Non-destructive evaluation of Scots pine (*Pinus sylvestris* L.) to determine timber quality following conversion to continuous cover forestry systems

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Abstract

There is currently a policy shift within the UK towards transformation of forests to continuous cover forest (CCF) systems, which are expected to rely on natural regeneration and increased use of native species, such as Scots pine. The impact of this policy on future timber quality is difficult to determine using conventional destructive testing, due to the rarity of mature CCF stands. Whether non-destructive acoustic evaluation (NDE) techniques using a dedicated standing tree tool (i.e. the Director ST300) can be justified in assessing timber quality in Scots pine, is not yet clear. The background literature to these issues is discussed in Chapter 1. Chapter 2 reports the results of a study designed to validate the use of the ST300 to predict the intrinsic mechanical properties of Scots pine. Acoustic testing was carried out on Scots pine in two even-aged plantations (Mount High and Seafield Estate) and one naturally regenerated stand (Glengarry), in order to validate the use of the ST300 to predict the strength properties of Scots pine, and then to compare these properties in timber from plantation-grown and naturally regenerated stands. One hundred trees were acoustically assessed at Mount High and Seafield Estate, of which 12 trees were felled (Mount High) for cutting into small clear specimens. These were then subjected to static 3-point bending tests. There was a good correlation between ST300 acoustic velocity and modulus of elasticity (MoE, r^2=0.527) and an even better correlation between acoustic velocity and modulus of rupture (MoR, r^2=0.589). Forty nine Scots pine regenerants from the fenced, naturally regenerated stand were also acoustically assessed, and data from all three sites were corrected for age. *T*-tests on the age-corrected mean MoE and MoR values indicated that, at age 60, timber from the naturally regenerated trees showed small but statistically significant improvements in mechanical properties over timber from the plantation-grown trees ($P<0.05$). Replicated, randomised long-term silvicultural trials are required to justify wholesale conversion to CCF.

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TABLE OF CONTENTS

CHAPTER ONE

Wood properties and non-destructive evaluation of logs and standing trees using acoustics and its potential for assessing timber quality in the native Scots pine (*Pinus sylvestris* L.) resource: a literature review

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Overview

In this section I aim to deliver a selective review of the current knowledge about the theory and application of non-destructive acoustic evaluation of logs, sawn timber and standing trees to determine intrinsic wood properties, and its implications for the forest industries. A review of wood structure and properties is presented, together with an overview of factors that affect the strength and elastic properties of timber. I then look at the effect of silvicultural practices on wood properties, with particular reference to the current trend for the restructuring and transformation of even-aged stands to management under continuous cover forestry (CCF) silvicultural systems, and how this might be expected to influence timber quality in Scots pine. Finally, the rationale for the current study and the aims of this thesis are outlined as an introduction to the experimental work presented in Chapter Two.

Background

Due to its natural origin wood exhibits wide variability in both its structure and appearance, resulting in an equally wide range of properties affecting its suitability for various end-uses. This range of variation occurs between species, between trees of the same species and also within a single tree (Dinwoodie, 2000). There is thus a need to control the quality of sawn timber for certain markets, particularly construction, where safety and performance are critical, but also for other markets such as pulp and joinery. Since many intrinsic mechanical properties of timber, such as strength and stiffness, cannot be accurately assessed by visual grading – the traditional approach to classifying timber for construction purposes – various mechanical grading techniques have been developed in the past few decades which are better able to predict wood properties. However, such techniques are only applied after the processing stage, which is expensive and often results in wastage and reduced volume-recovery of the potentially higher-value structural timber, due to the high rejection rates. The need for improved quality control and assessment of timber prior to the sawmill stage has seen the adoption of non-destructive evaluation (NDE) techniques using acoustics. Such methods, developed over the last 30 years or so, were originally used by the wood-using industries for the assessment of wood products such as panelling and veneers, but latterly have been shown to improve log segregation and value-recovery across the supply chain (Sandoz, 1993; Mackenzie *et al.* 2005; Carter *et al.* 2005).

In Scotland, a move towards managing forests for multiple uses under CCF systems, which might be expected to influence the quality and quantity of future timber supplies, coupled with low timber prices and the forthcoming peak of the softwood production cycle in 2020, has highlighted the need to assess the native Scots pine resource with a view to enhancing its value by increased penetration of the high-value construction sector (Macdonald and Gardiner, 2005a). Because it is a new concept in the UK, our current knowledge of the impact of CCF systems on timber quality here is limited, with most information coming from studies conducted in Europe. Consequently, the closest we have to fully developed CCF stands in Scotland which have arisen as a result of natural regeneration are the native pinewoods. As these are a protected resource with a high conservation value it is not possible to fell trees to assess timber quality, indicating the need for non-destructive evaluation techniques for use on standing trees. With this in mind, acoustic testing will be a valuable assessment technique with an important role in helping to build an accurate picture of the extent and quality of the Scots pine resource in Scotland, and for measuring the effects on timber quality of changes in management and silvicultural interventions following transformation to CCF systems.

1.0 Wood structure and properties

1.1 Cellular structure of wood

Wood cells perform three main functions within the tree: structural support, conduction of minerals and water and food storage. In softwoods, the dual functions of support and storage are performed by vertically-aligned cells known as tracheids, which constitute 95% of the total cells in the tree, while most of the remaining cells are storage cells, or parenchyma. Tracheids are approximately 100 times longer than their diameter, rectangular in cross-section with hollow centres (lumens). The primary components of tracheid cell walls are cellulose, hemicellulose and lignin which make up 40-50%, 20-35% and 15-35% of the dry mass of cell wall material respectively, plus minor components such as tannins, volatile oils and resins, known as extractives (Panshin and de Zeeuw, 1980). Cellulose molecules are aggregated into long crystalline strands, or microfibrils, embedded in a non-crystalline matrix composed of lignin, hemicellulose and non-crystalline, or amorphous cellulose, the microfibrils conferring tensile strength and the matrix lateral stiffness and toughness (Desch and Dinwoodie, 1996). Water can penetrate the cell wall structure through a series of long and slender cavities, or microcapillaries (Panshin and de Zeeuw, 1980).

The millions of microfibrils in normal tracheid cell walls are arranged in a multi-laminate composite structure in different layers; a thin primary wall and a thicker, 3-layered secondary wall (Figure 1). Each layer in the secondary wall has a characteristic alignment of the microfibrils within it. In the S_1 layer (which constitutes <10% of wall thickness) they are parallel to the cell axis in two distinct spirals, whereas in the S_2 layer (comprising 60-90% of total cell wall thickness) they are oriented in a spiral at an angle of 10-30° to the vertical cell axis. The microfibrils in the S_3 layer (1% of wall thickness) are arranged in a similar pattern to those in the S_1 layer. It is the angle of orientation of microfibrils in the S_2 layer relative to the vertical cell axis (microfibril angle, or MFA) that is the single biggest determinant of wood properties and timber performance such as strength, stiffness and dimensional stability on drying (Desch and Dinwoodie, 1996; Huang *et al.* 2003). MFA varies widely within and between trees of the same species, and between species, and it is widely accepted that there is an inverse relationship between MFA and tracheid length within a sample (Barnett and Bonham, 2004; Dinwoodie, 2000). MFA also decreases from pith to bark i.e. with cambial age, which reflects the need for increased flexibility in saplings and young trees to enable them to withstand strong winds, since high MFA is associated with low stiffness (Barnett and Bonham, 2004). Additionally, MFA decreases with transition from the thin-walled, larger-diameter early wood tracheids to the thicker-walled, stiffer and denser late wood tracheids, as the emphasis changes during the growing season from conduction to support. In temperate regions with well-defined growing seasons, softwood species will have equally well-defined growth rings (Desch and Dinwoodie, 1996). Alteyrac *et al.* (2006) modelled the effect of MFA and ring density on the strength properties of small clear samples of black spruce (*Picea mariana* (Mill.) B.S.P.), and demonstrated a strong negative correlation between MFA and stiffness, or modulus of elasticity (MoE), but with no effect of ring density, whereas most of the variation in strength, or modulus of rupture (MoR) could be accounted for by a combination of MFA (50% of the variation) and ring density (16%). They also noted that MFA and ring density vary with cambial age from pith to bark, as do the mechanical strength properties (MoE and MoR).

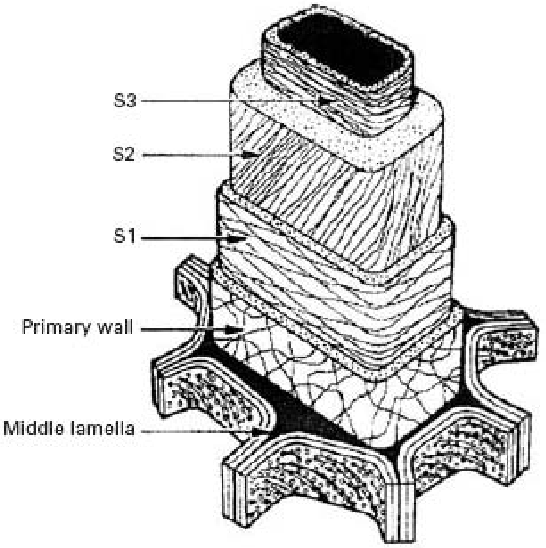

Fig. 1: Diagrammatic representation of the cell wall of a softwood tracheid showing the general orientation of microfibrils in the primary and secondary cell wall layers. *After Barnett and Bonham (2004).*

1.2 Variation in wood properties

The variability of wood accounts for considerable variation in its performance as a structural material, and this has systematic, genetic and environmental causes, explained briefly in the following sections, which also includes a brief discussion of reaction wood.

1.2.1 Systematic variation

In a single tree, features such as tracheid length and diameter, cell wall thickness, MFA and grain angle show systematic variation with cambial age and height in the tree stem. This results in the formation of a core of wood, known as juvenile wood or corewood, which has certain characteristics which negatively affect its mechanical properties. These can be summarised as follows (Panshin and de Zeeuw, 1980; Walker and Nakada, 1999; Huang *et al.* 2003; Dinwoodie, 2000):

- Low density and stiffness
- High moisture content
- Lower percentage of cellulose
- Large MFA in the S_2 layer
- Low dimensional stability
- Greater proportion of compression wood
- Spiral grain
- Short tracheids.

Juvenile wood is usually defined as comprising of the first 10-20 growth rings from the pith, though the point at which the different characteristics are deemed to have reached maturity varies depending on the characteristic, hence it is the faster rate of change of any characteristic in the earlier growth rings which tends to define juvenile wood (Dinwoodie, 2000). Since the above characteristics are all intrinsic qualities of the wood it is axiomatic that a substantial quantity of juvenile wood will be converted into timber, with serious economic consequences for the wood processing industry. The problem is exacerbated by the shift in silvicultural practice to shorter rotations for fast-grown softwoods (Walker and Nakada, 1999).

1.2.2 Genetic variation

The mechanical properties of wood vary between species as a result of genetically determined differences in cell wall thickness and distribution of cell types (Dinwoodie, 2000). But there is also considerable genetic variation within a single species, with trees of different provenance displaying a wide variation in wood properties, indicating that selection of superior seed sources or tree breeding programmes have great potential to improve timber quality (Panshin and de Zeeuw, 1980). Many tree characteristics, such as specific gravity, tracheid length and latewood cell wall thickness, show a large degree of heritability and can be selected for in tree breeding programmes. Even traits with low heritability, such as earlywood cell wall thickness and stem form, can still provide opportunities for large improvements in wood quality if they show sufficient natural variation (Haygreen and Bowyer, 1996). In species where wood density is negatively correlated with growth rate, such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.), selection for concurrent improvements in density and growth rate has in the past proved problematic, though recent genetic research into other quality indicators, such as MFA and grain angle, is now being incorporated into tree breeding programmes (Macdonald and Hubert, 2002).

