The growth and quality of UK-grown Douglas-fir

by

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Abstract

Timber is a local, sustainable and valuable building material, but it is highly variable compared to other building materials (*e.g.* concrete, steel). The quality of wood is its suitability for the end-user, in this case the construction industry (via timber processors).

Douglas-fir is a tall conifer capable of producing high construction grade timber. Native to the north-western Pacific regions of America and Canada, Douglas-fir was introduced to the UK in 1827. After World War 1, the planting of conifers greatly increased due to the establishment of the Forestry Commission. Despite being a high value timber crop in North America, Douglas-fir was not highly utilised in Great Britain due to a perceived lack of suitable growing sites (requiring nutrient-rich soil) and a lack of knowledge on its qualities (mechanical). Consequently, it still to this day covers a relatively small amount of the total UK conifer plantation area, but under predicted climate change projections an increased range of sites will become more suitable for Douglas-fir, thus investigation now is imperative.

To investigate the quality of Douglas-fir timber and its biological variation, a variety of sites were sampled in Scotland and Wales. The variation in the physical and mechanical properties of UK-grown Douglas-fir were investigated to determine how strength and stiffness of Douglas-fir compares to other commercially important timber species in the UK (as well as compared to Douglas-fir grown in different countries). Standing and felled tree measurements relating to tree architecture and important for timber volume (*e.g.* size, height, branching habits and taper) were collected in the forest. This was followed by laboratory testing of wood samples obtained from those trees to determine important raw material properties. Ultimately this will enable some explanation and prediction of the variation in mechanical and physical properties in Douglas-fir.

It was found that Douglas-fir is stronger, stiffer and denser than the UK's most planted conifer, Sitka spruce. Wood adjacent to the pith (middle of tree) termed as juvenile was weaker, less stiff and less dense. Within-tree variation accounted for most of the variation for the key properties of strength, stiffness and density. It was possible to build models for some of these properties based on cambial age (ring number from the pith). Considering branches, it was found that within-tree variation in size, frequency, angle and status (alive or dead) were highly variable but it was possible to build empirical models to describe branch architecture for a typical tree. It was possible to measure the rate of swelling in oven dry Douglas-fir in the radial and tangential dimensions, but swelling of the longitudinal dimension was below the limit of detection for the apparatus. Heartwood area can be successfully predicted from the diameter of tree at a given point. It is hoped the information in this study will detail some characteristic Douglas-fir traits that may be deemed beneficial for the timber construction industry and allow understanding of its variability plus provide important models to use in helping to describe Great Britain's forest resource.

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Firstly, it has to be noted for any future students wishing to undertake a PhD, I would recommend not moving country, learning a new language, cutting off three extremely important digits (a thumb, index and middle fingers to be precise) or becoming engaged and married.

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Thomas Ashley Drewett

Author's declaration

I, the author, declare that the work presented here is my own, except where information and assistance obtained has been acknowledged. This thesis has not been submitted for any previous application for a degree.

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Abbreviations, acronyms, Latin and common names

Below is a list of acronyms used in this thesis. Various specific acronyms for variables used are given in each chapter.

Abbreviations/acronyms

CV: coefficient of variation (*i.e.* the ratio of standard deviation to the mean)

CW: compression wood

DF: degrees of freedom

EW: earlywood

GYC: general yield class, which is mean annual increment (m^3/ha)

JW: juvenile wood

LME: linear mixed-effect (models)

LW: latewood

MC: moisture content

MFA: microfibril angle

MOE: modulus of elasticity

MOR: modulus of rupture

MW: mature wood

N/mm^2: Newtons per square millimetre

NDE: non-destructive evaluation

NLME: non-linear mixed-effect (models)

RSE: residual standard error

SD: standard deviation

WHCL – Windthrow Hazard Class (where 6 has the highest susceptibility and 1 indicates the lowest susceptibility to windthrow)

YC: Yield Class

Measurement (numerical) acronyms

cm: centimetres

g: grams

kg: kilograms

ha: hectare (10,000 m^2)

kN: kilonewtons

km: kilometres

m: metres

m^3: square meters

mm: millimetres

MPa: megapascal

(Note: MPa to N/mm^2 is the same, *i.e.* 16 MPa is equal to 16 N/mm^2)

N: newton(s)

Common conifer species found in UK

DF: Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco)

Larch: (*Larix spp.*)

LP: lodgepole pine (*Pinus contorta*)

NF: Noble fir (*Abies procera* Rehd.)

NS: Norway spruce (*Picea abies* (L.) Karst)

SP: Scots pine (*Pinus sylvestris* L.)

SS: Sitka spruce (*Picea sitchensis* [Bong.] Carr.)

WH: western hemlock (*Tsuga heterophylla* [Raf.] Sarg.)

WRC: western red cedar (*Thuja plicata* D.Don)

1 General Introduction

1.1 Introduction to study

Timber is a renewable, low embodied energy, carbon-storing material used in construction. Sawnwood (not just construction timber) from UK-grown conifers will account for between 10-14 million m^3 per annum in the near future (UK Forestry Standard, 2011). High quality timber is beneficial for the architectural and construction industries, as the mechanical properties of wood predominantly affect its performance in construction applications (Dinwoodie, 2000; Bowyer *et al.,* 2007; Moore, 2011). Some construed problems with UK-grown timber are lower strength and stiffness (mechanical properties) compared to the same species grown in different countries under their unique conditions; either environmental or management (Moore *et al.*, 2013). Higher quality of timber relies upon having high strength and stiffness. Anatomical and growth-related features such as density, ring width, presence of knots, heartwood content, latewood content or grain angle will all influence the mechanical properties of wood (*e.g.* Bendtsen and Senft, 1986; Burdon *et al.,* 2001; Cave and Walker, 1994; Downes *et al.*, 2002; Evans and Ilic, 2001; Kretschmann, 2008). Mechanical properties can vary greatly within (*e.g.* in the longitudinal and radial axis) and between trees (Haygreen and Bowyer, 1982; Maguire *et al.,* 1991; Megraw, 1986; Zobel and Van Buijtenen, 1989; Burdon *et al.*, 2004) and between species (Cown and Parker, 1978; Lavers, 1983).

Of the four main conifer species grown in the UK, Sitka spruce (*Picea sitchensis* [Bong.] Carr.) is the most important economically. The National Inventory of Woodlands and Trees (Forestry Commission, 2003) reports that Sitka spruce covers just over ~690,000 ha in the UK (from a total conifer area of 1,405,604 ha). This accounts for 49.2% of all conifers in the UK, or 29.1% of the total trees. This is much higher than Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), which lies marginally above 45,000 ha in total for the UK (~4% of total conifers).

Originally, the ability of Sitka spruce to grow on a wide range of sites (Robinson, 1931) enabled it to be planted on upland sites with poor soils (Stirling-Maxwell, 1931). In comparison to Sitka spruce, Douglas-fir, which has superior timber properties (Lavers, 1983) is site-specific in that it is described as requiring a more nutrient-rich and freely-drained soil. It is predominantly for this reason that Douglas-fir has not been planted extensively in the UK despite being an important timber species elsewhere in the world. Although the least available of the four main coniferous species (with the others being spruce, larch and pine), Ray *et al.* (2002) predict under likely climate change scenarios Douglas-fir will remain suitable across most of south and east England, and become very suitable in the west Midlands and much of the southwest and east Wales and more suitable across the whole of Scotland (particularly in the east).

Not enough is yet known about the current timber quality and characteristics of Douglas-fir, from the perspective of end-users in the UK or how this quality varies. A recent study (Bawcombe, 2013) showed some basic information about DF growing in the southwest of GB, however research in Sitka spruce (Moore *et al.*, 2009b) that environment, and particularly growing latitude can have an effect on estimated stand stiffness. Therefore it is also necessary to investigate DF growing also at more northerly latitudes. The aim of this study is therefore to include both complimentary and comparable research to Bawcombe (2013). In particular it was aimed to produce empirical models of key timber properties for DF that will help forest management.

1.2 Objectives/aims

The main aims are to describe and model:

- 1 – The timber properties of UK-grown Douglas-fir
  - Age-related trends in strength, stiffness and density of clearwood samples
  - Strength, stiffness and density of structural-sized samples
  - Distortion of structural-sized samples
- 2- Branching characteristics of Douglas-fir
  - Branch size
  - Branch frequency

    - Mortality probability
    - Angle of insertion
- 3 - Heartwood formation and dimensional stability of heartwood
    - Heartwood/sapwood (proportion) variation up the stem
    - Taper profiles of Douglas-fir
    - Swelling rates of heartwood/sapwood

1.3 Thesis outline

Chapter 2 introduces the Douglas-fir tree, why it is being investigated and what is to be achieved. This section will cover the physical tree (crown and stem characteristics, the microscopic level of wood, the macroscopic level of wood, heartwood and sapwood, branching and finally juvenile wood). Following this, the growth and timber quality of Douglas-fir in the UK (the concept of timber quality, growing conditions for Douglas-fir, mechanical and physical properties of Douglas-fir and timber grading) shall be examined, as will factors affecting quality.

Chapter 3 explains both the materials used and methods applied throughout entirety of the study.

Chapter 4 determines the density, strength and stiffness of clearwood and structural battens (destructively and acoustically). Distortion for structural battens is also tested. Investigating the radial differences and variation within trees and sites is undertaken. The aims and objectives are to investigate these attributes and describe the variation in structural battens

Chapter 5 determines the density, strength and stiffness of clearwood samples (destructively and acoustically). Investigating the radial differences and variation within trees (*i.e.* age-related trends) and sites is undertaken. The aims and objectives are to investigate and model these attributes and also to look at the differences between data for this study and Bawcombe (2013). The results and models will be presented alongside thorough discussion and resulting conclusions.

Chapter 6 examines branching characteristics of Douglas-fir grown in Scotland and will contain the background (*e.g.* branch physiology, the effect of branches on wood quality, the effect of management on branch growth and modelling and previous studies). The aims and objectives are to investigate and model size, angle of insertion, mortality probability and frequency of branches. The results and models (predominantly bases upon vertical position in stem) are presented alongside thorough discussion and resulting conclusions.

The dimensional stability of Douglas-fir heartwood is investigated in chapter 7. Discs taken from the stem were scanned and investigated for heartwood content and sapwood content. Swelling samples were also taken to see if heartwood (both extracted and not) or sapwood changed the dimensional stability of wood. The aims and objectives are to investigate and model these attributes as well as taper profiles. The results and models will be presented alongside thorough discussion and resulting conclusions

Chapter 8 is a review chapter and tie everything together, discussing in detail how the physical and mechanical properties of Douglas-fir are affected by their key drivers, with the express outlook to informing timber processors and users of the key properties and suggestions of implementing changes in Douglas-fir regimes (if deemed necessary).

2 The growth and quality of Douglas-fir in the UK

2.1 Why investigate Douglas-fir?

2.1.1 The concept of timber quality

In managing forests for timber production, it is important to understand the connection between the growth of trees and the quality of timber that can be produced. Larson (1969) states the concept of wood quality is the arbitrary evaluation of an isolated piece of wood, tree part, or wood derivative, while Mitchell (1960) states that the physical and chemical characteristics possessed by a tree that enable it to meet the property requirements for different end products are what defines quality. From a forest owner or manager's perspective, this would likely include large volume returns of straight timber (lack of defects such as large steep branches, "twisted" stems) as these better quality logs fetch a higher price and are less prone to be rejected by sawmills. For the processor (*i.e.* sawmillers), the quality may refer to similar objectives such as straight timber with less branching (knots) but also include certain mechanical properties or limited warping (*e.g.* timber that has twisted). Architects typically stipulate certain criteria for timber, *i.e*. a certain grade, depending on the timbers intended use (*e.g*. flooring, roofing). Thus, wood quality is predetermined by the end-user who ultimately looks for certain aspects of the timber relating to their specific use; predominantly these aspects are mechanical for softwoods. Not all processed trees are the same quality, with the Forestry Commission (1993) classifying sawlogs into two grades (green and red[1]).

2.1.2 The state of the market and UK Forestry in relation to Douglas-fir

Douglas-fir coverage lies marginally above 45,000 ha in total for the UK, with less than half currently owned by Forestry Commission (FC) or Natural Resources Wales (NRW). For this public forest estate, 18,871 ha of Douglas-fir

[1] The "better" green sawlogs must reach a minimum of 16 cm (top-end) and not exceed 1% sweep (*e.g.* bend) and there is explicit specifications for branchiness (80% of the branches in a whorl must be less than 50 mm in diameter). Red sawlogs must not exceed 1.5% sweep and must reach a minimum of 14 cm (top-end) diameter with no limits on branchiness.

lie in category 1 (high forest which is or can become capable of producing saw logs) and only 147 ha lie in category 2 (stands of lower quality than category 1). Private/other coverage of Douglas-fir is 25,953 ha for category 1 and 250 ha for category 2. The highest planting decades for total coverage are the 1950's and 1960's (10,973 ha and 11,036 ha respectively). According to current (FC, 2011) statistics, the coverage of Douglas-fir lies at around 24,000 ha in England, 11,000 in Wales and 10,000 in Scotland. For the EU taken as a whole, total land covered by all forests exceeds 35% compared to the UK, at 12% (Forestry Commission, 2011).

