zone in Sitka spruce is considered by Mitchell and Denne (1997) to include the nine growth rings from the pith while Brazier and Mobbs (1993) referred to the first 12 growth rings from pith as juvenile wood. However, there is no clear demarcation line between juvenile and mature wood because wood properties change gradually, often taking place over a number of years, which form a transition zone (Zobel and Sprague 1998). Furthermore, the location and extent of the transition zones differs for the different wood properties such as density, microfibril angle and tracheid length. In the case of loblolly pine (*Pinus taeda* L.), Szymanksi and Tauer (1991) reported that the transition period between juvenile wood and mature wood can last six years, while Zobel and van Buijtenen (1989) believed it to be five years.

Despite the difficulties associated with identifying the exact extent of the juvenile wood zone, a number of researchers have attempted to do so. Most commonly, density differences have been used to define the juvenile wood zone (Zobel and van Buijtenen 1989). For example, for Sitka spruce, Evertsen (1988) estimated the demarcation line between juvenile wood and mature wood to be the 16th growth ring from the pith, while Schaible and Gawn (1989) estimated it to be the 12th ring.

In their work on loblolly pine, Loo et al. (1985) used regression analysis to determine the age of transition from juvenile wood to mature wood. This involved successively regressing density on age for 'juvenile' and 'mature' parts of the stem, based on an arbitrary cut-off point of age 4 and less for the juvenile zone, and greater than age four for the mature zone. This cut-off point was moved upwards in two-year intervals. The age of transition was estimated as the age at which the mature wood regression of density on age provided the best fit (defined as the smallest error sum of squares) (Loo et al. 1985). A similar approach was used by Szymanski and Tauer (1991).

Materials and methods

The study area

The trees selected were from a stand of pure Sitka spruce in a Coillte-owned forest in Co Wicklow. The stand was at an elevation of 175 m, on a free-draining acid brown earth, on a gently sloping, south-east facing site. The stand was planted in 1957 at 1.82 m spacing using a Washington seed origin. It was thinned in 1976 by removing one line in three. Subsequent selective thinnings were carried out in 1984 and 1996. The second thinning was delayed due to poor markets for pulpwood in the late 1970s and early 1980s. The estimated yield class (YC) for the stand was 24 m^3 $ha^{-1}an^{-1}$.

Sampling

In selecting trees for study, the aim was to choose trees as similar in height as possible. The estimated top height for a 42-year-old, YC 24 Sitka spruce stand is 29.5 m (Hamilton and Christie 1971). Nine trees whose heights were within 5% of this height were selected for study. Diameter at breast height ranged from 38.5 to 45.1 cm.

After the trees were identified and before they were felled, the northern and southern cardinal points and tree number were marked on the stem at breast height (1.3 m above ground level). Once the trees had been felled a 40 mm disk was cut from the stem at breast height. Disks were numbered from 1 to 9 and the north-south, west-east axes were marked on the upper face of each disk.

Density measurement

Disks were stored and room dried, from March to August, 2000. In addition, they were prepared for density measurements by planing the unmarked face of each disk. They were sent to the Forestry Commission, Northern Research Station at Roslin Scotland in September 2000 for density measurement.

Density was assessed using computer-aided tomography. The scanner used was a Siemens Somatom™ CR. The raw output of the scanner is in Hounsfield units. Nominal values of -1024 and 0 are representative of water and air respectively. Based on this calibration, the readings from the scanner were converted to kg/m^3. Each output picture from the scanner was interogated by a specially written computer programme in Mathcad®. The operator marked the position of the disk pith and slices were extracted across the disk in north-south and west-east directions. The programme then fitted a cubic spline to the individual data points, which were at 2 mm spacing. The peaks in the cubic spline fit were then determined and were regarded as the end of each growth period (latewood). The mean, maximum and minimum density between each peak, the distance between peaks (ring width) and the distance of the centre of the ring from the pith were established and the information from each of the slices exported to a spreadsheet ready for analysis and archiving.

Minimum, maximum and mean densities (kg/m^3) for each growth ring, for compass directions north-south and west-east, were recorded. In the results section that follows the data from the various compass directions are considered replications and are averaged for each growth ring. Only data from rings 1 to 26 were used, for two reasons:

1. densities fluctuated widely at the edges of the disks where the growth rings were narrow, leading to problems with the scanner resolution;
2. as some of the tree disks split on drying, it was not possible to record densities for all growth rings to the outermost ring. Thus in order to have a consistent number of readings for all of the disks, the number of growth rings used was confined to 26.