1.2.3 Environmental variation

Environmental factors and silvicultural interventions such as climate, site conditions, thinnings and initial spacing will also affect wood properties, as these affect growth rate which in turn affects density and cell length, and thus the strength properties of the timber (Desch and Dinwoodie, 1996). Generally in conifers, growth rate will influence the proportion of late wood to early wood, as the amount of late wood remains fairly constant. This means that there is a general tendency towards a larger ring width and thus a higher proportion of early wood for faster grown trees, which will negatively influence both density and stiffness (Desch and Dinwoodie, 1996). Increased competition arising from the high stocking densities associated with natural regeneration will lead to slower growth in the years following establishment, which will negatively influence branching and the size of the juvenile core, and thus positively affect timber quality (Macdonald and Hubert, 2002).

1.2.4 Reaction wood

Reaction wood is the term used to describe the abnormal tissue which forms in leaning trees and heavy branches. In conifers it is called compression wood, and in hardwoods it is called tension wood. Reaction wood has different characteristics from normal wood and is a significant problem for the wood processing industry (Desch and Dinwoodie, 1996). Compression wood develops on the underside of leaning stems, on the lower part of trees growing on slopes, or as a reaction to wind-loading, as trees attempt to correct themselves to a more normal growth pattern: to the true vertical in the case of stems, or to counter excessive weight and retain branch angle, though the exact mechanism of its formation is not fully understood. Typical characteristics of compression wood include (Haygreen and Bowyer, 1996; Desch and Dinwoodie, 1996):

- Shorter tracheids (up to 30% shorter in some cases)
- Thicker cell walls and more rounded cell cross-section with intracellular spaces
- Increased lignin content of cell walls
- Abnormally high MFA in S_2 layer and absence of S_3 layer
- Pronounced longitudinal shrinkage / drying distortion
- Greater proportion of late wood and increased density
- No increase in strength on drying
- Brittleness and with lower MoE than normal wood – liable to fail under impact without warning.

Problems with the dimensional stability of compression wood will be exacerbated if sawn timber contains both normal and compression wood, with the large variation in MFA leading to distortion on drying due to differential shrinkage (Barnett and Bonham, 2004).

1.3 The concept of wood quality

The term ‘timber quality’ is assigned different meanings across the forestry and wood-using industries, and as such is difficult to define in a single objective statement. There is general agreement, however, that the relative importance of factors which determine timber quality is dependent on the intended end-use of the converted logs (Macdonald and Hubert, 2002; Haygreen and Bowyer, 1996; Panshin and de Zeeuw, 1980). For structural applications the principal criteria for performance and safety are dimensions, strength (MoR), stiffness (MoE) and dimensional stability on drying (Macdonald and Gardiner, 2005b; Macdonald and Hubert, 2002).

1.3.1 Mechanical strength grading

Structural applications require timber that meets certain minimum strength and stiffness standards. Since MoR and MoE are intrinsic properties of wood, they cannot be accurately predicted by visual assessment of external characteristics such as knot frequency and size or stem straightness indices. Consequently, strength properties are normally determined in the UK by machine stress grading, usually a bending machine which assesses the local MoE of a piece of timber perpendicular to the grain along its length, either by measuring the deflection under a fixed load or the applied load to give a fixed deflection. Because of the strong direct relationship between MoE and MoR the strength can be predicted from these MoE measurements. The process sorts timber into strength 'classes' containing similarly-graded 'species and grade' combinations. Under European Standard EN 338: '*Structural Timber – Strength Classes*', introduced in 1995, conifers are graded into 9 strength classes from C14 (weakest) to C40 (strongest), where the number is equivalent to the characteristic strength value for the class (Macdonald and Hubert, 2002). Recently there has been a move towards grading using X-ray technology in some countries (Benham *et al.* 2003), and the parallel development of acoustic NDE techniques.

1.3.2 Mechanical properties of wood

It is important to distinguish between the different types of strength properties because these can vary across a single sample: wood that has a high compressive strength may exhibit low shear strength, for example (Haygreen and Bowyer, 1996). Strength in a particular plane is determined by the deflection under an applied load, and up to a certain defined limit (the limit of proportionality) deflection will be proportional to the load applied (Hooke's law of elasticity). Above this limit applied loads will result in some permanent deformation of the sample. Because sample size is important, loads are expressed in terms of cross-sectional area, thus:

Stress (N/mm^2) = Load (N) / Cross-sectional Area (mm^2)

The amount of deformation under a load is expressed in terms of the original length:

Strain = Deformation / Original Length

Hence the modulus of elasticity (MoE or stiffness) is expressed as:

MoE (N/mm^2) = Stress / Strain (also expressed in Pascals: 1 N/mm^2=1 Pa)

and modulus of rupture (MoR, or strength) is:

MoR (N/mm^2) = Maximum stress at failure

(Haygreen and Bowyer, 1996; Panshin and de Zeeuw, 1980; Dinwoodie, 2000; Desch and Dinwoodie, 1996).

MoR is calculated from the maximum load at failure in a bending test, and is actually the equivalent stress in the extreme fibres at the point of failure. In a 3-point bending test MoR is given by:

$$\text{MoR} = 3PL / 2bd^2 \qquad (1)$$

where P is the load (N), L is the span, (mm), b is the width (mm) and d the depth (mm). MoE values are also calculated in the same test using the following equation:

$$\text{MoE} = P'L^3 / 4\Delta' bd^3 \qquad (2)$$

where P' is the load (N), at the limit of proportionality, L is the span (mm), Δ' is the deflection (mm) at the limit of proportionality, b is the width (mm) and d is the depth (mm) (Desch and Dinwoodie, 1996). MoE is closely correlated with MoR for any particular species, thought to be the case due to both having a strong relationship with density rather than any causal factors (Dinwoodie, 2000).

Modulus of elasticity will vary depending on whether a body is subjected to compressive, tensile or shear stresses, with bending stresses resulting from a combination of all three, hence the importance of stating the specific strength property being measured. The variation in wood properties along the directions of different structural axes is known as *anisotropy*, and is the result of the non-uniform organisation of materials in the cell wall and also of the tracheids and their alignment in relation to the stem axes. This can result in wide variations in strength properties when measured parallel to or perpendicular to the grain, which affects the suitability of wood for various end-uses (Haygreen and Bowyer, 1996; Panshin and de Zeeuw, 1980; Dinwoodie, 2000; Desch and Dinwoodie, 1996).

2.0 Factors affecting the strength and stiffness of wood

The strength properties of wood vary widely due to a number of contributing factors, including moisture content, density, MFA in the S_2 layer, grain angle, the presence of knots or defects, the presence or absence of compression wood, proportion of juvenile wood and temperature (Dinwoodie, 2000). MFA, juvenile wood and compression wood have been discussed in the previous section; some of the other factors are discussed briefly below.

2.1 Moisture content

The moisture content of a wood sample strongly influences its mechanical properties, and is expressed as a percentage of the dry mass of the wood (Panshin and de Zeeuw, 1980). Water in wood is either contained in the cell lumens (free water) or chemically bonded to hydroxyl groups in the matrix of the cell wall (bound water). On drying, water is first removed from the cell cavities with no effect on wood properties. The point where no free water remains, leaving the cell wall saturated with bound water is called the fibre saturation point (FSP). This is important because removal of bound water will result in shrinkage, and also in a large non-linear increase in timber strength due to the closer proximity of the microfibrils and the strengthening of the hydroxyl bonds between them (Desch and Dinwoodie, 1996; Haygreen and Bowyer, 1996; Dinwoodie, 2000).

2.2 Density

Density (mass per unit volume at specified moisture content) is commonly cited as one of the most important factors influencing the strength properties of wood, specifically compression strength parallel to the grain, bending strength and hardness. Other strength properties such as tensile strength, shear strength, and impact resistance are less influenced by density than by the cellular structure of wood (Desch and Dinwoodie, 1996). The basic density or specific gravity (ratio of weight to an equal volume of water) of dry cell wall material is constant for all wood, with differences accounted for by the amount of void space (porosity) in relation to cell wall material and the amount of bound water in the cell wall. Generally in softwoods, density increases significantly from pith to bark and more moderately with height in the tree stem, though it is influenced by factors such as growth rate, the proportion of late wood, ring width, tree vitality, site conditions and genetics, with consequent effects on timber quality and strength properties (Dinwoodie, 2000; Haygreen and Bowyer, 1996). An increased growth rate is generally associated with lower wood density, though this may be less applicable in Scots pine, where growth rate and density have been shown to be independent, with density being more influenced by cambial age than by distance from the tree pith (Karenlampi and Riekkinen, 2004). Kennedy (1995) also noted the age effect on wood density, and speculated that the degree of shade-tolerance of a species might influence the time taken for the tree to achieve maximum height increment and begin the transition from juvenile to mature wood, as the influence of the live crown is reduced. Shade-intolerant species such as the hard pines reach this point more rapidly than shade-tolerant species, which is thought to lead to a reduction in earlywood production.

2.3 Grain angle

Deviations in grain angle can seriously affect the strength properties of wood, with the degree to which such properties are affected dependent on the type and direction of the force being applied (Dinwoodie, 2000). The grain angle relative to the longitudinal stem axis in living trees varies at different heights in the stem and from pith to bark, beginning with a left-hand or 'S' spiral near the pith, gradually reaching zero in mature wood, but sometimes increasing again in a right-hand, or 'Z' spiral, in some older trees (Desch and Dinwoodie, 1996). It is thus more pronounced in juvenile wood, while the extent of age-related spiral grain deviation and its consequences exhibits large variation both within and between trees, and between species (Panshin and de Zeeuw, 1980). In Scots pine the grain angle in the outerwood of older trees in native pinewoods can be up to 45°, which reflects stand conditions: wide spacing, exposure, poor stem form and increased stem taper often cause increases in grain angle (Petty, 1995). Inherent grain angles can be magnified in sawn battens as a result of pronounced stem taper or poor form, and such battens are expected to show significant reductions in strength and stiffness as well as increased drying distortion (Macdonald and Hubert, 2002).

2.4 Presence of knots

Knots, or embedded branch bases, are considered as either intergrown or 'tight' knots, or loose or 'encased' knots. The former are the result of a dead branch being covered with successive cambial layers, and since they show no continuity with the surrounding wood will often drop out when timber is dried. Tight knots, on the other hand, arise from simultaneous growth of the main stem and branch, resulting in the knot becoming an integral part of the surrounding wood (Haygreen and Bowyer, 1996). Knots are associated with deviations in grain angle resulting in reduced strength properties of beams or pieces of timber that include them (Dinwoodie, 2000). The larger the knot, the greater the grain deviation around it and the greater the effect this has on strength properties. This is particularly true when timber is subject to bending stresses, since tensile strength is the most sensitive mechanical property to the presence of knots (Panshin and de Zeeuw, 1980). Knots also have more effect on timber strength if they are clustered together, hence *knot area ratio* (the ratio of knot area to cross-sectional area at any point) is a useful measure used to quantify their influence (Dinwoodie, 2000).

3.0 Acoustic testing of wood to determine the dynamic modulus of elasticity

Research into the non-destructive evaluation of wood using longitudinal stress-wave and time-of-flight techniques (described in Section 3.1) has demonstrated a good relationship between measured acoustic speeds in standing trees and logs, and the physical properties of wood sawn from those logs, such as MoE and MoR. The theoretical relationship between acoustic velocity, density and stiffness has long been understood and can be expressed by the following fundamental wave equation:

$$MoE_d = \rho \nu^2 \qquad (3)$$

where MoE_d is the dynamic modulus of elasticity (N/mm^2), ρ is the wood density (kg/m^3) and ν is the speed of sound (m/s) (Bucur, 2006).