The timber market in the UK is one of the largest net wood-based material importers in the world (65% of sawnwood in 2010 was imported; Forestry Commission, 2011). Sitka spruce is the most commonly planted commercial species in the UK and therefore dominates the UK forest products' industries. The UK Wood Production and Trade for 2010 (Forestry Commission, 2011) state that 9.9 million tonnes of roundwood was harvested and delivered to industries, a 12% increase from 2009. Of this, 5.6 million green tonnes went to sawmills, with the remaining going for fencing, woodbased panels, pulp and paper, woodfuel and export: 2.5 million tonnes (a 25% increase from 2009).

The production of wood products included 3.1 million m^3 of sawnwood, 3.4 million m^3 of wood-based panels and 4.3 million tonnes of paper and paperboard. The import was 5.7 million m^3 of sawnwood and 2.7 million m^3 of wood-based panels. In addition to this, 8 million tonnes of pulp and paper was also imported. All in all, total value of wood products imports was £6.7 billion (£4.6 billion was pulp and paper).

In 2011, over 7.6 million m^3 total sawn softwood was consumed by the UK (Moore, 2012). Construction timber accounted for 62%, pallet/packaging wood 18%, fencing and outdoor 17% and others (2%). Given the higher monetary return (than non-construction), attaining large volumes of construction grade timber from the UK resource is assumedly the principal objective (for the construction and thus by default the sawmilling, industry).

Douglas-fir can be compared to the main timber species grown in the UK which in order of quantity are spruce, pine and larch (followed by Douglas-fir in fourth place). However, as climate change scenarios predict that Douglas-fir will be more suitable for more UK sites in the near future and there is the possibility that Douglas-fir could consequentially become a “bigger player” in construction-grade timber in the UK. To address this, UK-grown Douglas-fir properties should be well-documented and investigated to determine their status with respect to current grading parameters. This is imperative to determine the marketability of Douglas-fir quality as a construction-grade material, and making the best use of the UK forests.

2.2 The Douglas-fir tree

While a conifer tree could be described as a paraboloid, there is virtually no marketable timber under seven cm in diameter thus the tree should be described as a frustum of a cone (*i.e*. tapered “cone-shape” with flat bottom and flat top). Because conifer trees taper upwards, there is a range in available raw products. Trees were traditionally cut into roundwood (originally pit props, structural poles, and piles) but sawnwood is primarily now divided into structural timber, pallet/packaging timber and fencing as well as external cladding. These products are grouped by their minimum (thus, “top-end”) size in diameter. They all have their own markets (*e.g.* fencing is made from small-diameter stakes from the top-end of the tree) but the construction industry calls for structural timber where the end-user requirements are crucial. In this case, strength and stiffness (along with density and distortion) are key properties of interest. As this thesis aims to describe the mechanical performance of UK-grown Douglas-fir for the construction industry, the key properties (strength and stiffness) and the drivers behind them (*e.g*. growing rate) are investigated. To understand the macroscopic characteristics of Douglas-fir, the microscopic properties are reviewed below.

2.2.1 The crown and stem

The crown (canopy/foliage) is responsible for photosynthesis. The crown is supported by the stem which has two clear physical functions: structural support and conduction (water and mineral transport). A conifer cross-section shows, from outside in: the protective bark; inner bark or phloem; cambium; and then xylem – otherwise known as wood, as highlighted in Figure 2-1.

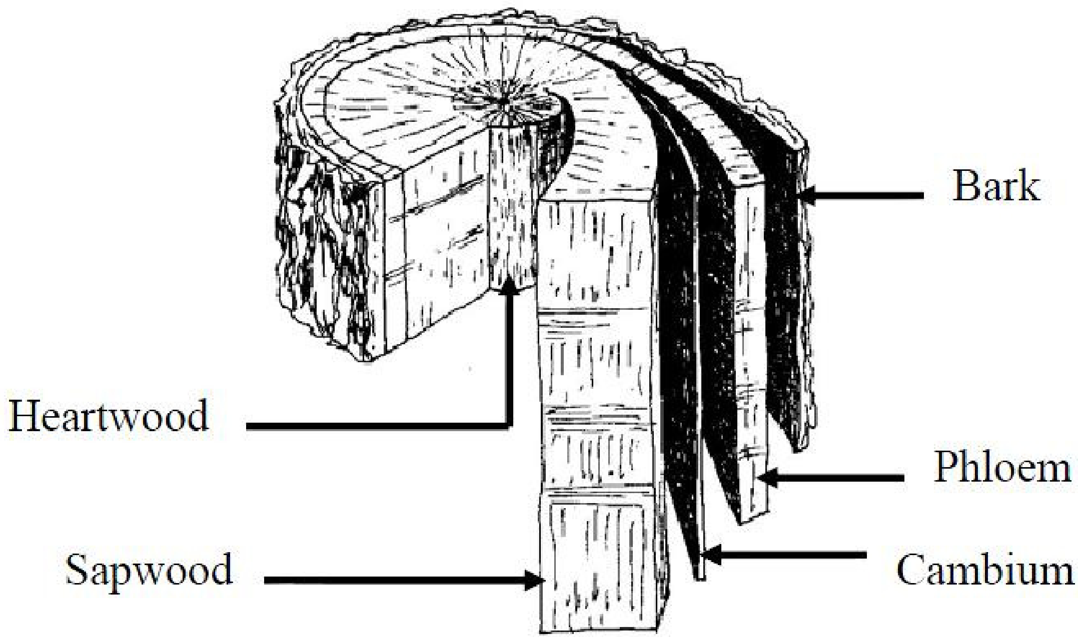

Figure 2-1. Diagram showing essential macroscopic features of a softwood stem. From Bangor University.

Xylem are responsible for transport of water and nutrients from the roots to the crown (physical process), and the phloem are responsible for the transport from crown to roots (biophysical process, Denny, 2012). Water is transported up through softwood tracheids and passes through bordered pits (a specialised valve or aperture at the microscopic level).

2.2.2 Microscopic level of wood

At the microscopic level, wood is a complicated material. For conifers (also termed softwoods) there are five major cell types: longitudinal tracheids, ray tracheids, strand tracheids, parenchyma and epithelial cells. Tracheids and parenchyma are the two cell types that influence macroscopic properties. Softwood is mainly comprised of tracheids (Walker *et al.,* 1993). These constitute about 90% of the cells in conifers and are aligned vertically (Dinwoodie, 2000), with most of the remaining being ray parenchyma (average volume 7.3%, Panshin and De Zeeuw, 1980) as seen in Figure 2-2.

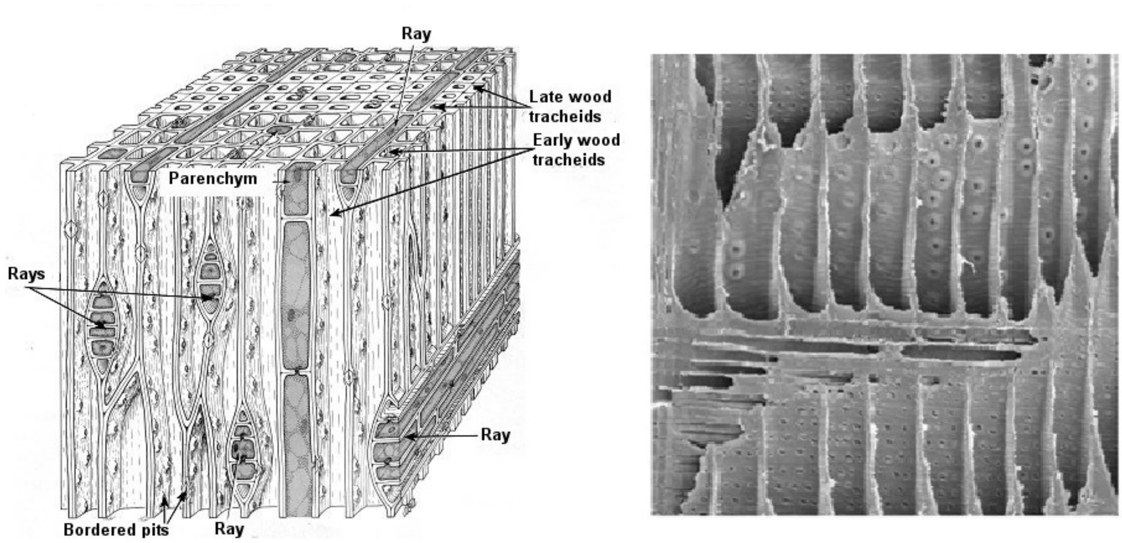

Figure 2-2. The left image shows a diagrammatic representation of conifer cellular structure, after Rose *et al*. (1979): Botany, a brief introduction to plant biology. The right shows a scanning electron microscope image of Douglas-fir tracheids and parenchyma.

These tracheids are long and thin (length/diameter ratio of about 100:1) and have pits for fluid exchange. Many cells have up to 100 bordered pits each, normally occurring at the ends of the cells. Rarely, in a certain few species, special spiral thickening of the tracheid occurs. This is the case with Douglas-fir, which comprises a ridge of cell wall material that spirals down the inside of the cell wall (Figure 2-3).

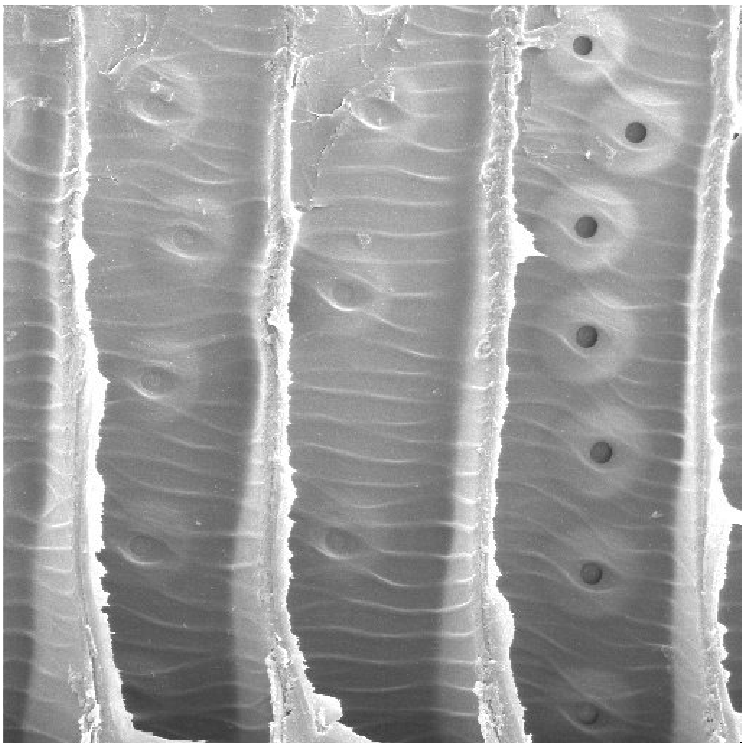

Figure 2-3. Scanning Electron Microscope (SEM) image of Douglas-fir spiral thickening (Edinburgh Napier University)

Tracheids provide support (*e.g.* Meylan and Butterfield, 1972) and the quality of timber can be influenced by tracheid length (Daniel *et al.*, 1979) as longer tracheids are stronger. The average length of a longitudinal tracheid of US-grown Douglas-fir lies between 3.00 and 3.88 mm (determined from specific examples in Panshin and De Zeeuw, 1980). Tracheid lengths vary between species, between tree and position within the tree. For example, Sitka spruce is generally less, *e.g.* 1 – 3 mm (Chalk, 1930; Dinwoodie, 1963; Brazier, 1967). Shorter, wider tracheids occur in the early part of the growing season (earlywood or "springwood") and increase in length as the season changes to summer for all temperate species of conifers.

Trees grow upwards (taller) and outwards each year. The vascular cambium (Figure 2-1, hereafter referred to as cambium) is the zone where new cells are produced (cell division), beginning in the spring of each year when growth is rapid and concentrated on water conduction. The cambial layer completely sheathes the tree and in spring, the cambium divides and produces phloem cells on the outside and xylem cells on the inside. Later in the growing season the formation of thin-walled cells changes to thicker-walled cells as the emphasis shifts from conduction to mechanical support (Zobel and Van

Buijtenen, 1989). Known as earlywood (EW) and latewood (LW) respectively, the proportion of each can have a significant impact on the strength and stiffness of wood, as LW is denser and has a lower microfibril angle (MFA, discussed below) than EW (Lachenbruch *et al.*, 2010). The difference between EW and LW is clearly seen in Douglas-fir as the rings are highly visible (latewood is much denser and quite dark). LW and EW have different hydraulic properties. In Douglas-fir, under normal climatic conditions, sap flows in LW tracheids could be neglected compared to early-season tracheids (Domec and Gartner, 2002; Martinez-Meier *et al.,* 2008). Each EW and LW "ring" together equates to one annual growth cycle (excluding lammas growth, a second flush of growth that sometimes occurs towards the end of the growing season).