Determination of the extent of the juvenile wood zone

In order to consistently determine the point of demarcation between juvenile and mature wood the assumption was made that the point of demarcation between the two occurred at the ring number where the mean ring density reached a minimum. In order to objectively determine the ring of mean minimum ring density, a number of empirical regressions were fit to the combined tree data, based on polynomials in ring number. The regression that provided the best fit between density and ring number was chosen. The minimum value of the function (and its associated number of years) was then obtained by differentiation.

Impact of rotation length on percentage juvenile wood content in a stand of Sitka spruce (yield class 24)

To determine the influence of rotation length on juvenile wood content, three ages were chosen for Sitka spruce (yield class 24):

a) 30 years – the rotation length recommended for this yield class by groups managing forestry investment fund portfolios in Ireland (Anon. 2000);
b) 37 years – the rotation length which represents 80% of age of MMAI and is commonly used by Coillte for Sitka spruce;
c) 46 years – the rotation length which represents the age of MMAI.

The yield model with characteristics closest to the stand was selected: Yield Table 61, the yield table for YC 24 Sitka spruce, planted at 1.7 m spacing with intermediate thinning (Hamilton and Christie 1971). The top heights and mean diameter breast height (dbh) overbark values for a Sitka spruce stand at each of the rotations listed above were obtained. The yield table also gave a mean volume per tree for each of the three rotations under consideration. The dbh and volume estimates were then converted to underbark values using conversion factors outlined in Hamilton (1975). All calculations were based on the tabulated yield model data, with information from the sample used to indicate where the juvenile wood ended.

To estimate the volume of juvenile wood for each rotation, it was assumed that the juvenile wood zone was cylindrical. While some studies show that the juvenile wood zone tapers slightly from the base of the tree upwards, a number of studies which have examined proportions of juvenile wood to mature wood have used the simplifying assumption that the juvenile wood zone forms a cylindrical column with the pith as its centre (Walker and Butterfield 1995, Zobel and Sprague 1998). The juvenile wood cylinder was assumed to extend from the base of the tree to a top underbark diameter equal to the diameter of the juvenile wood zone. Thereafter the remaining wood in the tree was assumed to be juvenile to the top 7 cm diameter (Section 2, Figure 1). Yield Table 61 showed that the mean dbh for a YC 24 Sitka spruce stand at the age/ring number at which the juvenile wood zone ended - 14 years - was 10.8 cm overbark, 10.0 cm underbark (Section 1, Figure 1). Hamilton's tables (1975) gave the estimated height to the underbark diameter equal to the diameter of the juvenile wood zone and the height to 7 cm top diameter. The total volume of juvenile wood in the two sections was estimated from:

$$Volume = \frac{\pi D^2 h}{4} + \frac{\pi}{12}(D^2 + Dd + d^2)H$$

where
D = underbark diameter of the juvenile wood core (10 cm);
H = height from base of tree to point where diameter of tree is D;
d = diameter of top of frustum (7 cm);
h = height from point where diameter is D to point where diameter is d.

Results

The radial trend in density was estimated based on the nine sample disks. Density, when plotted against ring number from pith (Figure 2), declined from the second ring to rings 13–14, after which it rose slightly.

Mean density was regressed on polynomials in ring number, a good fit (R^2 96% $p \leq 0.0001$) was obtained using a three-degree model.

$$\textit{Mean density (MD) (kg/m}^3\textit{)} = 598.87 - 37.08(RN) + 2.06(RN^2) - 0.03(RN^3)$$

where:
RN = ring number;
RN^2 = square of the ring number;
RN^3= cube of the ring number.

The predicted density values for the ring numbers were plotted against the observed density values (Figure 2).