3.1 Acoustic NDE techniques

Three important techniques are described briefly in the following sections. For a detailed overview of NDE techniques for assessing MoE in small-diameter logs see Wang *et al.* (2001), and Ross and Pellerin (1994). For the standing tree method see Wang *et al.* (2000) and Carter *et al.* (2005).

3.1.1 Resonance flexure method

Resonance flexure (or ‘transverse vibration’) is a technique which uses a microphone and oscilloscope to record the resonance frequency of the fundamental mode of flexural vibration in a freely-suspended sample of timber following a hammer-blow perpendicular to the length of the sample. The MoE is then calculated using the recorded frequency and the sample’s known density (Haines *et al.* 1996).

3.1.2 Resonance longitudinal method

This technique involves introducing a longitudinal acoustic stress-wave into a log or batten using a hammer-blow on one end of the sample. As the wave resonates back and forth along its length it is detected by an accelerometer at the opposite end of the sample and the resonant frequencies recorded. The weighted acoustic velocity (m/s) can then be calculated from the observed frequency and sample length, and the MoE derived using Eq. (3). The Fibre-Gen Director HM200^{TM} tool employs this method.

3.1.3 Acoustic 'time-of-flight' method

This technique measures the time-of-flight of an acoustic stress-wave (induced by a hammer blow) between transmitter and receiver probes aligned vertically at a known distance apart in the tree stem. From here it is a simple step to record the acoustic velocity (m/s) and thus derive dynamic MoE values, also using Eq. (3). One advantage of this method is that it can be used on standing trees. The tool used for standing tree assessment in this study was the Fibre-Gen Director ST300^{TM} (see Chapter Two *infra*.).

3.2 The effectiveness of acoustic evaluation techniques

Many recent studies have demonstrated that impact-induced acoustic velocities using the various methods described are highly correlated with static MoE measurements in standing trees, logs and sawn timber for a range of species, with the degree of correlation dependent on the method employed and the material tested (Carter *et al.* 2005; Tsehaye *et al*. 2000; Wang *et al.* 2002; Wang *et al.* 2004; 2004 Ross *et al.* 1997; Matheson *et al.* 2002, Haines *et al.* 1996; Haines and Leban, 1997; and Grabianowski *et al.* 2006).

Haines *et al*. (1996), and Haines and Leban (1997) compared MoE values obtained from acoustic speeds in samples of Norway spruce (*Picea abies* (L.) Karst.) timber using the resonance flexure method with static MoE values and found them to be almost identical. Using data on specific gravity and MoE values obtained from the Wood Handbook (Forest Products Laboratory, 1999), the authors were then able to compare predicted frequencies with actual results, which demonstrated a strong correlation. They found that the dynamic MoE values were higher if they used a longitudinal resonance method, and those obtained with the time-of-flight technique higher still. Ilic (2001) also found these differences between methods when testing small clear specimens of *Eucalyptus delegatensis*. Haines *et al.* (1996) attributed observed differences in MoE values between the various methods to the non-homogenous and anisotropic behaviour of wood and its viscoelasticity: acoustic speeds are greater in the higher density and stiffer latewood, and the acoustic wave may follow this path through the log (also noted by Wang *et al.* 2004). Properties associated with viscoelasticity include the capability of a material to dampen vibration, which predicts higher acoustic velocities for waves at the higher frequencies characteristic of the shorter pulses employed in longitudinal resonance techniques (Haines *et al.* 1996). Ross *et al.* (1997) assessed balsam fir (*Abies balsamia* (L.) Mill.) and eastern spruce logs and found a strong agreement between MoE values obtained using the time-of-flight technique and those obtained using resonance flexure. In contrast they found a weak relationship between visual sawlog grades for these species and average MoE values of timber cut from the logs.

3.3 Using acoustics for log segregation

Acoustic assessment techniques are now widely used in forest industries to assess timber quality at the stand level and for segregation of logs which might produce structural grade timber and thus improve high-grade out-turn and financial profitability (Mackenzie *et al.* 2005). Tsehaye *et al.* (2000) compared acoustic velocities using time-of-flight sonics in 300 logs of radiata pine (*Pinus radiata* D. Don) from unthinned stands on New Zealand's North Island with average MoE values obtained from machine stress grading of boards sawn from the same trees. They concluded that despite some problems with experimental technique, they were still able to reasonably correlate acoustic speeds in logs with static MoE values and thus predict intrinsic properties of logs more accurately than visual grading. Like other studies (Carter *et al.* 2005; Wang *et al.* 2002; Ross *et al.* 1997; Matheson *et al.* 2002), they concluded that that this was the basis for more efficient log segregation into structural and non-structural markets, and improved financial returns from a stand, for instance by avoiding processing the least stiff logs and thereby more efficiently allocating resources. Wang *et al.* (2002) found that both longitudinal stress-wave and resonance flexure techniques can be used to successfully evaluate and sort small-diameter logs of jack pine (*Pinus banksiana* Lamb.) and red pine (*Pinus resinosa* Ait.), with resonance flexure techniques showing a stronger correlation with static MoE due to them being less sensitive to geometrical imperfections in logs such as irregular stem form and cross-section, which might make density measurements less accurate. Matheson *et al.* (2002) also found that the correlation of acoustic speeds with wood stiffness in logs of radiata pine was strong enough to allow them to be sorted into classes, and that wood stiffness could be predicted with reasonable accuracy by a stress-wave technique used on standing trees.

3.4 Acoustic evaluation of standing trees

A logical extension of using NDE in logs and wood materials is the recent development of stress-wave techniques for use in standing trees to ascertain the average quality of a stand, and thus identify the best stands for specified markets, or to improve our ability to select single trees for their potentially valuable high-grade structural lumber (Carter *et al.* 2005). Such techniques might also be of value to forest managers in assessing the effects of changes in silvicultural practice, such as the current trend for conversion of plantations in the UK to a more diverse stand structure, a process which might be expected to affect timber quality both positively and negatively (Macdonald and Gardiner, 2005a).

Wang *et al.* (2000), in a study of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce, found good agreement between the dynamic MoE values obtained from acoustic velocities and static MoE values from bending tests on small clear specimens cut from the same trees, concluding that stress-wave NDE techniques in standing trees provide a ‘reasonably accurate’ means of predicting mechanical properties of wood in standing trees. Carter *et al.* (2003) describe how the development of dedicated acoustic tools such as the Director ST300 has proved to be very effective in assessing timber quality across a range of species, with applications in stand valuation, harvest planning and timber marketing, though information on their application in assessing Scots pine is less readily available. In a later paper the same authors describe the deployment of acoustic testing as a more accurate and reliable method than visual grading for assessing the internal properties of wood such as stiffness and strength, and its application to enhance forest value at a time when silvicultural practices such as shorter rotations and wider spacings are leading to increased variability in wood supply from western forests (Carter *et al.* 2005). Concern about the need to identify structural grade timber used in the higher value construction markets has seen the parallel development of machine stress grading since the 1960s, but this is expensive and time-consuming, as well as wasteful due to the greater quantity of non-structural timber being graded after harvesting and processing. The authors argue that the strong relationship found between acoustic speeds in logs measured using the HM200 and static MoE values of lumber from those logs and the strong linear relationship between standing tree measurements using the ST300 and HM200 readings on logs cut from those trees, justifies the use of these tools as a surrogate indicator of dynamic MoE, with the potential for significant financial benefits to the processing industry and forest owners (Carter *et al.* 2005).

3.5 Acoustic testing and wood properties

Eq. (3) applies to a truly homogenous, elastic material in the form of a long, slender rod. In reality, stress-wave propagation in wood is affected by a number of factors related to the variation in internal wood properties, such as the presence of knots, grain angle, moisture content, wood temperature and dimensions and form of the sample being tested. Wang *et al.* (2004) looked at deviations between dynamic and static MoE values in red pine, ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.), jack pine and Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco), and found that in red pine stress-wave speeds decreased with increase in diameter, presumably due to growth rate differences producing wood of lower stiffness in the faster-grown trees. The same was true for static MoE values, but these decreased at a slower rate with diameter. This deviation between dynamic and static MoE values increased in proportion to the increase in log diameters, and was attributed to the tendency for stress-waves to follow the high density and stiffness path through the log. Including these diameter effects together with acoustic speeds and density in a multivariate regression model gave a more accurate prediction of static MoE than the fundamental wave equation alone because it reduced errors in density and MoE measurements by taking into account stem form and geometrical imperfections.

The presence of knots also affects stress-wave propagation in wood. Gerhards (1982) noted that there could be problems in timing stress-waves through knots due to an irregular waveform caused by the wave lagging behind the knot. Static MoE values were reduced when knots were present, and acoustic speeds were also slower. The grain deviation around a knot also significantly affects timber strength. Again, dynamic MoE values were higher than those measured from static bending tests, and this deviation was greater when knots were present. There is also a significant negative correlation between velocity and knot area ratio (KAR) as measured in 400mm sections of Sitka spruce beams, with speeds decreasing with higher KAR (Mackenzie *et al.* 2005). Foulon (2006) looked at the effect of knots on acoustic speeds in logs of Sitka spruce, and found that systematic removal of whorls from the logs tended to increase acoustic speeds, but the effect was smaller than expected, perhaps as a result of failure of the testing tool to detect internal defects. Similarly, both wood temperature and moisture content affect wave propagation, with acoustic speeds decreasing as both moisture content and temperature increase, though moisture content has a much stronger influence on wave-propagation than temperature, and the relationship is independent of wood quality (Sandoz, 1993; Kang and Booker, 2002).

3.6 Pith-to-bark variation of wood properties

Acoustic velocity in logs is closely correlated with averaged MoE across the stem section, which in turn is a function of average MFA values and therefore directly reflects intrinsic wood properties. Opportunities exist for the use of acoustics in tree selection during thinning operations, for grading pulp logs for specified applications, and in tree breeding programmes to select seedlings with the best wood properties (Huang *et al.* 2003). One problem for the industry is that identifying the exact boundary of the juvenile wood zone is difficult because different characteristics change at different rates both radially from pith to bark, and longitudinally up the stem (Walker and Nakada, 1999). Grabianowksi *et al.* (2006) looked at correlations between the results of tests on standing trees, logs and green lumber using both time-of-flight stress-wave techniques and longitudinal resonance techniques, and found that on young logs of radiata pine, acoustic velocities using the two methods were highly correlated, though with generally higher average time-of-flight speeds due to the fact that these are measuring the outerwood properties of the logs. They also found a strong relationship between time-of-flight results from logs (taken immediately after felling to resemble standing tree evaluation) and the green corewood properties of the same logs. This is significant because the authors have shown that it is possible to predict juvenile wood properties using time-of-flight evaluation of outer- or stemwood, for these young trees at least. The experiment enabled the authors to construct stiffness maps for 'composite' trees reflecting age-related differences in stiffness, where the acoustic velocities measured in young trees were assumed to represent the corewood velocities of older trees (Grabianowski *et al.* 2006).