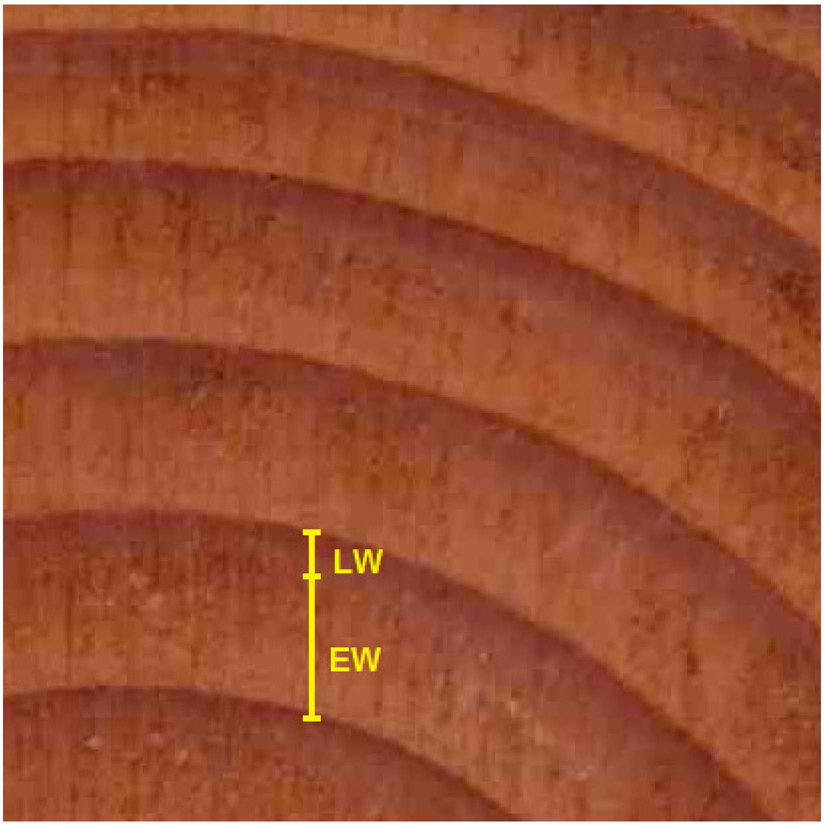

Figure 2-4. Showing the difference in colouring between earlywood (EW) and latewood (LW), where LW is darker due to higher density.

Figure 2-4 shows the obvious darker colouring of LW rings, while Figure 2-2 (left side) demonstrates the cell difference between EW and LW.

The cell wall of tracheids is comprised of several layers which are (after the middle lamella which is the material used to bond neighbouring cells) the primary wall (P) and secondary wall (S). These are laid down sequentially as the cell is formed (Bailey and Kerr, 1935). As exhibited in Figure 2-5, the S_2 layer is the largest of the three layers in the secondary wall (75-90% of entire cell wall is comprised of the S_2 layer), and thus can heavily influence the behaviour of the wood.

These three layers all have a different MFA, which in the S_2 layer is usually 10-40° for most conifers. MFA relates to the winding angle of the cellulose microfibrils in the middle layer of the secondary cell wall, and this angle is usually larger nearer the pith and decreases with tree height (Donaldson, 2008). As the MFA decreases from *c*. 40° to 10°, the stiffness of the cell wall increases, from pith to bark (Walker and Butterfield, 1996). Higher longitudinal shrinkage occurs at higher MFA angles (*e.g*. Cave, 1968; Walker and Butterfield, 1996) and is responsible for some degrade on drying. Given that the S_2 layer is so substantial, the longitudinal stiffness of wood will be largely dependent on its MFA (Cave 1968; Cave & Walker 1994).The outer and inner (S_1 and S_3) secondary wall microfibrils are approximately transversely orientated, while the S_2 layer is axially orientated (*e.g.* Wardrop and Preston, 1947; Barnett and Bonham, 2004). This alternating structure provides crucial axial stiffness and collapse resistance for the upright growth needed by plants (Bamber, 2001; Donaldson, 2008).

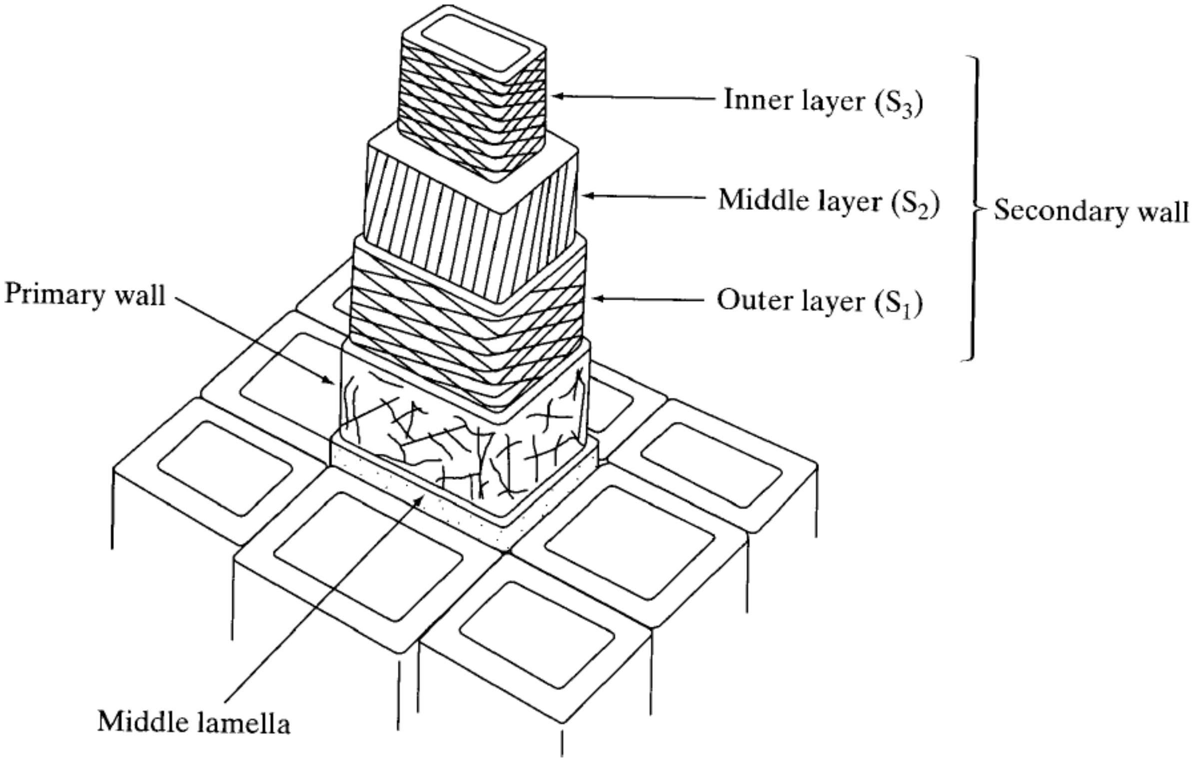

Figure 2-5. Diagrammatic representation of a softwood cell displaying the primary and secondary walls and their constituent parts. From Dinwoodie, 1989.

2.2.3 Heartwood and sapwood

Douglas-fir has a noticeable difference in colour change between the inner and outer wood, known as sapwood and heartwood (Figure 2-1 and Figure 2-6). Heartwood is the inner layer of wood in the tree which no longer transports water, formed in the transition zone when the ray cells die and is normally a deeper/darker colour, resulting from extractive materials being deposited in the tracheid walls and cavities at the time the cells die (*e.g.* Graham and Kurth, 1949; Hillis, 1962; Megraw, 1986). It is generally accepted that heartwood formation is an active developmental process (*i.e.* a form of programmed cell death). The lighter-coloured sapwood is the zone where conduction and storage of starch and lipids happen (Dinwoodie, 2000). Heartwood of Douglas-fir has a higher resistance to fungal and insect attack. In a living conifer, sapwood shows typical moisture percent around 150%, compared with 40% for heartwood (Megraw, 1986).

Megraw (1986) states that the width of sapwood remains approximately constant regardless of tree age, size or height position in the tree; therefore sapwood has a larger percentage of total tree volume in younger trees/top of tree while Dinwoodie (2000) states the width of conifer sapwood varies widely with rate of growth and age of tree. Beauchamp (2011) shows that in UK-grown Sitka spruce and Scots pine there is significant variation in sapwood depth and ring number from the pith between sites and trees.

Figure 2-6. A transverse section of Douglas-fir displaying the difference from pith to bark between heartwood (HW) and sapwood (SW) and the noticeable latewood rings

2.2.4 Moisture content

Wood holds water both physically (free water) and chemically (bound water). The moisture content (MC) of a piece of wood is usually expressed as a percentage of oven-dry weight. Oven-dry density is given as:

$$Density_{OD} = \frac{Weight_{OD}}{Volume} \quad [2\text{-}1]$$

and moisture content is given as:

$$MC(\%) = \frac{Weight_G - Weight_{OD}}{Weight_{OD}} 100\% \quad [2\text{-}2]$$

where $Weight_{OD}$ is the oven-dry weight of sample and $Weight_G$ is the green weight of sample. Adjustment factors (*i.e.* to 12% MC) are given in chapter 3.

Wood is hygroscopic and the MC is dependent on various factors. As the wood dries, it first comes from within the cell (*i.e.* vacuole) then at fibre saturation point (FSP) the water comes out of the cells walls. The fibre saturation point is usually described at being 27-30% MC (*e.g.* Dinwoodie, 2000) but could be up to 40%. Quirk (1984) found that the FSP (extractive-free cell wall) for Douglas-fir is 35%. It must be noted it not a simple linear process, some cell wall moisture will inevitably be dried before fibre saturation point and *vice versa*.

UK sawmills routinely condition their timber to a nominal value of 20% MC, but standard testing conditions specify it is to be dried to 12% as this will more accurately portray in-service conditions. While longer kilning schedules may prove a slightly higher cost for sawmills, the distortion occurring undoubtedly will cause much more timber to be rejected visually. Timber will dry naturally in-service, leaving some customers disgruntled with the behaviour and performance as it distorts from a MC of 20% down to 8-14% MC depending upon how it is used.

Dinwoodie (2000) presents data on various MC's of a sample of conifers in green condition (*i.e.* freshly felled) highlighting the difference between sapwood and heartwood. Typical values for Douglas-fir are 40% MC in heartwood and 116% MC in sapwood. Compared to similar 'growth or akin' species *e.g.* western hemlock (*Tsuga heterophylla* (Raf.) Sarg), the heartwood MC % in DF is low, *c.f.* 93% MC in heartwood and 167% MC in sapwood for western hemlock. Douglas-fir has a lower MC in the heartwood compared to Sitka spruce.

2.2.5 Juvenile wood

The formation of what is widely-accepted as juvenile wood is generally considered to be within the first 10-20 rings from the pith. There is no universally accepted definition of juvenile wood, it is either generally defined as the point where wood density becomes constant (*e.g.* Kennedy, 1995) or at a given cambial age as above, generally between 10-20 rings (*e.g.* Brazier and Mobbs 1993; Zobel and Sprague, 1998; Verkasalo and Leban, 2002; Cown et al., 2004; Cameron *et al*., 2005; Auty, 2011). This "cylindrical" formation around the pith as a young tree grows with abundant space has characteristics which affect the performance of timber, namely lower density, shorter tracheids, larger microfibril angle and spiral grain (Dinwoodie, 2000; Larson *et al.,* 2001; Macdonald and Hubert, 2002; Burdon *et al*., 2004). The potential problems it causes for structural timber were observed as far back as 1966 (Koch,1966).

Cameron *et al.* (2005) describe that researchers now make the distinction between “juvenile wood” and “crown formed wood” (*e.g.* Amarasekara & Denne 2002, Gartner *et al.* 2002). The commonly-known interpretation of “juvenile wood” is best described as the region around the pith in which the wood properties are associated with cambial age, independent of crown influences. Crown formed wood (usually dominated by knots) implies an effect of the presence of green branches and the associated proximity of the cambium to foliage and actively growing terminal meristems (Burdon *et al.,* 2004). Burdon *et al*. (2004) proposes that alternative terminology be used to describe juvenile wood. Instead of being termed “juvenile and mature wood”, they propose “corewood” and “outerwood” be used based on the inadequacy of the former on two main counts: basing a characterization only on radial variation does not fit the well-established botanical concept of maturation (Burdon *et al*., 2004) and the fact that various other important wood properties show substantial axial variation at equal ring number from the pith. The authors go on to argue for a two-dimensional characterization of wood properties, adopting a description which can show within-stem variation that occurs from the pith outwards and the ground upwards (*i.e.* “…juvenility versus maturity for the progression up the stem, and corewood versus outerwood for the radial progression from the pith to bark”) as seen below in Figure 2-7. As wood sampled in this thesis will primarily relate to the crown-free stem, juvenile wood will therefore refer to the corewood ascertained by ring number from pith (*e.g.* rings 1-15).