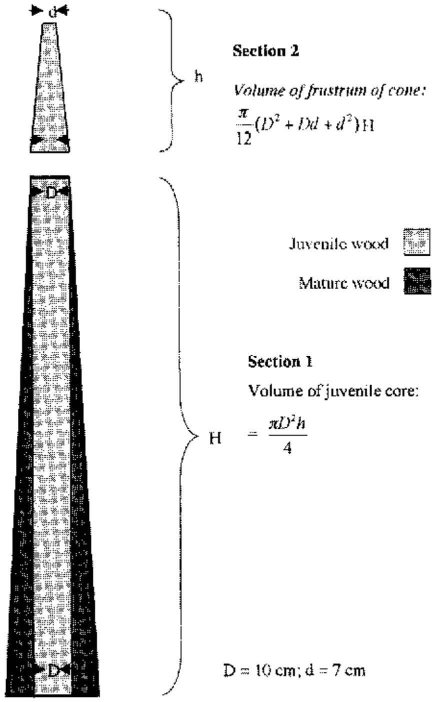

***Figure 1**: Assumptions made in calculating the amount juvenile wood Sitka spruce stems.*

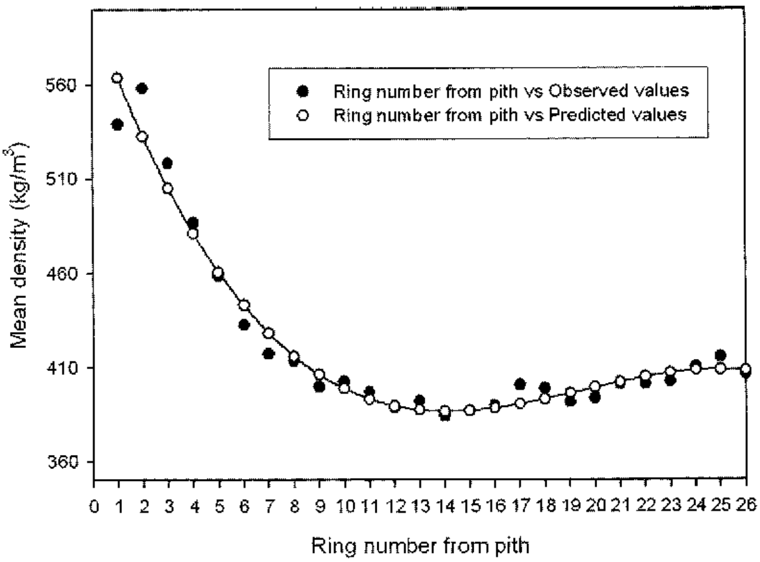

***Figure 2**: Observed and predicted mean density versus ring number.*

To determine the minimum point of the equation, the first derivative with respect to ring number was:

$$\frac{dMD}{dR} = -37.08 + 4.116RN - 0.10551\,RN^2$$

To obtain the minimum point on the curve the function was first set equal to zero. The roots were ring numbers 14.04 and 24.96. To confirm that 14.04 was the minimum point of the curve, the second derivative was found to be 3.905. As this value is positive it showed that 14.04 was the minimum point on the curve. This led to the result that the juvenile wood zone ended at ring 14 for the Sitka spruce examined.

Proportionate juvenile wood in Sitka spruce stands of varying ages

Using the approach outlined in Materials and methods, the total volume of juvenile wood per tree was calculated for the three rotations (Table 1).

The results show that the percentage of juvenile wood in a 30 year old Sitka spruce stand of yield class 24 was 30.3%. At 37 years it was 20.3%, while at 46 years the average juvenile wood content was 13.7%.

Discussion

To accurately assess trends in juvenile wood, all the main characteristics that define juvenile wood would need to be measured, in particular wood density, microfibril angle and fibre length. The scope of this study allowed for the measurement of only one property. Thus, wood density was chosen, because density trends have been most commonly used to define the juvenile wood zone (Zobel and van Buijtenen 1989). In addition, a rapid and reliable method was available to measure wood density.

The radial trend in density recorded in this study is in agreement with that recorded for Sitka spruce in other studies. Brazier (1967), O'Sullivan (1976), Harvald and Olesen (1987), Petty et al. (1990) and Mitchell and Denne (1997) all found high densities close to the pith in Sitka spruce. Specifically, Harvald and

***Table 1**. Percentage juvenile wood in Sitka spruce at three ages (yield class=24 m^3 ha^{-1} an^{-1}).*

	ROTATION LENGTH YEARS		
	30	*37*	*46*
Top height (m)[1]	*22.0*	*26.5*	*31.0*
Mean dbh overbark (cm)[1]	*25.4*	*32.0*	*39.3*
Mean dbh underbark (cm)[2]	*24.3*	*30.7*	*37.8*
Mean tree volume underbark (m^3)[2]	*0.48*	*0.93*	*1.63*
Volume of juvenile wood per tree (m^3)	*0.15*	*0.19*	*0.22*
Juvenile wood (%)	*30.3*	*20.3*	*13.7*

[1] Hamilton and Christie (1971) [2] Hamilton (1975)

Olesen (1987) found, on one site in Denmark, that the "basic density decreased with increasing ring number until ring 17 where it seemed to stabilise" when measured in the tree at a height of 1.3 m. At another site, they found that the decrease in basic density ceased at rings 10-11, followed by an increase in density until stabilisation was reached between ring 16 and 25. Petty et al. (1990) found that, while density was approximately 400 kg/m^3 in the five growth rings close to the pith, the average density in rings 16 to 20 was approximately 350 kg/m^3. O'Sullivan (1976) found that density decreased to ring 10, reaching a minimum between ring 10 and 15, and gradually increased thereafter. In this study, wood density was found to be lowest at ring 14. In contrast, Mitchell and Denne (1987) suggested that the mature wood zone began at ring 10, Evertsen (1988) selected ring 16, while the point of demarcation between juvenile wood and mature wood was identified at growth ring 12 by Schaible and Gawn (1989).