4.0 Scots pine timber quality in Northern Scotland

As Scotland's only native coniferous commercial timber species, Scots pine has an important role to play in rural development in the Highland and Grampian regions, where 80% of Scotland's total area – 140,000 hectares - of Scots pine high forest is situated. Scots pine is a strong, easily worked timber which compares favourably with timber from other UK-grown commercial conifer species in terms of basic density, stiffness and bending strength (Petty, 1995; Lavers, 1983, Table 1). With timber production in UK forests forecast to increase over the next 14 years to a peak in 2020, Forest Research, in conjunction with partners in the forestry and wood-using industries, have initiated the *Scots Pine Timber Quality Project*, aimed at establishing the potential for utilization in higher-value end-products in order to increase the value to the rural economy of the Scots pine resource (Macdonald and Gardiner, 2005a). Policy shifts emphasizing the management of forests for additional benefits such as conservation of wildlife habitats, recreation, amenity and landscape enhancements, coupled with a decline in timber prices paid to growers, have led to changes in management which have had an impact on timber quality, such as reduced stocking densities, planting at wide spacing and the transformation of even-aged stands to continuous cover forestry (CCF) management systems (Worrell and Ross, 2001). This latter change has the potential to have both positive and negative effects on timber quality, but these will depend on the timing and nature of management interventions such as thinning regimes, gap creation, pruning and the use of natural regeneration or planting (Macdonald and Gardiner, 2005b). There is potential to grow high quality timber under CCF systems which, if fully realised, will have beneficial effects on the rural economy of northern Scotland. In order to reverse a general decline in timber quality, detailed data on the quantity and quality of the Scots pine resource is required, and non-destructive acoustic evaluation of standing trees, logs and timber can play a major role in providing a rapid and accurate assessment.

	Scots Pine	Lodgepole pine*	Sitka spruce	Douglas fir	Japanese larch**
Density (kg/m3)	510	480	380	500	480
MoR (MPa)	89	81	67	91	83
MoE (MPa)	10,000	9,200	8100	10500	8300

Table 1: Density, bending strength (MoR) and stiffness (MoE) of UK-grown commercial conifer species at 12% moisture content. (Lavers and Moore, 1983)

(**Pinus contorta* Dougl. ex Loud. ** *Larix kaempferi* (Lamb) Carr.)

5.0 The implications for timber quality of conversion to CCF systems

Transformation to CCF silvicultural systems is underway in the UK as part of a general policy shift towards mixed, uneven-aged, structurally diverse forests managed for multiple uses, under the general banner of ‘sustainable forest management’. The scale of the transformation in terms of the total forest area that will be converted, and the likely impact on both the quality and quantity of the wood-supply as a result of transformation remain unclear. It is likely that there will be a reduction in total volume of timber and/or sawlog recovery following transformation, but the process has until now tended to focus on stand manipulation to achieve natural regeneration, with the result that there has been less emphasis on the implications for timber quality following conversion (Macdonald and Gardiner, 2005b).

5.1 Continuous cover forestry

Mason et al. (1999) have defined CCF as the application of selective silvicultural systems which *"maintain the canopy during the regeneration phase, with a presumption against clearfelling of areas greater than 0.25 ha*." One of the assumptions of CCF is that it mimics natural structures and is a 'low-impact' system, and thus allows for fewer disturbances of the ecosystem and increased species and structural diversity (Malcolm *et al.* 2001). These in turn afford greater ground cover, enhanced visual impact, protection from erosion and frost, and potentially better quality timber, though trees are often retained beyond their normal financial rotation age to attain this (Hart, 1994; Mason *et al*. 1999). The move towards CCF was given further impetus by the requirements of certification under the UK Woodland Assurance Standard (UKWAS, 2000) which requires the use of lower impact systems in suitable windfirm conifer plantations. Restocking and planting costs are also reduced if there is adequate natural regeneration, though adequate protection from weeds, pests and browsing is essential. The silvicultural systems most applicable to the transformation process on suitable sites in Scotland are uniform or group shelterwood or group selection systems, the final choice depending on the degree of shade-tolerance of the species present (Macdonald and Gardiner, 2005c). These systems use the old crop to provide seed and shelter for the regeneration of new trees by the gradual opening of gaps in the canopy, and as Scots pine is relatively shade-intolerant it is likely to require larger gaps with a diameter of at least twice the height of the surrounding trees in order to encourage adequate natural regeneration under group selection or seed tree systems (Malcolm *et al.* 2001; Mason *et al.* 2004).

5.2 CCF and timber quality

The move towards alternative silvicultural systems is likely to have a number of effects on timber quality, but whether these are positive or negative will largely depend on the timing of skilled interventions and continuity of management during the conversion process. A comprehensive review of the implications of conversion from even-aged stands to CCF systems on conifer log quality and wood properties has recently been presented by Macdonald and Gardiner, 2005c (summarised in Table 2). They identified the factors most likely to influence timber quality in conversion to CCF systems as:

- Gap creation
- Increased variability
- Increased thinning
- Longer rotations
- Restricted genetic change due to increased use of natural regeneration.

	Longer rotations	Gap creation	Increased thinning		Variability	Restricted genetic change
			Early thinnings	Later thinnings		
Diameter	+	+/=	+	+	=	-
Stem straightness	+	-/=	+	+	-	-
Branching/knots	+	-	+/=/-	+	-	-
Grain angle	=/+	-	+/=	+	-	-/=
Wood density	+	SS- SP L DF =	-	SS- SP L DF =	SS -/= SP L DF =	SS +/= SP L DF =
Tracheid length	+	+/=/-	-	+	+/=/-	=
Microfibril angle	+	+/=/-	-	+	+/=/-	=
Juvenile wood	+	+/=/-	-	+	+/=/-	=
Compression wood	=	- -	=/-	=/+	-	=

Table 2: Silvicultural changes under CCF and their likely effect on factors affecting timber quality during and following transformation. NB: Indicators reflect broad trends and factors are expected to interact.

Key: Green (+): positive effect; Red (-): negative; Yellow (=): neutral
SS: Sitka spruce; DF: Douglas fir; SP: Scots pine; L: larch

(From Macdonald and Gardiner, 2005b, reproduced with kind permission of the authors)

Increased gap creation under CCF systems might be expected to lead to poorer stem form and stem taper, and increased branching in surrounding trees, as will the increased variability in stand structure and composition, which will lead to decreased uniformity of surrounding competition. The increased number of ‘edge’ trees in such circumstances might be subject to greater wind-loading or uneven crown development, leading to a higher incidence of compression wood (Brazier, 1977). Increased thinning can be expected to positively influence timber quality by removal of trees with poor form and excessive branching, thus favouring better quality trees. Heavier early thinning at the start of the transformation process, however, might lead to larger knots and increased stem taper in trees in the residual stand. Brazier

(1977) looked at the effects of forest management on tree growth and how this influences wood properties, and stated that knot size is influenced by the depth of the living crown, which responds to the amount of available light, so wider initial spacing or increased early thinning prior to crown closure will prolong branch retention and growth in the lower part of the stem, which can be expected to lead to larger knots. Heavier thinning will also result in increased stem taper in residual trees, the effects of which can be reduced by heavy pruning, which also has a negative effect on knot size and frequency (Brazier, 1977).

The longer rotations expected under CCF systems will result in the production of logs with a lower proportion of juvenile wood, so careful selection of trees is important to minimise the negative effects on timber quality of the retention of seed trees with excessive taper and branching. There may also be implications for sawmill operations of more logs of both larger and smaller diameter (from more regular thinnings) being produced, with some sawmills more able to process such material than others, thus emphasising the benefits of using acoustics to enable early segregation of quality material so that sawmill capacity can be utilised in the most efficient way. The emphasis on natural regeneration in stands managed under CCF systems means that form and quality of regenerated trees will depend on the quality of the existing crop, though in some circumstances the increased stand densities associated with natural regeneration will result in earlier branch suppression and improved stem straightness, as well as greater choice in early thinnings when selecting stems with good form for retention (Macdonald and Gardiner, 2005c).

The factors highlighted by Macdonald and Gardiner (2005c) as the most likely to exert an influence on the quality and suitability for certain end-uses of sawn timber from stands managed under CCF systems are expected to interact in complex ways, so the development and use of timber quality models for Scots pine which simulate growing conditions and silvicultural interventions will be of benefit in evaluating the overall effects of conversion on timber quality. They conclude that given continuity of management, careful timing and intensity of thinning operations favouring the best trees, and the use of pruning where necessary, there is the potential to produce good quality timber where the quality of the original stands is high enough. Where this is not the case this might also be achieved by planting rather than relying on natural regeneration.

6.0 Rationale for current study

The complex structure and variable nature of wood is the single biggest limitation on its use as a structural material. Factors such as the presence in trees of a large juvenile core, spiral grain, the presence of knots, a high incidence of compression wood and a large microfibril angle in the S_2 layer of the cell wall, have a detrimental effect on the stiffness and strength of sawn timber, and these are influenced by growing conditions which in turn are affected by forest management practices. Scots pine is an important native species for Scotland, and since timber production in the UK is set to peak around 2020 it is imperative for the rural economy that a greater proportion of this resource is sold into the higher-value construction markets. Policy shifts towards the management of forests for multiple uses and changes in silvicultural practices such as the conversion of even-aged plantation stands to management under CCF systems which are largely dependent on natural regeneration, will create conditions with the potential to affect timber quality both positively and negatively, depending on the nature and timing of silvicultural interventions, the provision of adequate training and continuity of management in the longer term. Such changes will also affect the volume and variability of future timber supplies.

Non-destructive evaluation of trees, logs and sawn timber using stress-wave propagation techniques is showing great promise within the forest industries as a reliable predictor of timber quality and an invaluable tool for log segregation and value recovery, since it can assess important intrinsic properties of wood such as stiffness and microfibril angle prior to the processing stage. The use of acoustics will therefore be important for an accurate assessment of the quality of the Scots pine resource in Scotland, and can help inform decision-making for both growers and the processing sector, with applications along the supply chain.

Acoustic tools such as the ST300 and the HM200 have been shown to reliably predict timber quality in a variety of species, with much work conducted on radiata pine in New Zealand, but only recently has work commenced on Scots pine. This thesis aims to examine the strength of the correlation in Scots pine between dynamic MoE and MoR values measured in standing trees using the Director ST300 standing tree tool, and static strength values as measured on small clear specimens cut from logs, by analysing data collected as part of this study alongside data collected by Forest Research as part of the *Scots Pine Timber Quality Project*. It is hoped that a strong relationship between standing tree assessment and timber quality in Scots pine will be demonstrated, which will enable further assessment of naturally regenerated trees in a plot with a known silvicultural history, in order to examine the practical implications of using acoustics to assess potential timber quality from woods managed under CCF systems. Analysis of data from both even- and mixed-aged stands, along with tests on small clear specimens, will allow further investigation of age-related patterns of variation in MoE and MoR values, and afford some insight into the relationship between mechanical properties, age and growth rate.

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CHAPTER TWO

The relationship between standing tree acoustic assessment and timber quality in Scots pine (*Pinus sylvestris* L.), and the practical implications for assessing timber quality from naturally regenerated stands

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1.0 Introduction

As the production cycle for UK-grown commercial conifer species is forecast to reach its peak in 2020, the emphasis in British forestry will be to increase penetration of potentially higher-value construction timber markets as existing markets become saturated with both home-grown and imported timber (Mackenzie *et al.* 2006). The relative importance of the forest industries to the Scottish rural economy, coupled with an increasing emphasis on conversion to continuous cover forestry (CCF) systems, which is expected to lead to increased structural diversity (age-class and species mix) and an increased use of native Scots pine, presents a commercial opportunity to increase the production of high quality Scots pine timber (Macdonald and Gardiner, 2005a). CCF systems tend to rely on natural regeneration (Mason *et al.* 1999), yet little is known about timber quality from naturally regenerated stands. The relative rarity of mature CCF sites means that it is not possible to assess timber quality using conventional destructive testing methods. Non-destructive evaluation (NDE) techniques using a dedicated standing tree tool such as the Fibre-Gen Director ST300 therefore present an ideal opportunity to increase our knowledge of the quality of the Scots pine timber resource following transformation to management under CCF systems. The use of such techniques is gaining widespread acceptance in the forest industries as a reliable predictor of the mechanical properties of sawn battens, and has been shown to increase structural grade out-turn and value recovery (Carter *et al.* 2005; Wang *et al.* 2000).