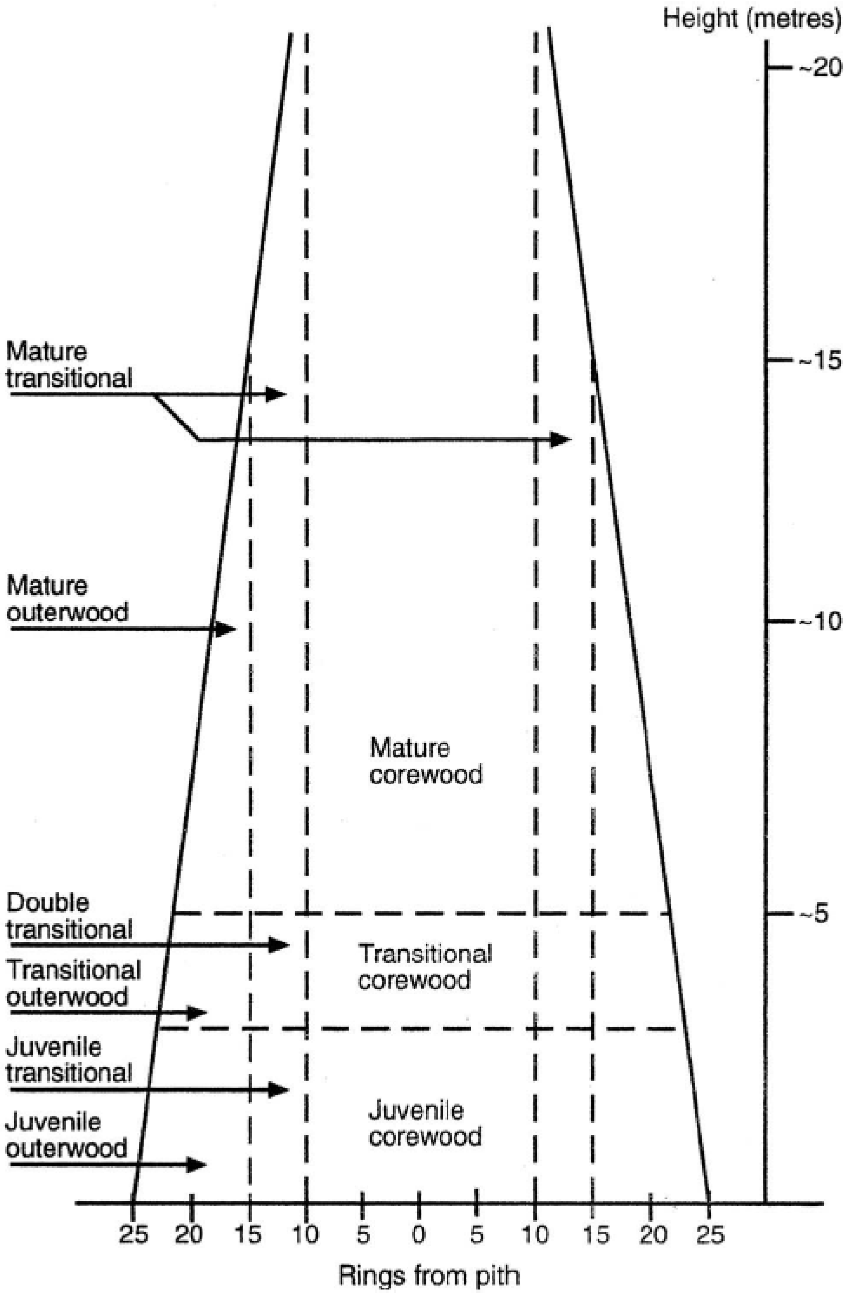

Figure 2-7. Schematic section of a typical *Pinus radiata* D. Don stem showing proposed categorization of wood zones from Burdon *et al*. (2004).

With Douglas-fir, the term “juvenile period” is complex, as density initially decreases going outwards from the pith, levelling out after 7-10 rings, then increases gradually but steadily over the following 30-50 years (Megraw, 1986). This is also noted in Sitka spruce by McLean (2008), who noted wood density decreased with increasing cambial age (during first 10 years) then increased, with most of the variation due to radial variation within a tree. However, Megraw (1986) shows fibre length increases abruptly for first 20 rings then gradually out to at least ring 30 and MFA follows an approximately opposite pattern, while most of the excessive longitudinal shrinkage has diminished by rings 7-10. With Sitka spruce for example, the boundary between juvenile and mature wood is difficult to define and a cambial age of 12 – 13 years has been arbitrarily chosen (*e.g.* Brazier and Mobbs, 1993; Cameron *et al.,* 2005). In Douglas-fir, a study by Abel-Gadir and Krahmer (1993) the period of juvenile wood (as defined by density variation) varied as much as 11-37 rings from the pith. As well as juvenile wood, knots severely affect the mechanical performance of timber.

2.2.6 Branching

Trees need leaves and branches for survival. Branches, which radiate out from the stem, are the structures that hold the needle or leaf up to the sunlight (the main site for radiation interception and incoming precipitation, *e.g*. Aoki, 1989; Whitehead *et al.,* 1990; Bartelink, 1996; Keim, 2004). In conifers, branches usually occur in whorls on an annual basis, and these collective branches contain masses of needles. This foliage is responsible for transpiration, photosynthesis and respiration, thus essential to the tree's life. While influencing tree growth, as they control the amount of needle/leaf area (Vose *et al.,* 1994), branches are affected by competition for these resources. Consequently, silviculture (*e.g*. spacing) which affects stand density will likely alter branching characteristics as intraspecific competition occurs while branches vie for dominance in the canopy.

The severity of branching habits (*e.g.* size and frequency) may affect the quality of timber produced. Most branches extend all the way to the pith (Megraw, 1986) and cause deviation of the grain due to the annual ring bending and deviating around a branch until it dies (or is pruned), wherein the cambium of the tree will grow around the now-dead knot. If timber is cut before the branch dies, it will be intergrown ('tight') as opposed to an encased knot ('loose') where branch growth has stopped. Whatever space an embedded knot occupies, the deviation of grain around said knot will be a greater area. As branches grow and are incorporated into the stem, they do so both individually and collectively in varying amounts (*i.e.* in whorls or interwhorl branches). As they represent a discontinuity, knots induce stress concentration in sawn timber (Dinwoodie, 2000) and cause varying amounts of strength reduction based on their size, frequency, position and status. The angle of insertion will affect knot area as steeper angles (*e.g.* ramicorn branches) relative to stem will give a larger knot area (Figure 3.1 below).

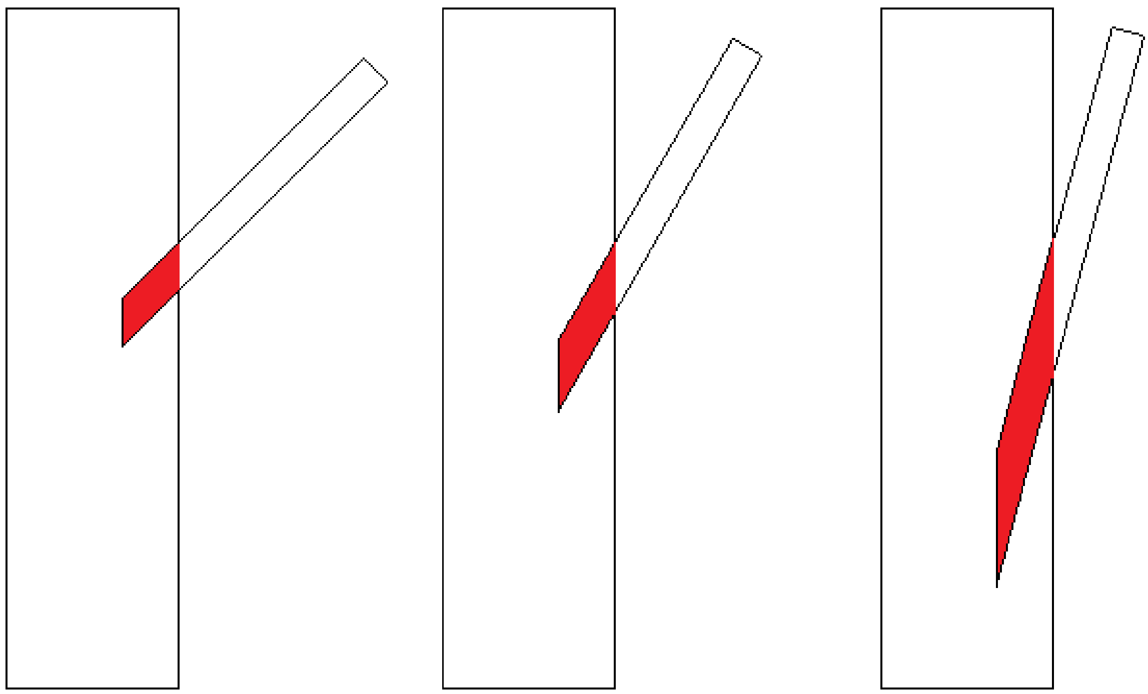

Figure 2-8. Showing (from left to right) as branch angle decreases (parallel with stem) from 45°, 30°, to 15° the knot area for the same given depth (horizontally into stem here) increases.

McKimmy (1986) highlights that in Douglas-fir, knots cause the greatest economic degradation (or loss) when grading structural timber. While some of the more frequently occurring stem form defects in Douglas-fir are basal sweep (Sundström and Keane, 1999) and persistent and vigorous branching (Cahill *et al.,* 1986; Oliver *et al.,* 1986) which affects timber and veneer grade recovery (Fahey *et al*., 1991), it is typically branch size that is of greatest importance (*e.g.* Maguire *et al*., 1991; Weiskittel *et al*., 2007b). One of the main factors affecting the size of branches and therefore knots is stocking density (*e.g.* Achim *et al.,* 2006; Hein *et al.,* 2008; Maguire *et al.,* 1991; Smith 1961).

Models of branching habits have not been undertaken for UK-grown Douglas-fir and existing studies and models (both destructive and concurrent) have been developed mainly in the Pacific N.W. (*e.g.* Hann 1999; Maguire and Hann 1987; Maguire *et al.,* 1991; Maguire *et al.,* 1994; Maguire *et al.,* 1999; Weiskittel *et al.,* 2007 A/B) and Germany (Hein *et al.,* 2008) where climatic conditions and silvicultural techniques are decidedly different, or for other species such as Norway spruce (*Picea abies* (L.) Karst *e.g.* Colin and Houlier, 1991), Scots pine (*Pinus sylvestris* L. *e.g.* Auty, 2011; Makinen and Colin, 1998) and Sitka spruce (Achim *et al.,* 2006). Various tree-level attributes such as height to crown base, total tree height or diameter, alongside branch-level attributes, *e.g.* branch height or growth unit (GU) position will often relate to and influence branch characteristics (size, angle, status or frequency).

2.2.7 The forest stand and its control

Silviculture is human manipulation of the forest environment for a particular benefit. Spacing (distance between each plant at a given phase) is deemed to be one of the most important (silvicultural) factors for determining conifer timber quality (*e.g.* Brazier and Mobbs, 1993; Macdonald and Hubert, 2002; Moore *et al*., 2009[a]; Smith and Reukema, 1986). Space available for a tree to utilize will affect its stem and crown characteristics and consequentially wood properties. There are three main ways of controlling spacing: firstly - at establishment; secondly - respacing of normally stocked stands before canopy closure and thirdly - thinning of older stands.

For timber purposes, rotation length (age at harvest) is another important management decision. Shorter rotations will generally yield less volume and a higher proportion of low quality juvenile wood. Increasing rotation length is a way to improve mechanical properties and volume yields (Bendtsen and Senft, 1986; Moore *et al*., 2012). An estimation of how rotation length might affect the timber produced can be obtained by looking at the radial variation in timber properties which represent the trees at different ages.

2.2.8 Site and growing conditions for Douglas-fir

As substantial (conifer) afforestation occurred with the founding of the Forestry Commission (FC) after World War 1 for greater national security of the timber resource (Birch, 1936), Douglas-fir was not originally highly utilised (Scott, 1931). This was due to various complaints (*e.g.* susceptibility of the tree to disease, liability of the timber to split in nailing, and dressing difficulties due to hardness of knots). However, in 1931 advantages due to its shade tolerance (*i.e.* less tree growth constraint with lower light availability compared to certain other species) were noted (Scott, 1931).

Originally, the ability of Sitka spruce to grow on a wide range of sites (Robinson, 1931) enabled it to be planted on upland sites with poor soils (Stirling-Maxwell, 1931). In comparison to Sitka spruce, Douglas-fir is quite site-specific in that it is thought to require a more nutrient-rich soil. It is predominantly for this reason that Douglas-fir has not been planted extensively in the UK despite being an important timber species largely elsewhere in the world.

Characteristically, Douglas-fir has particular criteria to ensure adequate growth. Tyler *et al.* (1996) indicate that the best root penetration of Douglas-fir occurs on fine, well-drained podzolic earths (Kupiec and Coutts, 1992), for example favouring valley slopes while unsuitable for exposed positions, heather ground, waterlogged and shallow soils. Traditionally Douglas-fir has been planted in the UK on higher quality soil such as brown earth, brown earth intergrades and upland brown earth. Pyatt and Suarez (1997) indicate that UK-grown Douglas-fir is very intolerant of ericaceous vegetation and the ideal conditions are fresh and rich. While brown earth or fertile soils are generally considered best for Douglas-fir (on sheltered sites), Tyler *et al.* (1996) showed that Douglas-fir can (on average) can have a higher general yield class (GYC *i.e.* the increment growth per year as expressed as m^3 ha^{-1}) on podzolic soil.

The UK has a unique climatic range where windiness is always a factor to consider in forest management scenarios. Douglas-fir prefers a 'Detailed Aspect Method of Scoring' (DAMS) wind score under 12 as optimal, possibly up to 16 being suitable (Raynor, 2009). Anything over DAMS score of 16 is unsuitable. The DAMS score is an index developed by Quine (1993) which measures the physiologically constraining effect of wind on growth. Douglas-fir is liable to windthrow on soft wet ground (except where drains are well maintained). In Scotland, windiness is probably the second most important limitation to tree growth after warmth (Pyatt and Suarez, 1997).

2.2.9 Latitude and climate change

Currently, Douglas-fir is a minor species compared to pine and spruce. As suggested earlier, it is possible that Douglas-fir may become a more economically important species in the future (*e.g.* Ray *et al.*, 2002).

The latitudinal range of mainland Great Britain is ~50° N to ~58° N. Using this latitudinal range to examine the possible effect of a changing environment (climatic) on timber properties by investigating distinct areas (a south England region, a mid-wales region and a mid-north Scottish region) will be undertaken. This will facilitate an examination of extent of the variability of the Douglas-fir timber resource, which is needed for a timber grade to be produced.