The pith-outwards radial trend in density in Sitka spruce differs from that of many conifers. In general hard pines have a rather uniform pattern of low density at the pith, a rapidly increasing density through the juvenile period followed by a series of annual rings that have an essentially constant density, albeit fluctuating from year to year (Zobel and van Buijtenen 1989). In contrast, the general rule for *Abies, Picea* and *Tsuga* species is a high density near the pith with a decrease for some rings followed by a levelling off or a moderate increase toward the bark (ibid).

Regression analysis, combined with finding the minimum point of the function it provided, were used to demarcate the boundary between juvenile wood and mature wood in this study. While similar approaches have been elsewhere (Loo et al. 1985; Szymanski and Tauer 1991), we are not aware of the specific approach employed in this study having been used previously. In the study by Loo et al. (1985) of juvenile wood in loblolly pine, density data were regressed against age/ring number data to determine the end of the juvenile wood zone. Szymanski and Tauer (1991) used a similar approach to compare the age of transition from juvenile to mature wood specific gravity in provenances of loblolly pine.

The impact of rotation lengths on the percentage of juvenile wood in a Sitka spruce stand

The results show that there is a substantial difference in the proportion of juvenile wood in a Sitka spruce stand grown to different rotations. We estimate that a high yielding Sitka spruce stand, if felled at 30 years, will comprise about 30% juvenile wood. If felling is delayed for seven years or sixteen years the proportion of juvenile wood in the stand will be considerably lower at 20% and 14% respectively, with the amount of juvenile wood at 30 years over twice that at 46 years. This finding supports the view that extending rotation length is a way to improve overall wood quality (Brazier 1986; Simons Strategic Services Division 1991; Zobel and Sprague 1998). Indeed, Schaible and Gawn (1989) found in a study of the strength of timber from unthinned stands of Sitka spruce (YC 20 - 24) that if rotations were extended to a point where top height was greater than 19.3 m, the volume of juvenile wood as a percentage of total tree volume, could be reduced by an equivalent of 4-5% for every metre gained in top height. However, sawing method will strongly influence how much of the additional mature wood is converted to sawnwood. For example, where chipper canters are used it is likely that much of the mature wood will be chipped.

Conclusions

The debate on juvenile wood and wood quality has been underway for a considerable time in all countries with a strong dependence on fast growing plantations. Growers and processors in all regions acknowledge that juvenile wood is undesirable for products requiring stability and strength. Zobel and Sprague (1998) indicate that the presence of juvenile wood is especially critical to the quality of solid wood products. Indeed, Senft et al. (1985) argue that "unless accounted for in some manner, the effect of juvenile wood on strength and performance of future wood products could be disastrous". The issue of juvenile wood content is especially critical in Ireland because of the processing sector's reliance on fast-growing Sitka spruce. Even though the juvenile wood zone in Sitka spruce is denser on average that the mature wood zone, it shares the other quality-lowering features of juvenile wood from other species including large microfibril angle (Treacy et al. 2000) and short tracheids (Ward and Gardiner 1976).

Concerns regarding the quality of high yielding Sitka spruce were expressed in a report on the sawmilling industry in Ireland (Simons Strategic Services Division 1991). It also indicated, however, that high yielding Sitka spruce could provide excellent raw material for the sawmilling sector, provided that rotations were not excessively short. It also stated that the policy of using reduced rotations may satisfy the fibre and low quality sawlog market but will not bring Sitka spruce into the high quality end of the market.

Sawlog production and processing in Ireland need to be quality driven to increase domestic and export market share. The onus will be on sawmills to continue improving quality, which will need to be matched by an increase in quality of the raw material. This will be necessary to ensure that domestic sawlog material is in a position to compete with exports from countries such as Sweden, where 40% of all sawlogs are older than 100 years (Simons Strategic Services Division 1991). On the clear evidence that the presence of juvenile wood limits the end use potential of solid wood products, it is perhaps time to reconsider the policy of managing stands in Ireland for short rotations and consider reverting over time to forest rotation ages based on MMAI, or longer, with adjustments to these based on biological and environmental reasons.

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