Due to the wide variability of wood properties, there is no single objective definition of the term 'timber quality'. There is general agreement, however, that the relative importance of factors which determine timber quality is dependent on its intended end-use. For structural applications two of the most important criteria are stiffness (modulus of elasticity, or MoE) and bending strength (modulus of rupture, or MoR). Opportunities for increased penetration of the construction sector will therefore require Scots pine timber to meet certain minimum requirements for these key mechanical properties, so they are of primary concern in this paper. The expectation was that timber from naturally regenerated stands would be at least comparable to plantation-grown timber in terms of these intrinsic mechanical properties.

The experiment is divided into two sections. First, acoustic studies were conducted on standing trees in even-aged Scots pine stands and small clear specimens cut from trees from one of the sites were subjected to static bending tests, in order to examine the effectiveness of using acoustic assessment of standing trees as a predictive tool to assess the static properties of Scots pine timber. In the second part of the study, standing trees in a naturally regenerated uneven-aged pinewood with a known silvicultural history were acoustically assessed in order to draw preliminary conclusions about timber quality in naturally regenerated stands following transformation to CCF systems.

2.0 Materials and Methods

2.1 The fundamental wave equation

The relationship between acoustic velocity, density and wood stiffness is described by the fundamental wave equation (derived from Hooke's law of elasticity):

$$MoE_d = \rho v^2 \qquad (1)$$

where MoE_d is the dynamic modulus of elasticity (N/m^2), ρ is the wood density (kg/m^3) and v is the speed of sound (m/s) (Bucur, 2006). This has been shown to hold true for many species, but to-date has not been studied in detail for Scots pine.

2.2 Plantation studies – acoustic sampling at Mount High and Seafield Estate

Acoustic velocities were measured in 100 randomly selected standing trees in Scots pine stands at Mount High, Ross-Shire (Grid Ref: NH714622) and Seafield Estate, Aberdeenshire (Grid ref: NJ496637) using the ST300 testing tool. Diameter at breast height (dbh) was also measured using a diameter tape. From the Mount High sample 12 trees were then randomly selected across the range of diameters, and felled using a chainsaw. A 1.5m log was cut from above breast height (1.3m) from each tree and the logs transported to Forest Research NRS at Roslin, Midlothian, for cutting into small clear specimens for static 3-point bending tests. The standing tree acoustic data from Seafield Estate were collected by Forest Research as part of the Scots Pine Timber Quality Project, and was kindly made available for use in this study.

2.3 Procedure for standing tree assessment using the Director ST300

The transmitter and receiver probes were driven through the bark into the outerwood of each tree using the hammer supplied. The probes were aligned vertically along the stem at a distance of approximately 1m apart. The exact distance between the probes was measured using an integral laser-guided ultrasound rangefinder. An acoustic stress-wave was induced into the tree through the lower transmitter probe by a hammer blow (Figure 1). The receiver probe detected the acoustic signal and calculated the time-of-flight of the wave. Distance and time-of-flight information were transmitted to a (personal digital assistant) PDA storage device via a Bluetooth wireless connection, which calculated the velocity of the acoustic stress-wave in meters per second (m/s). Stand information, tree number and dbh were also entered into the PDA.

2.4 Preparation of small clear specimens for static bending tests

Strength testing perpendicular to the grain required small clear specimens with nominal dimensions of 300 x 20 x 20mm. A 23mm slab was cut from each log (bark-pith-bark along the log length) using the Wood-Mizer^{TM} portable saw (Figure 2). Each slab was planed to 22mm using a planer. On each board, every fifth ring in one radius was numbered from pith to bark using a pencil on the radial face. Starting from the pith, boards were then cut into strips of width 21 mm (to account for shrinkage on drying) using a table saw. From each strip a clear (i.e. knot- and defect-free) or clear as possible section of 300mm was selected and any ring markings transferred to this section together with the log code. This section was then cut using a chop saw. The small clear specimens were then conditioned to approximately 12% moisture content in a conditioning chamber maintained at 65% relative humidity and 20° C, for 1 week.

Fig. 1: Acoustic assessment of naturally regenerated Scots pine with the Director ST300, Glengarry, June ’06.

Fig. 2: Cutting of logs for small clears using Wood-Mizer saw. June, ’06.

2.5 Testing small clear specimens on the Tinius Olsen^{TM} H5KT static bending rig

The procedure measured bending strength properties perpendicular to the grain, and was carried out according to BS 373: 1957, *Methods of Testing Small Clear Specimens of Timber*. First, each specimen was tested for moisture content using a Brookhuis FMW^{TM} electrical moisture meter, and its weight in grams recorded on Sartorius^{TM} portable digital scales.

Depth, width and length dimensions (mm) were measured using callipers and a measuring tape, as was the ring number (from the pith) of the central growth ring (a measure of cambial age), and the average number of rings per centimetre (RPC) (an indicator of growth rate). The specimen was then placed on the bending rig oriented so that the load was applied to the radial face (Figure 3). The rig is controlled by dedicated QMat^{TM} software running on an attached desktop PC. The rate of loading was set at 6.6 mm/min. On commencement of the bending test a graph of the stress / strain curve appeared on the screen, the slope of this graph being the modulus of elasticity in megapascals (1 MPa = 1 N/mm^2). The test was continued to failure and the modulus of elasticity (flexural stiff) and modulus of rupture (flexural strength) were calculated by QMat and displayed numerically and graphically on the PC. The procedure was repeated for all 40 small clear specimens that were cut from the 12 Mount High logs.

Fig. 3: Static bending rig with a small clear specimen in position.

2.6 Studies in a naturally regenerated stand: acoustic sampling at Glengarry

Acoustic speeds were recorded in a sample of 50 naturally regenerated trees selected from a total of 102 regenerants at Forest Research long-term monitoring plot 23/2000 at Glengarry (Grid Ref: NH258011). The experimental area was fenced in 1929 and then subjected to a seed tree felling, leaving approximately 100 trees/ha to encourage natural regeneration, though some were lost to windblow, leaving 69 seed trees in the 0.96 ha plot. Dbh and tree ages of the regenerants were known from a dataset collected in 2003/4, and the trees were divided into 4 diameter classes. The sample was selected using a computer-generated random number sequence to encompass the range of diameters over 12cm found at the site (ST300 readings are known to be unreliable if dbh < 12cm). These trees were then assessed using the Director ST300 standing tree tool and the dbh measured again using a diameter tape. One tree was subsequently omitted from the analysis because its age had not been accurately determined.

2.7 Statistical Methods

A number of different statistical tests were employed to study the relationship between velocity and mechanical properties, including simple linear regression, multivariate linear regression, and non-linear modelling.

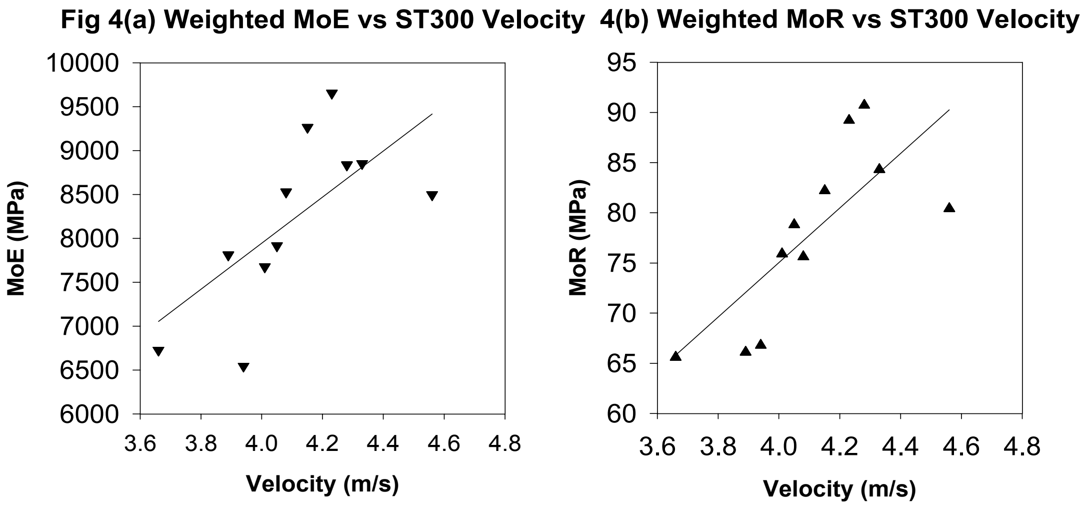
Firstly, the relationships between recorded MoE and MoR values in the small clear samples and ST300 velocities in the corresponding trees were analysed using linear regression, in order to investigate how closely acoustic speeds reflect actual strength and stiffness. The strength of the correlation between MoE and MoR and velocity-squared (v^2) was determined, as was that between MoE and MoR and velocity-squared multiplied by density (ρv^2), after Eq. (1). Thirdly, the Glengarry data was analysed using simple linear regression to establish the strength of the relationship between acoustic velocity and cambial age. The results of the static bending tests on small clear specimens were then analysed in Sigma Plot using simple linear regression in order to determine the relationship between static MoE and each of density, cambial age and growth rate (expressed as rings per centimetre, or RPC), since it is known that these parameters affect the strength properties of timber. A multivariate linear regression was then carried out to incorporate all three parameters. The process was then repeated using MoR as a dependent variable. The equations describing the slope of the best-fit trendlines for the MoE versus velocity and MoR versus velocity relationships measured on the Mount High samples were used to predict MoE and MoR values from acoustic speeds measured in the total sample of 100 trees at Seafield and Mount High and the 49 Glengarry trees. A non-linear model, as developed by Leban and Haines (1999), was then applied in order to account for age-related variation in MoE, but it was found that the equations describing the best-fit logarithmic trendlines for the MoE and MoR versus cambial age relationships in the Mount High samples gave a better prediction of MoE and MoR. These equations were therefore used to age-correct the inferred MoE and MoR values from all three sites. The sample mean values for MoE and MoR at age 60 were compared between sites using student's *t*-tests, in order to determine whether there were any significant differences between them, with confidence levels set at 95%.

3.0 Results

3.1 The relationship between strength properties and ST300 velocity

Each clear sample was deemed to represent a consecutive radial cross-section of the tree and so a weighted average for MoE and MoR was calculated for each tree. In this way it was possible to correlate ST300 readings with the whole tree and not just the outer 2-3 cm. Figures 4(a) and 4(b) demonstrate the strong relationship found between acoustic velocity and weighted MoE (r^2=0.527), and an even better correlation between velocity and MoR (r^2=0.589). The same relationships were then examined using v^2 and ρv^2 as predictor variables, and though v^2 explained just over 50% of the variance in weighted MoE (r^2=0.505), and almost 57% of the variance in weighted MoR (r^2=0.569), best results were obtained using velocity alone. The corresponding values of r^2 using ρv^2 as the predictor were 0.34 for MoE and 0.46 for MoR. One of the felled trees was removed from the analysis because it produced an uncharacteristically high MoE value in the small clear specimen nearest the pith (12804 MPa at ring number 4) and a 'zero' value in the second small clear sample.

A measure of the degree of age-related variability in acoustic speeds can be seen by plotting ST300 readings against age for the Glengarry trees (Figure 4(c)). Though strength and stiffness might be expected to increase with age, it was found that the relationship for the Glengarry trees was quite weak, with just 1.8% of the variation in velocity explained by age.