While the rate, intensity and extent of climate change (temperature increase) is a topic that sparks debate, it is a common agreement amongst scientists that a global shift in climate to higher temperatures will occur. As the temperature in temperate and boreal regions in the future is predicted to rise under various emissions assumptions (*e.g.* IPCC, 2007), the projected impacts of climate change on forests in northern and western Europe show that warmer temperatures are expected to result in positive effects on forest growth and wood production, at least in the short to medium term (Lindner *et al.*, 2010). However this faster growth may have a negative impact on timber properties. In the UK, temperature typically increases from south to north; therefore the effect of increasing temperature may be partly examined.

The differences of inherent wood properties between UK countries (*i.e.* latitudinal differences) may be pronounced with future climate change and warrants investigation (for the purpose of this study, Northern Ireland was not included in latitudinal range).

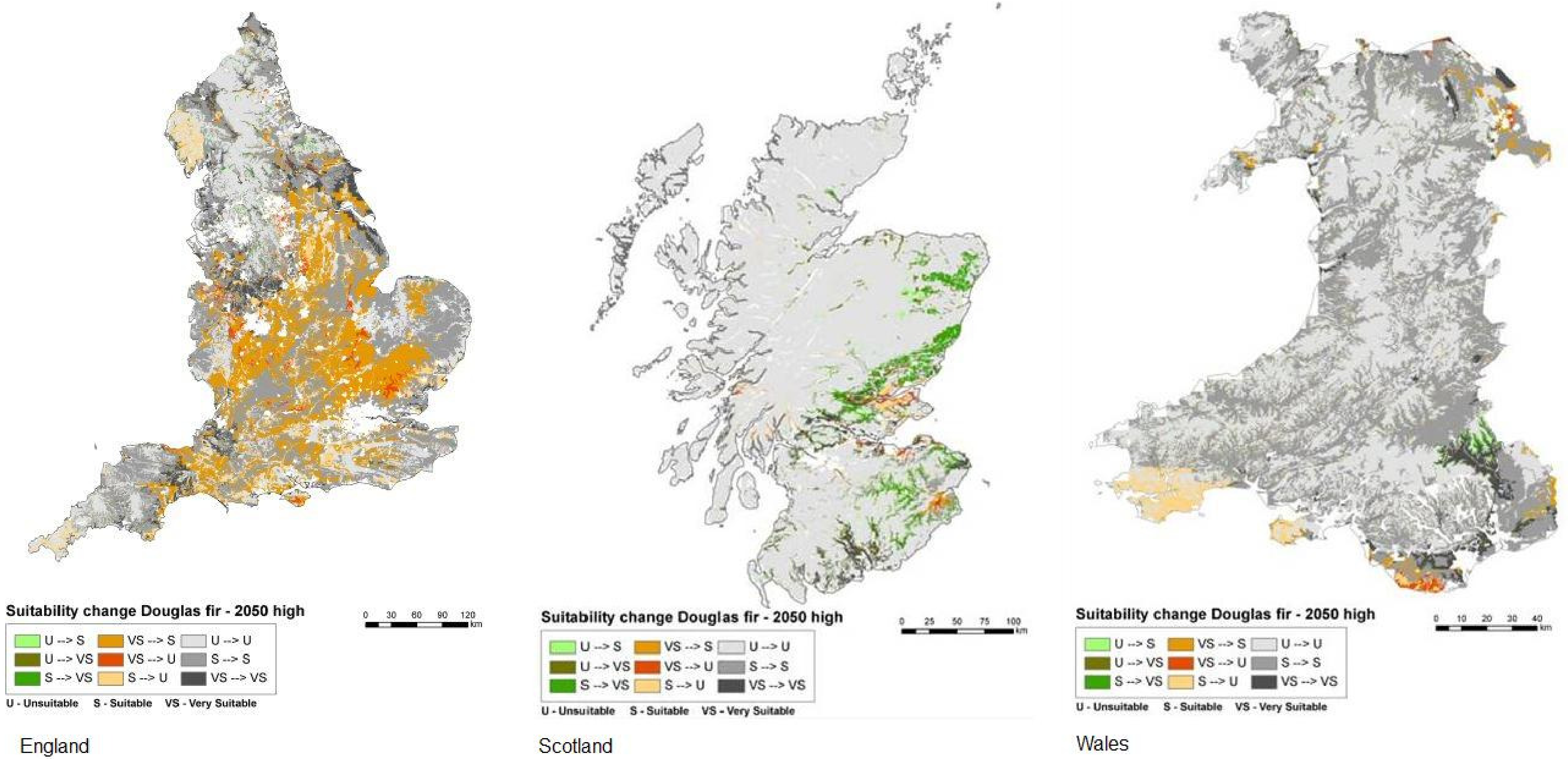

Figure 2-9. Showing England (left), Scotland (middle) and Wales (right) species suitability with climate change predictions using high as opposed to conservative estimations , in this case Douglas-fir (Forestry Commission, 2011) in the year 2050. While it is estimated large areas will remain unsuitable, Scotland in particular shows an increase in suitability.

2.3 Mechanical and physical properties of Douglas-fir

2.3.1 Individual properties

High quality timber is beneficial for the architectural and construction industries, as the mechanical properties of wood (stiffness and strength) affect its performance in construction applications (Dinwoodie, 2000; Bowyer *et al.,* 2007; Moore, 2011).

Using defect-free or "clearwood", Lavers (1983) presents the mechanical properties of British-grown species. Table 2-1 highlights that Douglas-fir is comparable in strength (with European larch and Scots pine) and marginally highest for stiffness.

Species	Density (kg/m^3)	Strength (N/mm^2)	Stiffness (N/mm^2)
European larch	545	92	9,900
Hybrid larch	465	77	8,500
Japanese larch	481	83	8,300
Scots pine	513	89	10,000
Sitka spruce	384	67	8,100
Douglas-fir	497	91	10,500

Table 2-1. Showing the mean density, mean strength and mean stiffness for certain species in the air dry condition (~M.C. of 12%). Data are from Lavers (1983)

Lavers (1983) based testing on British Standard BS 373:1957 and shows UK-grown Douglas-fir achieved a mean strength of 91 (N/mm^2) and mean stiffness of 10,500 (N/mm^2) using quasi-static bending (three point loading). For impact, resistance to suddenly applied loads (maximum drop of hammer) was 0.69 (m). For hardness (resistance to indentation on side grain) it achieved 3420 (N) and with shear (maximum shearing strength parallel to grain), 11.6 (N/mm^2). USDA (2010) presents clearwood American Douglas-fir MOR as 82 - 90 N/mm^2 and MOE as 10,300 - 13,400 N/mm^2 at 12% MC, and Canadian Douglas-fir clearwood as 88 N/mm^2 for MOR and 13,600 N/mm^2 for MOE (also at 12% MC) for clearwood specimens (property values based on ASTM Standard D 2555–88).

There are two main limitations to these results from the literature:

1. European standards for timber grading to design specifications, dictate that testing needs to be of structural sized timbers to reproduce actual service loading conditions (including all defects, *e.g.* knots, slope of grain). Therefore, for validity a study must be made on the variation of structural sized Douglas-fir timber in Great Britain.

2. Mechanical properties vary by age and this is not known for the literature results. In order to compare one tree or region to another, the age of the samples and something of the growing environment should be known.

Therefore, in this study, the aim was to investigate the timber properties of structural timbers and study clearwood specimens coming from known ring numbers from the pith to allow empirical modelling of a given property without confounding effects (*e.g.* knots, slope of grain).

2.3.1.1 Definition of stiffness

'Modulus' is a quantity that expresses the degree to which a substance possesses a property and Young's modulus of elasticity (MOE, often referred to as stiffness) is the ratio of stress to strain in the elastic range. Stress is force per unit area (the load) and strain is the ratio of change in length.

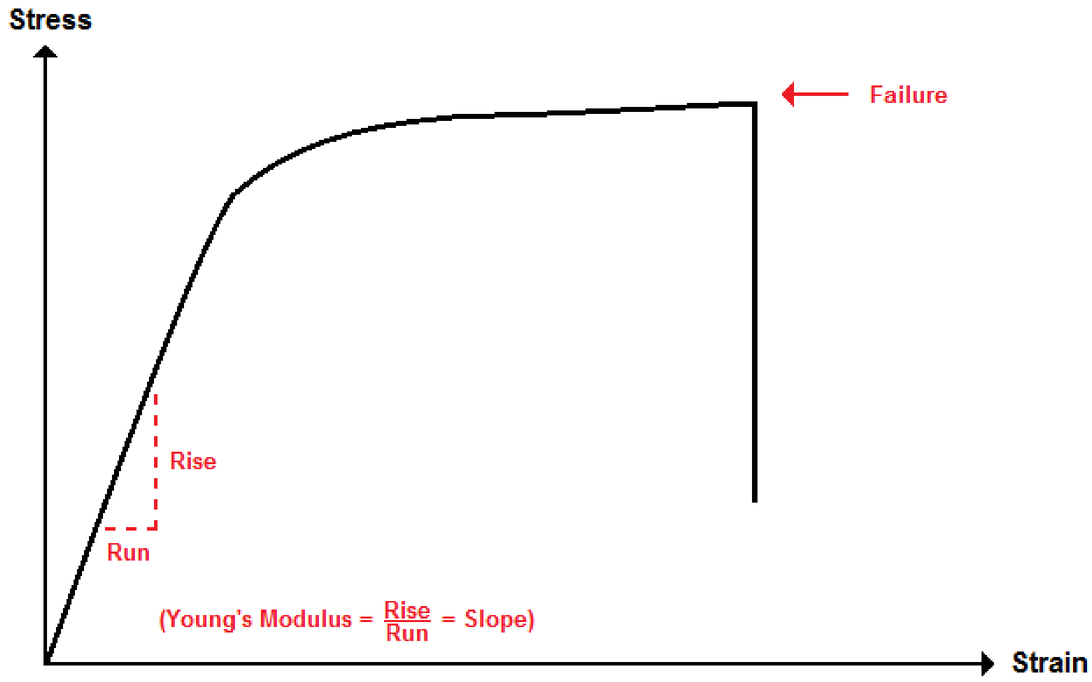

Figure 2-10. Showing typical stress curve for timber. Strain is the ratio of change in dimension to original dimension and stress is the force.

Lavers (1983) shows the stiffness of UK-grown Sitka spruce is less than UK-grown Douglas-fir, which in turn is less than Canadian Douglas-fir (12,700 N/mm^2), indicating there may be differences in mechanical properties of Douglas-fir grown in different countries. However, the background (*e.g.* age of trees sampled) was not given. The importance of stiffness is recognised as it is correlated with strength, consequently strength can be estimated from stiffness without destroying the sample(s).

Being anisotropic, wood stiffness will differ depending on the direction of loading (longitudinal, radial and tangential directions). Wood in the longitudinal direction will always be stronger than either the radial or tangential directions (both transverse). This difference in directions is due in part to the orientation of tracheids running approximately in the longitudinal direction as seen in Figure 2-5.

MOE will generally refer to the "static" measurement, where MOE is determined by mechanical testing (bending) of sample. However, MOE can also be ascertained dynamically (non-destructively), using stress wave velocity (*e.g.* acoustic tools). The acoustic tool(s) works by exciting (by hammer blow) the sample and following the speed of transmission of the disturbance through the test specimen (Searles, 2012) which is likely to be affected by the properties (*e.g.* stiffness and density) of the timber sample. Resonance does not directly measure the transmission of the disturbance, it measures the frequency and calculates speed (speed = frequency x wavelength). Searles (2012) gives an overview on plane waves, indicating that a structure such as a cut timber length (rod-like) will be more uniform than a structure that has no "end-point" (*e.g.* time of flight methods, commonly used for standing trees). Each dynamic sample was first struck at one end (for longitudinal vibration) and then perpendicularly in the centre (flexural vibration) with a small hammer, causing them to vibrate at their natural resonant frequency, allowing MOE to be estimated. The equation for estimating acoustic MOE is pv^2 (density x velocity^2).

For structural timber (large samples, including defects such as knots), four-point bending tests are undertaken (as opposed to three-point bending for small, defect-free samples). With four-point bending, there exists several "outputs" of MOE. EN408 demonstrates either local or global can be used to measure MOE. This is because EN384 has a separate adjustment that is intended to convert global MOE measurements (the way tests are normally done now) to be equivalent to local MOE measurements (the way tests are done in the past). This equivalent "local MOE" calculated from global MOE is actually the shear-free MOE which is used here in this thesis. Local MOE is the true bending while global MOE includes shear-deflection. "Local" and "global" MOE are different, because so-termed local MOE is determined in a four-point bending test with loads in the 3rd points via deflection measurement within the constant moment length of 6 times the depth (h) of the beam (actual length of l_m= 5 h). Contrary, so-termed global MOE is determined according to EN408 from deflection measurement over full span of 18 time depth (h) including the effects of shear and of indentations at the support locations. Thus, while it is the "local MOE" that is ultimately desired, global MOE (which takes into account the shear-span) is to be adjusted into a shear-free MOE (which should be similar to local MOE), using equation in EN384 (*shear-free MOE = 1.3 * global – 2690*).