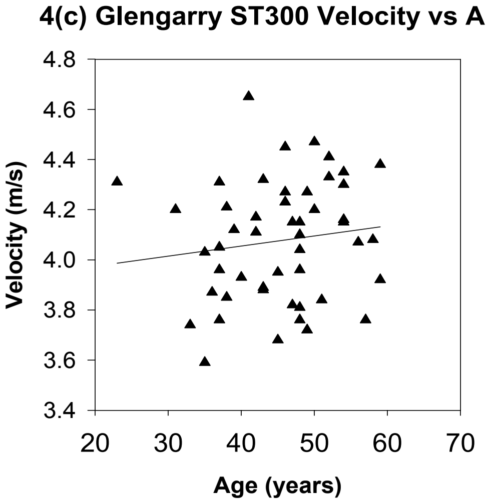


Fig. 4(a): Weighted MoE vs. ST300 velocity: N=40, r^2=0.527 (P<0.001).

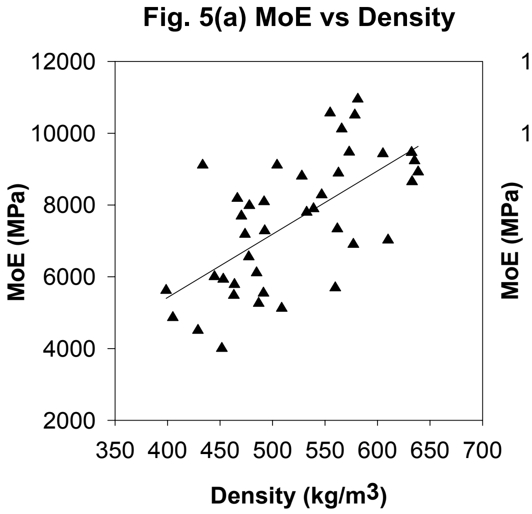
Fig 4(b): Weighted MoR vs. ST300 velocity: N=40, r^2=0.589 (P<0.001).

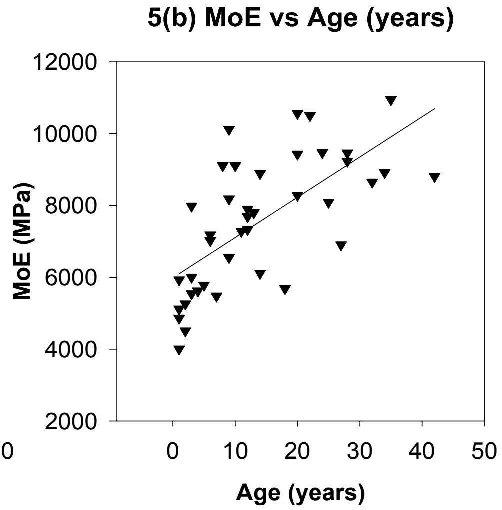
Fig 4(c): ST300 velocity vs. age at Glengarry: N=49, r^2=0.018 (P=0.362).

3.2 Linear models for predicting MoE and MoR from tree properties

3.2.1 Variation in MoE with density, age and growth rate

Density was well correlated with MoE in the small clear samples, explaining over 40% of the variance in recorded MoE values (Figure 5). The correlation between MoE and cambial age was even stronger, with age explaining over 45% of the variance in static MoE values. The relationship between MoE and growth rate was somewhat weaker, with growth rate explaining just 17% of the variance in MoE.





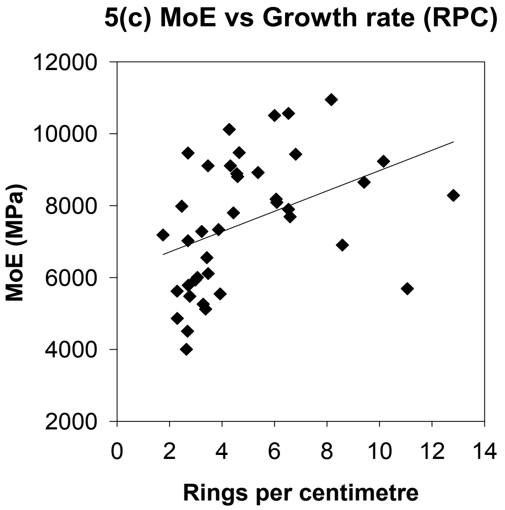


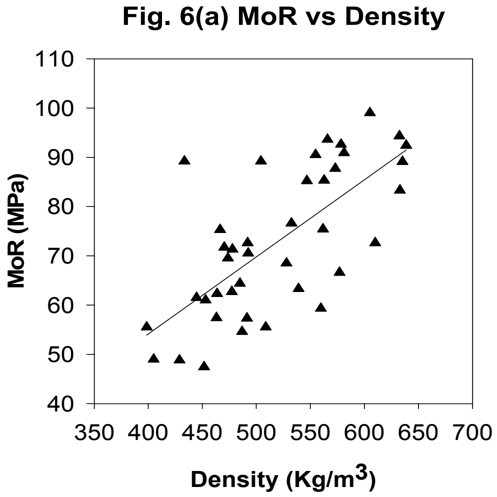
Fig. 5(a): MoE vs. density for all Mount High small clear specimens. N=40, r^2=0.411 (P<0.001).

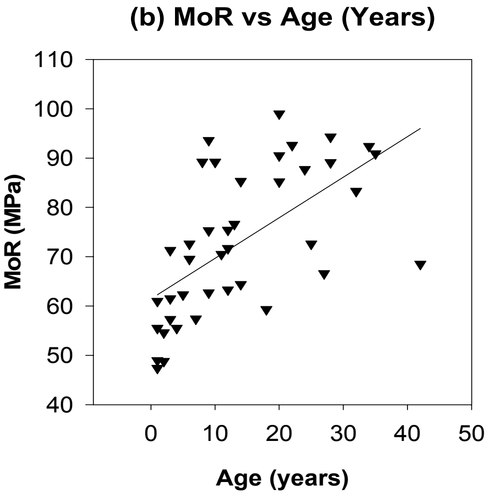
Fig. 5(b): MoE vs. cambial age (ring number from the pith at the centre of each small sample). N=40, r^2=0.458 (P<0.001).

Fig. 5(c): MoE vs. growth rate (expressed as rings per centimetre). N=40, r^2= 0.167 (P=0.009).

3.2.2 Variation in MoR with density, age and growth rate

MoR and density proved to be well correlated, with density explaining close to 50% of the variance in MoR (Figure 6), though MoR (r^2=0.375) was less closely correlated with cambial age than MoE (r^2=0.458). As was the case with MoE, the influence of growth rate is small compared to density and age (r^2=0.159).





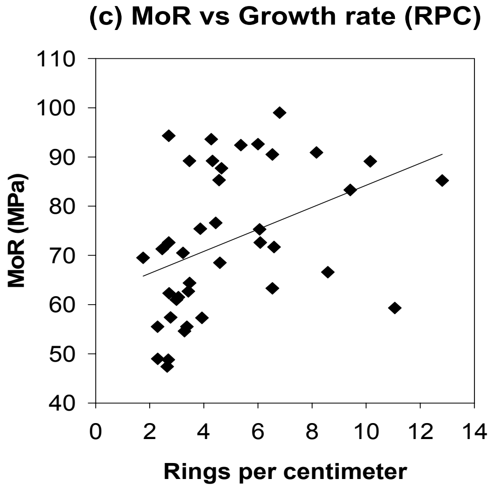


Fig. 6(a): MoR vs. density in the Mount High small clear specimens. N=40, r^2 = 0.492 (P<0.001).

Fig. 6(b): MoR vs. cambial age (ring number from the pith at the centre of each small clear sample). N=40, r^2 = 0.375 (P<0.001).

Fig. 6(c): MoR vs. growth rate (expressed as rings per centimetre). N=40, r^2=0.159 (P=0.008).

3.2.3 Multivariate linear regression combining parameters

The next step was to examine the relationship between MoE and MoR and all three parameters combined: density, cambial age and growth rate. It was found that for both MoE and MoR, the combined influence of all three parameters was an improvement on the relationships with each individual parameter, yielding combined values for of 0.508 (P<0.001) for MoE, and 0.533 (P<0.001) for MoR. For MoE, the regression equation was:

$$\text{MoE} = 1904 + 9.13*(\text{Density}) + 78.2*(\text{Age}) - 40*(\text{RPC})$$

with partial r^2 values of 0.048 (Density), 0.458 (Age) and 0.002 (RPC)

For MoR the regression equation was:

$$MoR = 6.8 + 0.120*(Density) + 0.374*(Age) - 0.303*(RPC)$$

with partial r^2 values of 0.140 (Density), 0.375 (Age) and 0.002 (RPC).

3.3 Further investigation of the effects of cambial age on strength properties

3.3.1 A non-linear model for predicting MoE from age

Leban and Haines (1999) presented a non-linear model to predict MoE in hybrid larch from cambial age. This model uses the exponential equation:

$$MoE\ (Age) = \beta_1 * [1-\exp(\beta_{21}*AGE)]^{\beta 3} \qquad (2)$$

with $\beta_{21} = \ln(1/\beta_3)/\beta_2 \qquad (2.1)$

where β_1 is the asymptote (an estimate of the ultimate MoE value which can be reached), β_2 is the ring age for which maximum increase in MoE is reached (a proposed limit between juvenile and mature wood), and β_3 is the parameter that defines the shape of the curve.

Using such a model has certain advantages over a linear model in that it allows extrapolation outside the range of data and provides meaningful constants which match biological observations. The constants derived by Leban and Haines for hybrid larch were applied to the Scots pine data from this study, then Eq. (2) was re-parameterised (in order to calculate values for β_1, β_2 and β_3 using the Mount High small clears data) using the NLIN procedure in SAS/STAT statistical software, which performs the task iteratively (i.e. by finding successive approximations to the solution of the equation) (SAS Institute, 1990). The results indicated that hybrid larch and Scots pine differ in the relationship between MoE and age. For instance, a negative value was derived for β_2 (-29.41), which is irrelevant if this is supposed to be the juvenile-mature wood boundary (age of transition) for MoE. Additionally it was found that the Leban and Haines model, applied to Scots pine, gave an absolute maximum value for MoE (β_1) of 9500 MPa, which is lower than the average value of 10,000 MPa for Scots pine described by Lavers and Moore (1983).

An alternative logarithmic model was therefore developed, of the form:

$$\text{MoE (or MoR)} = a * \text{Ln (Age)} + b \qquad (3)$$

This model, like the Leban-Haines model described above, respects the known variation of MoE and MoR from pith to bark (also noted by Alteyrac *et al.* 2006, and Biblis *et al.* 1993), and can therefore be extrapolated with more confidence than a linear model, as well as explaining a higher proportion of the variance (Figures 7 and 8). Unlike the Leban-Haines approach, this model does not show zero stiffness and strength at zero age, but it is arguable that cambial age cannot be lower than 1 in any case.

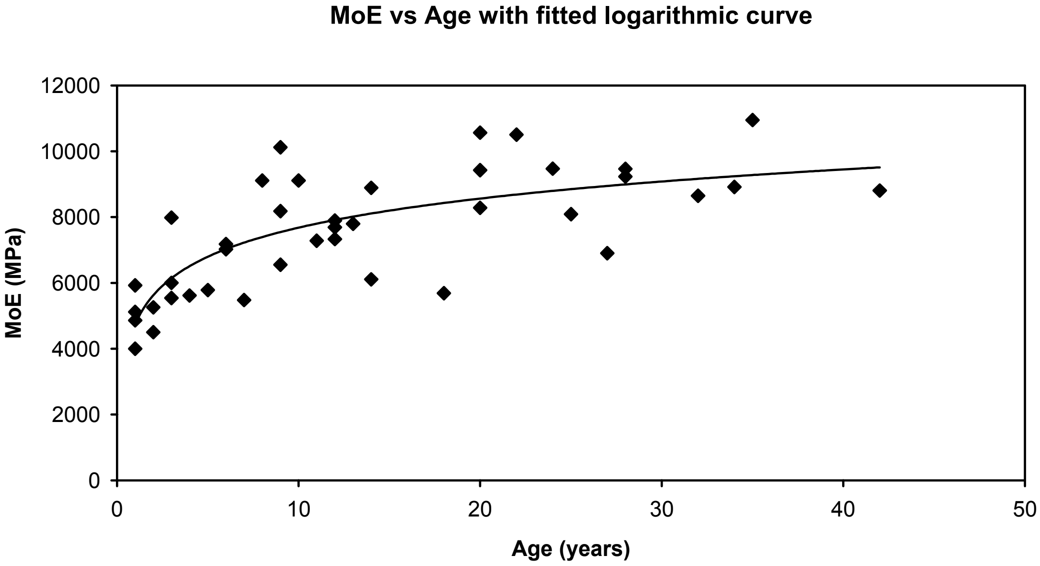


Fig. 7: MoE vs. age in the Mount High small clear samples fitted with a logarithmic curve with the equation: **MoE=1276*ln(AGE)+4742**.
N=40, r^2=0.577 (P<0.001).

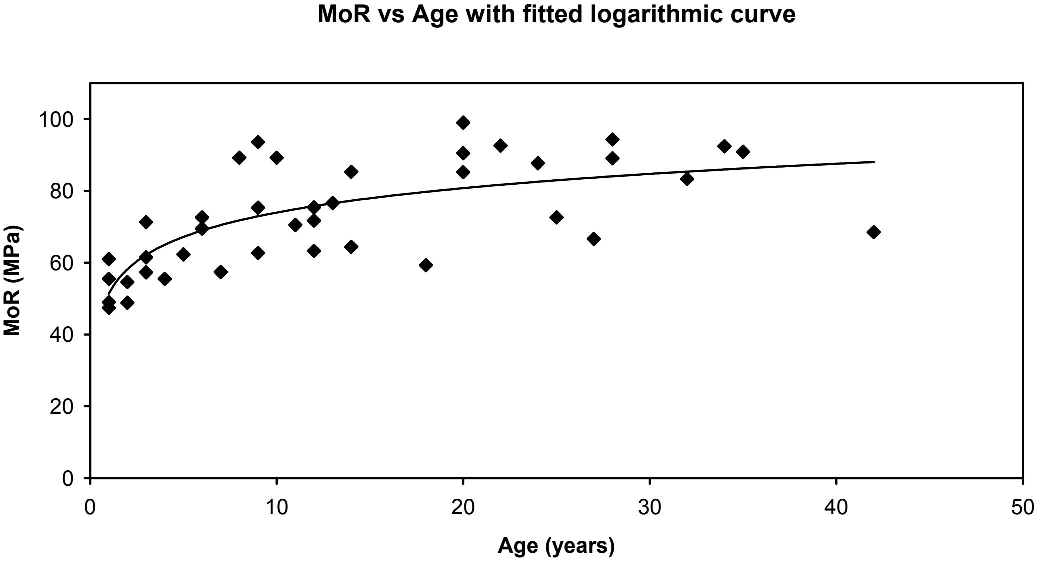


Fig. 8: MoR vs. age in the Mount High small clear samples fitted with a logarithmic curve with the equation: **MoR=9.803*ln(AGE)+51.38**.
N=40, r^2 = 0.519 (P<0.001).

3.3.2 Age-correction of MoE and MoR

Correcting the mean MoE and MoR values at each site to age 60 for direct comparison was a two-stage process. First, the relationships between weighted MoE and velocity and weighted MoR and velocity in the small clear samples in Figures 4(a) and 4(b) were used to derive MoE and MoR values from the ST300 speeds recorded at all three sites. Secondly, using the known planting dates for Seafield and Mount High and the individual ages of the trees at Glengarry, the logarithmic equations from the graphs in Figures 7 and 8 were used to determine the ratio of MoE at age 60 to MoE at the current age (and same for MoR). These ratios were then used as multipliers to calculate the corrected average MoE and MoR values at age 60. Results are displayed in the bar charts in Figures 9 and 10.

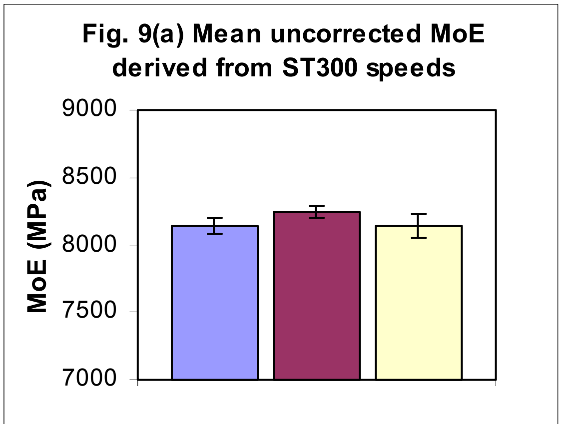
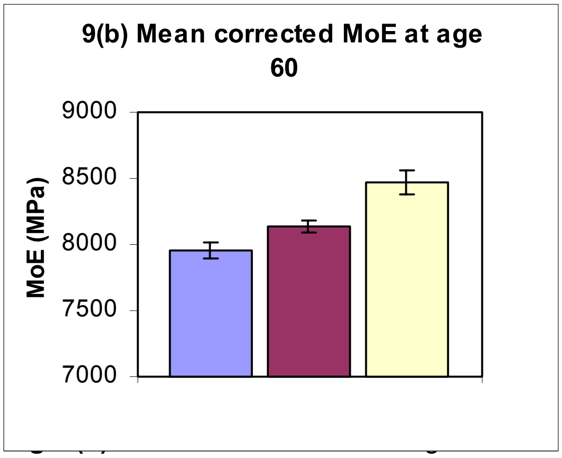


Fig. 9(a): Mean uncorrected MoE from ST300 speeds. Error bars denote standard error of the mean.



Error bars denote standard error of the mean.

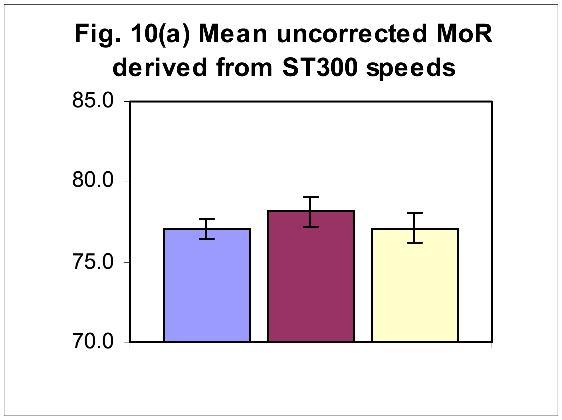


Fig. 10(a): Mean uncorrected MoR from ST300 speeds. Error bars denote standard error of the mean.

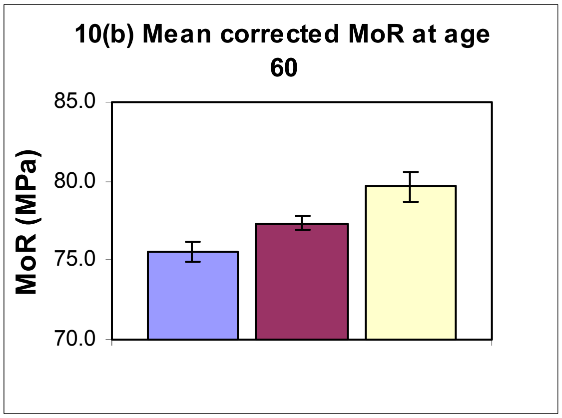


Fig. 10(b): Mean corrected MoR at age 60. Error bars denote standard error of the mean.

Legend: 🟦 **Seafield (age 72)** 🟪 **Mount High (age 66)** 🟨 **Glengarry (mean age 45)**

3.3.3 Testing for significant differences between sites

The graphical representation of the mean uncorrected and corrected values seems to indicate a trend that shows a significant improvement in the strength and stiffness of the naturally-regenerated Glengarry trees at age 60 compared to the two plantations. To test this, student's *t*-tests were carried out in order to evaluate whether the mean values of MoE and MoR for the Glengarry trees were statistically significantly different from the mean values in each of the plantations. The tests were performed on both uncorrected and corrected data and confidence levels were set at 95%. It was found that differences between mean mechanical properties in the Glengarry and Mount High trees and between the Glengarry and Seafield Estate trees were not statistically significant when the uncorrected data were compared (Glengarry vs. Mount High: $P=0.339$ for MoE and $P=0.334$ for MoR; Glengarry vs. Seafield $P=0.967$ for MoE and $P=0.967$ for MoR). Observed differences in uncorrected mean MoE and MoR values between Mount High and Seafield were also statistically insignificant ($P=0.196$ and $P=0.191$ respectively).

By contrast, student's *t*-tests on the age-corrected data showed that differences in mean corrected MoE values at age 60 between Glengarry and Mount High were statistically significant ($P=0.003$), as were differences between mean predicted MoR values ($P=0.032$). There were also statistically significant differences between Glengarry and Seafield in both corrected mean MoE ($P<0.001$) and corrected mean MoR ($P=0.001$) at age 60.

4.0 Discussion

4.1 Acoustic assessment of standing trees to predict strength properties

The results from acoustic sampling at Mount High and static testing of the small clear specimens indicate that acoustic velocities measured using the ST300 give a good indication of MoE in Scots pine and an even better estimate of MoR. This is in agreement with several studies which used NDE techniques on standing trees to confirm the relationship between acoustic speeds and strength properties for other species (Carter *et al.* 2005; Grabianowski *et al*. 2006; Wang *et al.* 2000). Results using v^2 as the predictor variable for MoE and MoR showed a slightly weaker, though still quite strong relationship, but an attempt to improve our predictions by incorporating density proved less successful. Eq. (1) suggests that ρv^2 should give the best relationship with MoE, but results are confounded because ST300 readings are taken in live sapwood (saturated with water), while the small clear samples were tested at approximately 12% moisture content. Evidence from other acoustic studies suggests that the fresh-cut density, rather than the specific gravity, should be used (Carter *et al.*2005; Sandoz, 1993). Any changes in the specific gravity (the mass of cell wall per unit volume) will lead to smaller changes in fresh-cut density because water is already present in spaces not occupied by cell wall. Using v^2 as the predictor of MoE and MoR is equally problematic because we cannot assume that the fresh-cut density is constant, which leads to the conclusion that the best predictor of MoE and MoR is velocity alone.

4.2 Age-related variation in strength properties

The effects of age were investigated firstly by looking at the results from acoustic sampling at Glengarry and then at the variation in MoE and MoR with cambial age in the Mount High small clear specimens.

4.2.1 The variation of acoustic velocity with age at Glengarry

Using the linear relationship between tree age and ST300 velocities at Glengarry in Figure 4(c) to derive projected velocities at a given tree age at other sites proved problematic. Firstly, although the relationship indicates that ST300 speeds have to be corrected for age, it appears that in this case the relationship is weak (r^2=0.017). Secondly, extrapolation outside the range of data is difficult because the straight line fit intercepts the Y-axis and assumes that stiffness increases indefinitely with age. The linear model therefore proved unacceptable for age-correcting ST300 speeds because it does not reflect the known variation in MoE and MoR with age, in particular the observation that stiffness and strength approach maximum values as a tree ages.