2.3.1.2 Definition of Strength

Strength is defined as timber's resistance to failure under loading. Strength is termed modulus of rupture (MOR) and is measured by determining the maximum force (through load) exerted at the time of failure. As with stiffness, strength will vary in different directions (*e.g*. over the stem radius). Lavers (1983) shows the strength of UK-grown Sitka spruce is less than UK-grown Douglas-fir (67 N/mm^2 and 91 N/mm^2 respectively).

2.3.1.3 Density

Density is mass per unit volume. It must be noted that both cell-wall material, water (free and bound) and extractives all contribute to the final density reading measurement. Extractives will usually count for less than 3% of the dry mass (Dinwoodie, 2000) but other species (*e.g.* pines) can be much higher. Bearing in mind that pure dry cell wall material has a density of 1500 kg/m^3 (Preston, 1974, USDA, 1999), the density measurement will be determined by the amount of cell wall present within the sample (*i.e.* space not occupied by vacuole) and the pores.

The density of wood significantly influences mechanical properties of timber (*e.g.* Bendtsen, 1978; Megraw, 1986; Cave and Walker, 1994; Auty, 2011). As the strength and stiffness of timber (*e.g.* its rigidity) comes from the cell wall which itself is a constant density, the volume of material present influences these mechanical properties (*i.e.* a higher density equates to more cell wall material) depending on how that material is arranged.

It is also an indicator of strength due to its positive correlation (*e.g.* Burdon et al., 2001; Downes et al., 2002; Panshin and de Zeeuw, 1980; Zobel and Jett, 1995). Douglas-fir shows a difference in density values between earlywood and latewood, which may considerably magnify the importance of latewood proportion on stiffness and strength (Lachenbruch *et al*., 2010). Lavers (1983) highlights that Canadian Douglas-fir appears to be denser than UK-grown Douglas-fir. X-ray machines in the UK use density (and knottiness) to predict strength. Grading machines assign battens into strength classes by using a measured "indicating" property (or properties).

2.3.2 Timber grading

The three properties above are arguably the most important mechanical (and physical) properties of wood as they are they are the primary factors by which structural timber classes are assigned in (EN14081, 2003; EN408, 2003; EN384, 2004; EN338, 2003). For structural timber, there exists global MOE in addition to local MOE. A simple explanation would be that local MOE is the true bending deflection while global MOE also includes shear deflection (to attain local MOE, global MOE should be used and converted to an equivalent shear-free). Solli (2000) notes that global MOE is more robust, due to the global deflection being around ten times that of the local, but will ultimately contain a higher number of possible errors. Nocetti *et al.* (2013) reported that while using the true local modulus, including knot values led only to slight improvements in their MOE model. The differences between global and local MOE are described in detail in Aicher *et al.* (2002). For this thesis, both local and global MOE will be covered but the emphasis will be on shear-free MOE for the reasons described above.

There are two main ways of grading lumber (Kretschmann and Hernandez, 2006), either visual (which is typically the more conservative) or machine grading. However, some studies have shown that the rules of visual grading are not really adapted to certain softwoods (*e.g.* Roblot et al., 2008) and tend to underestimate Douglas-fir mechanical properties (Lanvin, 2005). Strength classes play an important part in an engineer's/architects' design and specification. The most commonly used classes are defined in a European Standard (EN338, 2003), which sets out characteristic strength, stiffness and density values (below), with the rules for allocation of timber in EN14081 (2003). (In EN338 2003 strength classes for softwoods (prefixed C) range from minimum class of C14 (lower end of properties) to C50 (highest end). The numeral in the strength class name represents the characteristic bending strength (5th percentile) of the timber. Grading machines assign sawn timber into these strength classes using an indicating property (*e.g.* density, knots, stress wave speed or non-destructive reaction force).

Strength, stiffness and density are the grade determining properties. All other properties in EN338 (2003) are derived from these three properties. For a species/grade combination, one of the three properties above will be the limiting factor. As noted, strength cannot be measured unless by destructively tested, so evaluating the timber and predicting strength is critical. A timber grade does not apply to the properties of an individual piece, (although the pieces are individually assigned to grades) but as a population of timber which should meet the minimum characteristic values for a given strength class.

There is a minimum characteristic for strength (lower 5^{th} percentile), stiffness (mean) and density (lower 5^{th} percentile).

Property	C14	C16	C18	C20	C22	C24
MOR (N mm^2)	14	16	18	20	22	24
Mean MOE (kN mm^2)	7	8	9	9.5	10	11
Density (kg m^3)	350	370	380	390	410	420

Table 2-2. Selected softwood strength classes showing characteristic values for bending strength (MOR), stiffness (MOE) and density (CEN, 2003a). The 5^{th} percentile value of MOR/desnity is the value for which 5% of the values in the sample are lower or equal.

The structural properties of timber are crucial for its designated end-use. Building professionals (*e.g.* architects, engineers) will specify a certain grade (*e.g.* TR26 for roof trusses, or C16 and C24 timber frame construction that the timber must meet. The comprise that exists is to use either more material of a lower (cheaper, more attainable) grade, or less material of a higher (more expensive, less easily attainable) grade (*e.g.* C24 or TR26). The quandary therefore is the fact these higher grades, while "obtainable" are not readily available from UK-grown timber currently; hence timber of this quality is almost exclusively imported.

UK grown Sitka spruce, while being planted extensively, characteristically attains the C16 grade (Sitka spruce in other countries differs). UK-grown Douglas-fir is much denser than UK-grown Sitka spruce, in addition to being stiffer and stronger (*e.g.* Lavers, 1983), therefore is a potential source of higher grade timber than Sitka spruce (and could potentially alleviate the reliance on imports for higher graded timber).

3 Materials and Methods

3.1 Experimental overview

To understand Douglas-fir properties in the UK, three sites were chosen in Scotland and two sites in Wales, to represent a “north region” and “mid-region”. In chapter 5, clearwood (defect-free) properties which compliments this study in the South West of England (Bawcombe, 2013), is discussed to give an overview of the British Douglas-fir resource. The age range for the Scottish and Welsh sites was 42-58 years (based on relevancy to general practise in the UK).

Within the bounds of a PhD project, selecting sites/trees that represent the entirety of the UK’s resource is not possible without some difficulty or a lack of replication. For the purposes of this study (being an initial investigation into Douglas-fir growth in the UK), it was decided that trees ranging in age from 42-58 will show both radial trends (*e.g.* juvenile wood variation) and represent typical rotation/cutting patterns for Douglas-fir in the UK today.

3.2 Site selection

3.2.1 Northern sites

Three sites in Scotland were chosen for this study. There were differences in initial spacing and yield class (Table 3-1), with age (45-58 years old), wind class hazard, elevation and mixture (sites where chosen based on being a monoculture, not a mixed-species stand) being relative constant(s). The three sites were from three different forest districts around Scotland; all Scottish field work was undertaken between July - October of 2010 (age of stands linked to this date). The three sites, Laiken (NH901517), Pitfichie (NJ671173) and Loch Tummel (NN785593) were chosen on criteria below (Table 3-1) and are highlighted on the map (Figure 3-1).

3.2.2 Mid-range sites

Two sites were chosen in Wales were also based between the ages of 42-49, with spacing as main variable and yield class the second variable (again keeping wind class and mixture constant). All field work was undertaken June

2012 (age of stands linked to this date). The 2 sites, Mathrafal (SJ114105) and Ruthin (SJ101558) are also highlighted on the map below (Figure 3-1).

3.2.3 Southern sites

The English sites were not part of the experimental process of this study. Rather, the English sites were added from a complimentary study (Bawcombe, 2013).

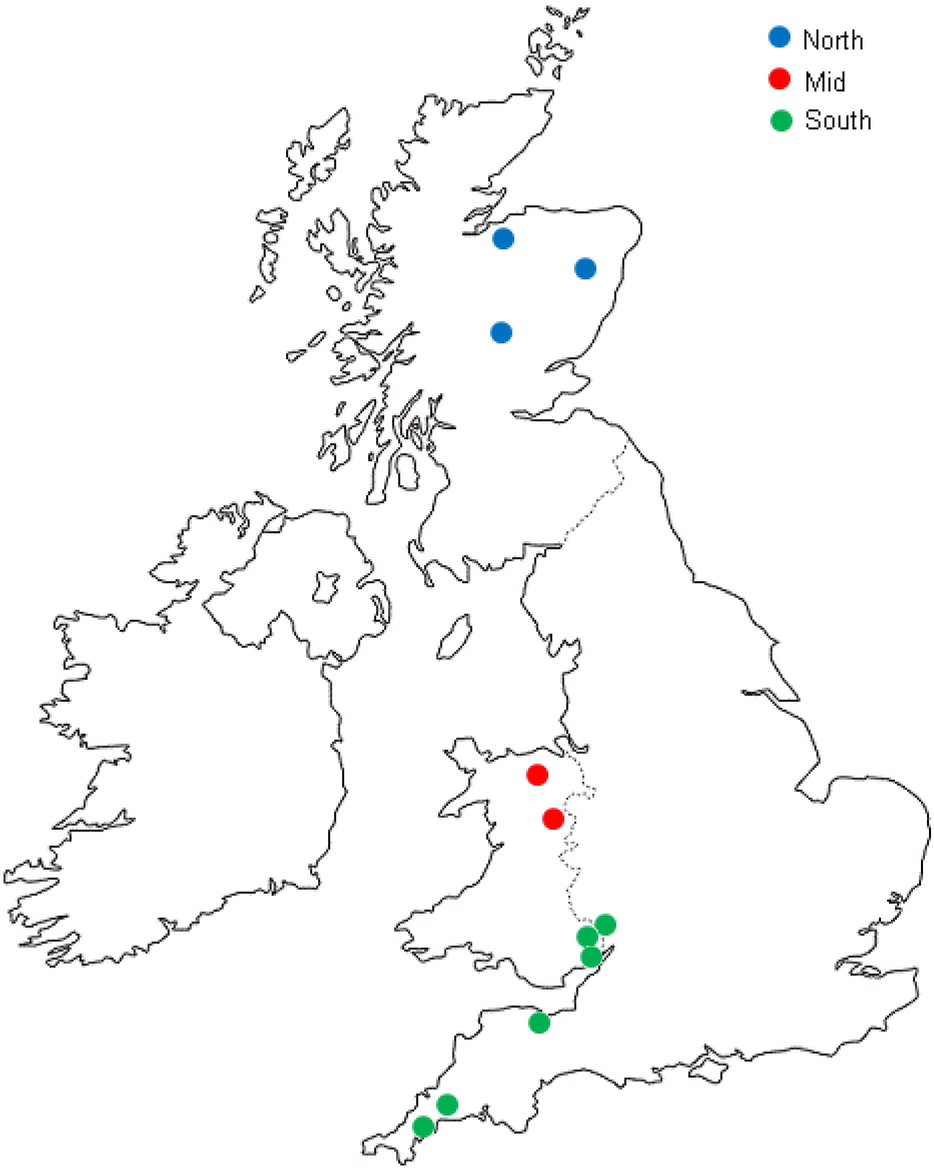

Figure 3-1. Showing map of UK with each site highlighted. In descending order (highest latitude first): Laiken, Pitfichie, Loch Tummel, Ruthin, Mathrafal, Nagshead, Highmeadow, Tidenham, Over Stowey, Quethiock and Lostwithiel. The key indicates the colour of the region (colours chosen at random). This portrays the range of latitude, where north England/south Scotland is currently lacking representation. The green sites (southern) were tested by Bawcombe (2013).

Country	Site	Location	DAMS	SMR	SNR	Elevation	YC	Age	Area	Mix	Spacing	DBH	HT	Stock	SS
Scotland	Laiken	NH901517	10.3	Very Moist	Very Poor	110	20	57	10.4	P	1.7	39	34.3	550	C
Scotland	Loch Tummel	NN785593	10.9	Fresh	Medium	180	14	45	19.4	P	1.5	36.8	27.9	315	C
Scotland	Pitfichie	NJ671173	10.7	Very Moist	Very Poor	200	10	58	6.2	P	2	33.2	27.4	535	C
Wales	Mathrafal	SJ114105	10.5	Wet	Medium	150	22	42	3.9	P	2.0	42.1	31.2	245	C
Wales	Ruthin	SJ101558	11.8	Fresh	Medium	180	12	49	5.1	P	1.7	43	29.2	215	B
England	Nagshead	ST607929	12.6	Very Moist	Rich	100	*	42	*	*	*	*	*	200	*
England	Highmeadow	SO540133	7.5	Medium Dry	Medium	75	*	50	*	*	*	*	*	250	*
England	Tidenham	SO563003	14.2	Fresh	Poor	210	*	48	*	*	*	*	*	200	*
England	Over Stowey	ST171359	13.2	Slightly Dry	Very Poor	220	*	46	*	*	*	*	*	300	*
England	Quethiock	SX343637	17.6	Fresh	Medium	50	*	75	*	*	*	*	*	*	*
England	Lostwithiel	SX117608	14	Fresh	Medium	80	*	78	*	*	*	*	*	*	*

Table 3-1. Showing site (and mean tree within site) variables. Location = OS Grif reference, DAMS = explained in text, SMR = Soil Moisture Regime, SNR = Soil Nutrient Regime, YC = yield class, Area = total coupe area in hectares, Mix = the mixture, whether pure (P) or mixed (M), Space = Original plant spacing (in square format, e.g. 2 x 2), DBH and HT = the average diameter or height at breast height of all trees in site, Stock = the total stems per hectare at time of felling, SS = stem straightness score. * = Unknown

3.3 Field work

3.3.1 Plot and standing tree measurements

3.3.1.1 Plot layout and measurements

Circular plots at a size of 0.02 ha^{-1} (8 m radius) or 0.05 ha^{-1} (12.6 m radius) depending on stocking density were used. Where sloping occurred, minor corrections to plot size (radius) were needed to compensate for slope factor. All slope conversions followed standard Forestry Commission protocols (Matthews and Mackie, 2006). Plots were placed in a randomly selected area at least 1.5 tree-lengths from any edge of the stand. Plot layout, distribution and size were in accordance with Forestry Commission Mensuration (Matthews and Mackie, 2006), each plot size per site being chosen to represent the stocking density, ensuring between 7 and 20 trees were contained in each plot. From each site, 3 plots were investigated and within each plot 3 trees were sampled, equalling 45 trees over the 5 sites.

All live Douglas-fir trees > 7 cm at breast height (DBH) were measured. Any other species were to be ignored but as each site was a pure mixture, no other noticeable natural regeneration occurred of differing species. The measured trees in each plot were divided into dominance class based on DBH. The DBH values for each plot were divided into quartiles, where Dominant is deemed as being from the upper quartile (75^{th} percentile to maximum), Co-Dominant is between 50^{th} and 75^{th} percentile, Sub-Dominant is between 25^{th} and 50^{th} percentile and everything in lower quartile (suppressed or dead/dying) was not used. For each plot, one tree was chosen from each of the 3 classes at random following all live tree measurements (section 2.3.1.2).

For each site, a soil pit (minimum of two per site) was dug and soil type(s) investigated. The protocol for soil identification was to dig a pit to identify the soil horizons and classify them. Normally 30-50 cm was adequate; however in some cases more was required to correctly define horizons. As there is no standard procedure for soil horizon nomenclature and almost every country has their own unique system, the system used by the British Soil Survey is used here. The soil in the forest was classified under standard soil classification terms for UK forestry, of which 7 groups are identified. These are: freely and imperfectly drained soils; poorly drained soils; organic soils or bogs; skeletal soils and ranker soils; littoral soils; calcareous soils; man made soils. The latter four groups can actually be described within the first three, but are sufficiently distinctive enough to justify separation at the major group level.

Site	Soil Survey	Main soils
PI	Podzols with brown earth intergrade (some Ironpan)	3b (some 4b)
LT	Podzol (mainly)	3 (some 1zs)
LA	Brown earth (very sandy)	1 (some 1u)
MA	Brown earths	1 (some 3)
RU	Mostly podzolic	3b (some 1u and 4b)

Table 3-2. Showing the soils identified on-site by digging a soil pit as described above. The first three sites (PI, LT, LA) are Scottish and the second two (MA, RU) are Welsh.

3.3.1.2 Stranding tree measurements

All live Douglas-fir trees (> 7 cm diameter at 1.3 m height) in each plot were measured for DBH to the nearest 0.1 cm. Top heights of all trees were recorded using a Haglöf Vertex hypsometer (Haglöf AB, Sweden) to the nearest 0.1m. Girth was taken by a rounded-down DBH tape and recorded to nearest 0.1 cm. Each tree was marked for both north and west aspects, for use in later protocols (*e.g.* branching and material processing). The slenderness ratio was recorded (total height/DBH) for each tree.

Acoustic measurements were taken on all trees using an IML Hammer (Instrumenta Mechanic Labor GmbH, Germany) to record velocity of each tree, using time-of-flight method (assuming a wet density of 1000 kg m^3) to give a 'green' dynamic MOE. The method was to test both north and south sides of trees separately, with a distance of 100 cm between the exciter (impact point) and the receiving sensor (both approximately 30° to the trunk).

The scoring system for stem form (straightness) that has been developed for assessing the straightness of Sitka spruce growing in the UK (Macdonald *et al.,* 2001) was conducted on Douglas-fir to test whether or not the same system can be applied. Each tree was appraised from ground level to 6 metres in height around the full circumference. A score was given between 1 (lowest) and 7 (highest) to each individual tree based solely upon straightness of the stem and stem form (*i.e.* major scarring/ramicorm branches) and then a set grade for the entire stand (*e.g.* Methley, 1998; Macdonald *et al.,* 2001).

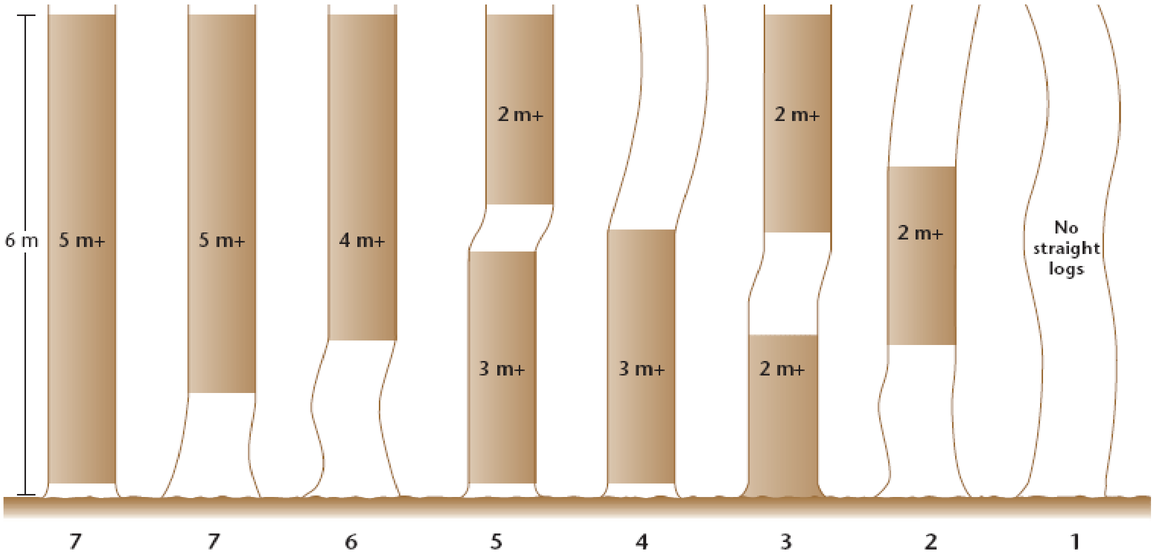

Figure 3-2. Showing different combinations of log lengths in first six meters, showing gradual reduction in quality from left to right (after Methley, 1998).

3.3.2 Felled tree measurements

3.3.2.1 Taper

Once selected the trees were felled then subject to various measurements. Taper measurements were recorded from the bottom of the tree (including stump) and the diameter measured every 1 metre (*e.g.* Fonweban *et al*., 2011). using callipers in two directions at angles of 45°. The 1 metre intervals were delimited using a measuring tape according to the method described above.

3.3.2.2 Branching

Only the Scottish sites (northern) were used for the branching study (LA, LT, PI) and as described above, three trees were chosen per plot (three plots per site, making 27 sample trees in total – however this number was reduced to 24 due to unforeseen circumstances where an entire plot had to be abandoned).

Once the samples trees were felled, they were measured for total height/length, then individual whorl-or-branch-level attributes. The exact position of each whorl along the stem was recorded from the stem apex. The first growth unit (GU, which contains an annual set of whorl and inter-whorl branches) is numbered 0, as this growth unit has no whorl branches. The first visible whorl belongs to growth unit 1 (below). Both the whorl and inter-whorl branches here belong to growth unit 1. The measurement is from the top of the whorl to the top of next whorl down (*i.e.* just above growth unit 2). Bud scars delineated where a growth unit end/started (*e.g.* Achim *et al.,* 2006). Only branches >5 mm in diameter were measured. The callipers for branch diameter were (perpendicularly) aligned with the stem at a specified distance (the distances from the stem were equivalent to diameter of the branch, *i.e*. if the branch is 50 mm thick, it was measured 50 mm away from the stem).

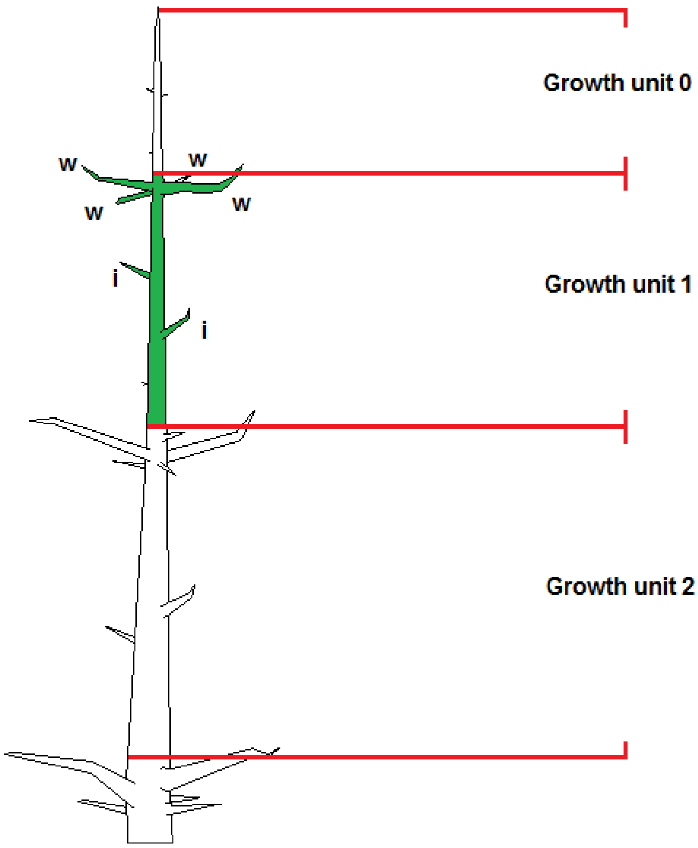

Figure 3-3. Showing branching protocols. The top is the stem apex, growth unit 0 contains small epicormic branches but as <5 mm, not counted. First whorl must belong to growth unit 1. The whorl (w) and interwhorl (i) branches are labelled in GU 1. The diameter of the stem is taken at the bottom of the growth unit.

The full list of branch characteristics recorded is:

1 - Tree-level measurements

A - Total length of tree (nearest 0.1 m)

B - Height to crown base (to nearest 0.1 m, defined as the lowest living live whorl (>75 % of whorl alive)

C - Height to lowest live branch (to nearest 0.1 m, defined as the lowest living live branch)

2 - Annual growth unit (GU) measurements

A - Distance from stem apex (nearest 0.1 m) to bottom of each GU

B - Length of each GU (nearest 0.1 m)

C - Diameter around stem at bottom of each GU (nearest 0.1 cm)

3 - Branch measurements

A - Each individual branches position along the stem (nearest 0.1 cm)

B - Branch frequency per GU (also stating whether an individual branch is either whorl or inter-whorl)

C - Status of branch in each GU (whether each individual branch is alive or dead)

D - Each individual branches diameter (perpendicular to branch axis) in 2 directions (horizontal and vertical, to nearest 1 mm)

E - Each individual branches angle of insertion to nearest 5°

All symbols for plot, tree, whorl and branch attributes used in the analysis are explained in chapter 6.

3.3.3 Log production (field conversion)

Using chainsaws, each sample tree had discs (transverse) removed and position (height from ground to base of disc) recorded for detailed analysis (*e.g.* heartwood content, growth rate analysis) approximately 5 cm thick every 2 m along the stem until the stem reached <7 cm diameter. The first disc taken at a height of 1.3 m but was 20 cm thick to allow for extra material. The second disc was taken at a height of 5.1 m after allowing for the first disc, billet and log (Figure 3-4). The appendix 10.2 demonstrates working method.

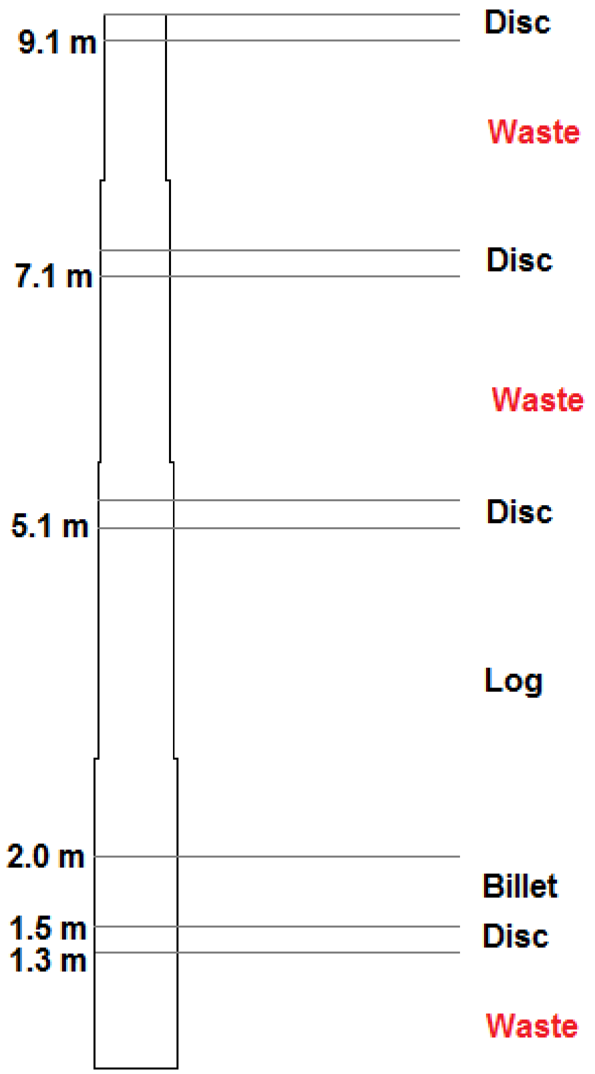

Figure 3-4. Showing which discs, billets or logs came from where for each selected stem.