4.2.2 The relationship between age and strength properties in the small clear samples

Results from the small clear samples indicate a strong correlation between static stiffness and strength and cambial age. It was found that fitting the regression plots with logarithmic trendlines gave a closer approximation to the actual variation of strength properties with age described above, and for Scots pine more closely approximates biological reality than when the non-linear modelling approach of Haines and Leban (1999) is applied, as well as explaining a larger proportion of the variance (Figures 7 and 8). For this reason, these equations were used to predict MoE and MoR at age 60 in all three sites once the measured velocities had been converted to MoE and MoR using the relationships described in Section

4.1. Extrapolating outside the data range using this model gave MoE and MoR values comparable to the average values for Scots pine in Lavers and Moore (1983). Biblis *et al.* (1993) have also noted a general increase in MoE and MoR with tree age in loblolly pine (*Pinus taeda* L.), with an associated increase in structural grade out-turn.

4.3 The influence of density and growth rate in the small clear samples

The partial r^2 values for each parameter in the multivariate analysis for both MoE and MoR in the small clear samples indicate that the influence of growth rate (expressed as rings per centimetre) on the mechanical properties of Scots pine is small compared to that of density or age, which was also observed by Pearson and Ross (1984) in studies of loblolly pine. Density appears to exert a stronger influence, though small in comparison to the influence of age. Kennedy (1995) postulated that the general pith-to-bark rate of increase in MoE and MoR proceeded faster than the general increase in relative density, indicating that other factors, such as decreasing microfibril angle and increasing tracheid length with age, might have a stronger influence than density alone. Since density measurements are not readily available to foresters anyway, and the inclusion of growth rate will not improve the model significantly, the alternative logarithmic model using age alone as a predictor of MoE and MoR proved acceptable.

4.4 Comparing plantation-grown with naturally regenerated Scots pine

The mean predicted MoE and MoR values at age 60 between Glengarry and the two plantations do not differ greatly in magnitude, but the differences have been shown to be statistically significant. At face value it appears that timber from Glengarry is at least as good, in terms of mechanical properties, as plantation-grown timber. It is possible that increased competition due to dense natural regeneration and the preponderance of birch at Glengarry contributed to slower growth rates, which could be expected to positively influence density and intrinsic wood properties (Panshin and de Zeeuw, 1980), though another study has shown that density in Scots pine is more influenced by cambial age than by growth rate (Karenlampi and Riekkinen, 2004). Additionally, analysis of the Mount High small clears data shows that growth rate exerts a much smaller influence on MoE and MoR than age or density (Figures

5(c) and 6(c)). Even so, one indirect effect of slower growth in naturally regenerated stands is that increased competition early in the life of the trees (due to higher stocking densities) will lead to the formation of a smaller juvenile core in proportion to the overall log size. This in turn will positively affect mechanical properties and structural grade recovery as the trees reach maturity (Macdonald and Hubert, 2002). Pearson and Ross (1984) found that whereas increased growth rates resulted in a larger proportion of juvenile wood, this did not affect the strength properties of the mature wood, though they recommended longer rotations in order to recover a greater proportion of such timber. Biblis *et al.* (1997) found that increased stand densities resulted in increased flexural stiffness but had no effect on flexural strength in plantation-grown loblolly pine. Another study by Bendtsen and Senft (1986) found that both MoE and MoR increased with age in loblolly pine, recording a fivefold average increase in mean MoE and a threefold increase in mean MoR from the early juvenile wood to the late mature wood, though they point out that strength properties of plantation-grown loblolly pine are not expected to reach levels where they are comparable to those of naturally grown trees until they are at least 60 years old.

The quality of the parent crop is important when using natural regeneration to grow high quality timber, as many of the aforementioned traits show varying degrees of heritability, and clearly opportunities for genetic improvements through planting will be lost. It is important, therefore, to consider selecting seed trees with good stem form and lighter branching if timber quality is an important management objective (Worrell and Ross, 2000). The uniformity of competition found in plantations might not exist in naturally regenerated stands, potentially causing increased taper, branching and uneven crown development in trees grown under CCF systems, which could adversely affect intrinsic wood properties. Where the initial stocking densities are very high, stands will produce trees of good form regardless of the quality of the parent trees, particularly if selective respacing operations are undertaken when the trees are between 1-3m tall (Worrell and Ross, 2000). Continuity of management should ensure that adequate attention is paid to such factors if timber of a consistently high quality is to be produced following transformation to CCF systems.

This study has answered in part the question of how Scots pine timber quality might be expected to change following transformation to management under CCF systems using natural regeneration. Age-corrected, the strength properties of the trees at Glengarry are at least comparable if not an improvement on MoE and MoR values in plantation-grown trees. A key question here is whether the statistically significant differences found have any practical implications for improved timber quality from naturally regenerated stands. It is likely that a proportion of the observed variation might be explained by other factors, such as the quality of the original seed trees (genetic variation), stem form, taper, grain angle, branching, knot size, microfibril angle, and climatic and site conditions, many of which will have an effect on sawlog recovery and pass rates (Macdonald and Gardiner, 2005b). There is thus a need for these sources of variation in mechanical properties to be investigated, in conjunction with the standing tree tool, in long-term, silvicultural trials.

5.0 Conclusions

From this study it is possible to make the following preliminary conclusions:

1. Acoustic speeds measured in Scots pine using the Director ST300 standing tree tool are a reliable surrogate indicator of static timber properties such as modulus of elasticity and modulus of rupture.

2. ST300 readings should not be accepted at face-value without some consideration of sources of variation in mechanical properties, such as age.

3. CCF systems such as uniform shelterwood or seed tree systems have the potential to produce high quality Scots pine timber which is at least comparable in terms of mechanical properties (MoE and MoR) to plantation-grown timber. But results should be viewed with caution because, though statistically significant, the gains found in this study are not large enough to justify large-scale conversion.

4. Further research is required, in the form of long-term, replicated, randomised silvicultural trials in suitable CCF sites, so that the influence of other tree properties and site factors can be investigated alongside acoustic assessment, before firm conclusions about timber quality from naturally regenerated stands can be made.

5. The results of machine stress grading of battens are needed in order to be able to effectively infer pass rates at structural grades C16 and C24 directly from ST300 velocities.

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CHAPTER 3

Critique of methodology and closing comments

1.0 Achievement of study objectives

The aims of this thesis were to examine the effectiveness of acoustic assessment of standing Scots pine using stress-wave propagation techniques, and to look at the practical application of such testing in measuring timber quality in naturally regenerated stands managed under continuous cover forestry (CCF) regimes. The first objective – validating the use of the standing tree tool for predicting the intrinsic mechanical properties of Scots pine timber – can be said to have been achieved due to the strong correlations found between acoustic velocity and both MoE and MoR. These findings were in agreement with previous studies on other softwood species, and bring acoustic NDE techniques to the forefront of Scots pine timber quality assessment. In the UK, policy shifts are driving the increasing transformation of even-aged stands to management under CCF systems, and this is expected to influence timber quality both positively and negatively, depending on the timing and nature of silvicultural interventions. The number of sites managed under CCF systems is relatively rare and, where they do exist, production, conservation and recreation objectives are often given equal weight in management plans, thus underlining the importance to the forest industries of NDE techniques. The second objective of this study was therefore achieved because this justifies the use of a well-calibrated standing tree tool such as the Director ST300 to predict timber quality from naturally regenerated stands, which in this study then enabled provisional conclusions to be drawn about potential timber quality in Scots pine following transformation to CCF systems.

2.0 Limitations of this study

2.1 Site limitations

Ideally, more than one naturally regenerated site would have been included in this study, but this was restricted by both the availability of suitable sites with a known silvicultural history and the time available to complete the research. It was originally intended that, in addition to data from Mount High and Seafield Estate, I would use ST300 data from two other plantations, Strathcarron and Reraig, in order to add further weight to the investigation. Unfortunately the ST300 tool, though not a prototype, is still in the development stage and not a full production model, and was not functioning properly for some of the testing period. Consequently acoustic assessment at these sites was carried out on logs rather than standing trees, but the effect of moisture content changes and release of internal stresses following felling on ST300 readings is not fully understood. It was therefore decided that this data might be unreliable and was omitted from the study.

2.2 Potential sources of inaccuracy in age-correction calculations

Use of the small clear samples data might also lead to another source of error in the age-correction calculations, which first relied on converting ST300 speeds into MoE and MoR using simple regression line slopes from the small clear specimen results, followed by another correction using the logarithmic curve equation from the MoE versus age and MoR versus age regression equations. Though these equations yielded coefficient of determination values of around 50% or more, there are clearly other sources of variation in strength properties which need to be considered. Consequently the accuracy of the age-correction calculations cannot be known, and we cannot apply them with absolute certainty to trees in naturally regenerated stands which have grown in very different conditions from those in plantations, and which cannot be destructively tested.

2.3 Limitations of the standing tree tool

Aside from periodic operational faults with the ST300, another source of unreliability is that acoustic speeds are only measured in the outer 2-3cm of the wood, and at a certain height in the bole. As stressed in previous chapters, there is known to be significant variation in timber properties both radially from pith-to-bark and with increasing height in the tree stem, so how well the ST300 readings reflect this variation is a source of debate. A two-stage approach is therefore necessary. Firstly, we need to know how well the ST300 speeds correlate with the strength properties of the outer column of wood being measured, and secondly, ascertaining whether ST300 speeds can accurately predict the mechanical properties of the wood in other parts of the stem. A partial solution to this problem in this experiment was to use *weighted* MoE and MoR data so that ST300 velocities could be related to the whole tree at a particular height, and also to model the effect of age using a logarithmic equation which respected the pith to bark variation. Clearly extensive measurements will be required, again in conjunction with destructive testing, in order to delineate the full effect, both radially and with height up the stem, with the eventual aim of producing a comprehensive Scots pine timber quality model for predicting wood properties throughout the tree stem.

2.4 Lack of mechanical grading data

One of the original aims of the study was to compare the results of acoustic testing of standing trees at four plantations with the results of machine stress grading from sawmill studies, in order to infer pass rates for Scots pine using the ST300. Unfortunately, the results of the mechanical grading were not available in time to be included, so the relationship between dynamic and static MoE and MoR was tested using the static bending tests on the small clear specimens cut from logs at Mount High. Though the results indicate a good correlation between acoustic velocity and static strength properties, the addition of mechanical grading data would have enabled some prediction of pass rates at construction grades. Since mechanical grading outcomes are binary, however, i.e. ‘pass’ or ‘fail’ at a chosen grade, I would suggest that actual MoE and MoR data are still necessary components of these studies, so pass rates should always be used in conjunction with actual strength and stiffness values.

3.0 Opportunities for further study

There are many opportunities for further research into both the effectiveness of the standing tree tool and its application in naturally regenerated stands. Firstly, the mechanical stress grading data will be a useful addition to this study in order to infer pass rates from standing tree assessment and further calibration of the tool for use on Scots pine. Secondly, other factors known to influence timber quality, such as grain angle, stem form, microfibril angle, knot size and frequency, and the presence of juvenile wood or reaction wood, need to be investigated in long-term silvicultural trials at sites being managed under CCF systems. Ideally, such experiments should be fully randomised and replicated in order to reduce the effect of differences due to random variation. This means that the experiment will be designed in such a way that all treatments are present on each site and the location of each treatment is randomised. Forest Research have identified several sites in the UK where CCF has been practiced for a number of years, or where transformation is underway, which they consider suitable for such research. An investigation of how these factors influence timber quality under varying site conditions and in different silvicultural systems is imperative if we are to know the full implications for timber quality and log supply of transformation to CCF systems. The development of a Scots pine timber quality model will form an important part of future research.