The billet was cut in the forest using chainsaws (1.5 – 2.0 m along the stem) and taken whole to the laboratory for further processing. The logs were processed on site. Each log was coded and marked for azimuth (north). Utilising a portable horizontal bandsaw from Woodmizer™ (Wood-Mizer Industries) to act as a breakdown system, structural battens were taken from a central cant along the pith. The bandsaw thickness (kerf) was 3 mm, *i.e.* same as a commercial sawmill thus maximising recovery. The nominal dimension of battens was 100 x 47 x 3100 mm. These structural battens were transported to a kiln for drying and further processing.

3.4 Structural batten and clearwood preparation

3.4.1 Clearwood sample preparation

For each sample tree, a 0.5 m flitch was cut longitudinally between 1.5 and 2.0 m above ground for each stem on the North side. Once cut, each flitch had each individual annual ring number (cambial age) recorded on the north face (pith=0) prior to conditioning. Each flitch was cut with a table saw into 25 mm sections. Then, the best possible clearwood sample was selected from each 25 mm section. These resulting clearwood samples were cut (avoiding all defects wherever possible) at a nominal measurement of 25 mm X 25 mm X 320 mm and allowed to condition for a further week (20℃ and 65% humidity).

Figure 3-5. Showing clearwood samples immediately prior to testing, with no visible defects.

From these samples, 20 mm X 20 mm (transverse) X 300 mm (longitudinal) small clears (Figure 3-5) were achieved (by way of a planer) and conditioned (BINDER™ KBF series– Constant Climate Chamber) in a controlled environment at 20℃ and 65% relative humidity (which corresponds to a nominal testing moisture content (MC) of 12% (EN 14081, 2005) with the ring numbers being transferred onto the transverse plane.

Using digital callipers, the length, width and depth were recorded for each sample piece at 3 points along each plane to the nearest 0.1 mm. Immediately after testing, the samples were weighed (to nearest 0.1 g) on a digital balance, thus allowing an accurate MC reading at time of testing after obtaining over-dry mass. All samples were adjusted to 12% M.C. prior to analysis using the methods described in EN384 (CEN, 2010).

While all 272 samples were aimed to be defect free, certain samples did contain minor amounts of grain deviation or small knots. As such, each sample was ranked 1 – 3, with 1 being perfectly defect-free (n=231), 2 being some small defects, some grain deviation, or small knots close to end of sample (n=36) and 3 being larger grain defects, pith in sample or medium knots around centre of sample (n=5). The samples were also categorised for 3 age groups; cambial age 0 - <15 (n=121), cambial age 15 - <30 (n=100) and cambial age 30 + (n=51). The clearwood properties chapter details which and how many samples were used.

3.4.2 Structural battens preparation

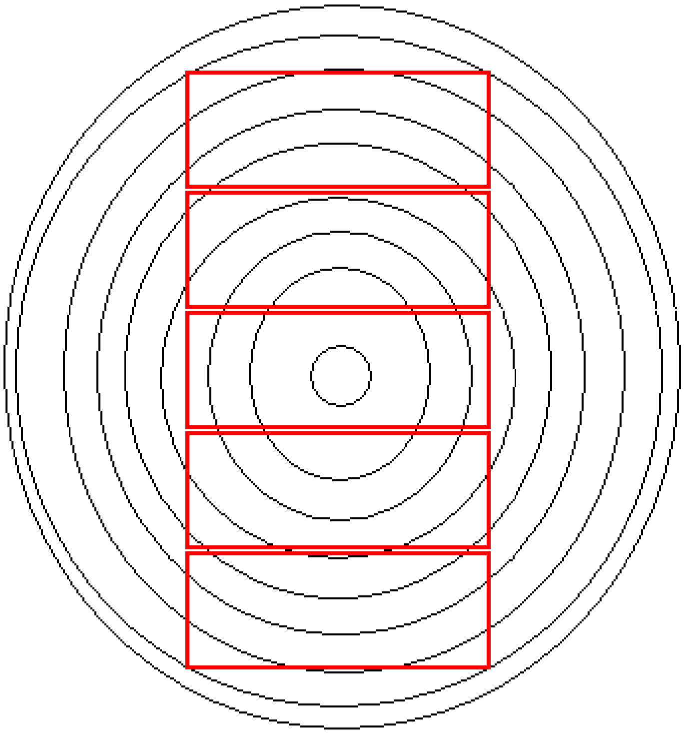

Figure 3-6. Showing the cutting pattern of structural battens from each log. Only a central cant was cut and the 47 X 100 X 3100 were taken from this, each position recorded.

As mentioned, for each tree a 3.1 m log was taken immediately above the clearwood flitch, between 2.0 and 5.1 m above ground. Structural battens (dimensions being 100 X 47 X 3100 mm) from these logs were taken from a central cant (above). All specimens were subject to tests including distortion testing and bending tests in accordance with the correct standards.

The 188 battens (from 44 trees as LT-3-18 was lost) were classified as either “inner” (n=32), “mid-range” (n=70) and “outer” (n=86) to highlight the radial variation as it was not feasible to collect individual rings information on-site prior to conversion. The “inner” samples contained pith or were immediately adjacent to pith (all deemed entirely juvenile) while the “mid-range” would likely have both juvenile and/or some mature wood and cannot be defined as purely “inner” or “outer”. The “outer” samples would not contain any material that may be classed as juvenile. All 188 structural battens were not ranked with quality as the entire purpose of structural testing is to investigate the mechanical properties with all defects associated with large specimens used in construction (*e.g.* knots).

3.4.3 Drying

Prior to destructive testing, the 188 battens were first kiln-dried in a Hydromat TKMP4032 kiln (Gann Mess-u. Regeltechnik GmbH) located at the Forestry Commission's Northern Research Station (NRS) to a mean (not peak) MC of 12%. This was in minimal restraint conditions (*i.e.* the load of timber was not secured or weighted from above; merely each sample was under the weight of the rest of the samples, stacked in rows with a wooden spacer between each row). After kiln-drying, they were immediately analysed for distortion.

3.4.4 Distortion

Distortion was measured using lasers mounted on a purpose-built FRITS (Freiburg's Improved Timber Scan) Frame (Seeling and Merforth, 2000). This determines twist, spring, bow and cup by the lasers measuring both the distance travelled along batten (horizontal laser) and the distance from batten to laser (vertical laser) to determine shifts in dimension.

Strength according to EN 338		C18 and below	C18 and above
Maximum permissible warp in millimetres over 2 metres of length according to EN 14081 Part 1 (2005a)	Bow	20 mm	10 mm
	Spring	12 mm	8mm
	Twist	2mm/25mm width	1mm/25mm width
	Cup	Unrestricted	Unrestricted

Table 3-3. Showing the designations for acceptable distortion below and above C18 according to EN 14081. Twist is determined by either 1 or 2 millimetres over 25 millimetres of width, unlike bow, spring and cup.

The battens were placed on the FRITS frame using three points of support (a constant reference point for continued replication).

The methodology was used by Searles (2012), distortion was calculated on the most distorted 2m length along the length of the batten. Bow and spring are calculated as the maximum deflection over that 2m length on the respective face, while twist is simply rise (or fall) of the unsupported corner over the worst 2m length on the broad face only. Note that the same 2 m section was not necessarily used in the calculation for each of the three modes of distortion in a single batten.

3.4.5 Theoretical strength class grading

The battens were taken to both the Adam Wilson and Sons LTD sawmill in Troon, Scotland and BSW Timber Group sawmill in Fort William, Scotland and were x-ray graded using a MiCROTEC™ GoldenEye 702[2]. Along with total-population grading (determined in-mill as a pack), each sample was given an individual assessment to determine the weakest part(s) on the board (*i.e.* the most likely area that breaking/rupture will occur in destructive testing). The area most likely to break (*i.e.* weakest) was calculated using confidential algorithms (MiCROTEC™) and used where possible (*e.g.* it was within the span of the subsequent testing machine - if too close to the edge/outside the acceptable span, the second weakest/most likely breaking area was chosen, and so on) for destructive testing. MiCROTEC™ also provided a ViSCAN unit which measured the resonant acoustic speed of each batten and provided a dynamic MOE (*e.g.* as given below in 3.5.2.1).

After all kiln-drying, distortion and sawmill measurements took place, the battens were taken to the timber testing laboratory at Edinburgh Napier University (Merchiston Campus). This has a controlled environment and to achieve a nominal MC of 12% in the battens (*e.g.* EN408, 2003), the laboratory was set at 20° C and 65% relative humidity and all battens were left to stabilise in this condition for >4 weeks.

3.5 Structural batten and clearwood testing

Following EN408/EN3841 and BS373, flexural testing occurred in three-point bending for clearwood and four-point bending for structural battens.

[2] The x-ray scanner MiCROTEC™ GoldenEye 702 is not measuring KAR (knot area ratio), but rather non-dimensional knot parameters of which are a confidential algorithm (the values have no scale). Essentially they are locally calculated models (*e.g.* a measure of knot cluster by density) built for Sitka spruce and applied here to Douglas-fir to give a relative scale of knot size/frequency.

3.5.1 Clearwood testing

3.5.1.1 Acoustical method for determining dynamic stiffness

Using a GrindoSonic, (GrindoSonic MK5, J.W. Lemmens, Belgium) the dynamic MOE was determined by way of impulse excitation technique. This involved loading the specimens (longitudinal axis, with the annual rings parallel to direction of destructive loading as below in Figure 3-7) at a distance of 22% of length from each end (Ilic, 2001), with one end in front of a microphone (~ 2 mm) and hit at opposite end with a small hammer (*e.g.* an xylophone hammer) causing them to vibrate at their natural resonant frequencies for the longitudinal vibration. Mounted in the exact fashion, but with the microphone placed perpendicularly on the top plane pointing down (~ 2 mm) and struck immediately adjacent to the microphone, gives the flexural resonance as stipulated in EN 843-1 (CEN, 2006).

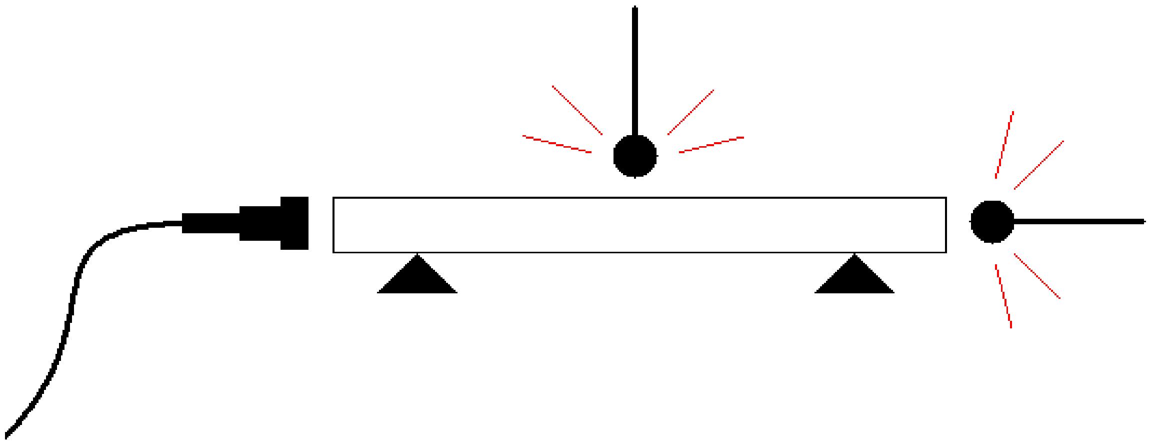

Figure 3-7. Showing how samples were loaded for acoustical testing of longitudinal and flexural (MOE). The samples were struck at the end, with microphone placed on the opposite end for longitudinal, and the flexural recording occurred by striking the top, with microphone immediately adjacent to it (not shown).

3.5.1.2 Loading clears

The sample pieces were subjected to static bending, in accordance with BS: 373 (BSI, 1957) to determine MOE (static) and MOR, using a Zwick/Roell testing machine (Model BT1-FB050TN). The loading head moved at a constant speed of 0.11 mm sec^{-1}. Samples were loaded with the annual growth rings parallel to direction of loading (*i.e,* load was applied in the tangential direction) and mounted on supports set 280 mm apart.

3.5.1.3 Clearwood determination of static MOE and MOR

Both static MOE and MOR were determined in three-point bending tests in accordance with BS373 (BSI, 1957). Modulus of elasticity is a measurement of deflection (strain, by gauge or extensometer) from an applied force (stress) and at stresses below the proportional limit (recoverable) this relationship is linear thus static MOE can be calculated with the following equation:

$$MOE_S = \frac{Fl^3}{48I\Delta} \quad [3\text{-}1]$$

where MOE_S is the static modulus of elasticity in three-point bending in N mm^2, F is the load applied to the centre of the span at the limit of its proportionality in Newtons, l is the distance between the supports in millimetres, I is the second moment of area of the section determined from its actual dimensions in (millimetres)^4 and Δ is the deflection at centre of the span at the limit of proportionality.

The samples were then continued until failure, whereby MOR (a measurement of the ultimate bending strength of timber for the given sample and rate of loading) was calculated using the equation in BS 373 (BSI, 1957)..

$$MOR = \frac{3PL}{2bd^2} \quad [3\text{-}2]$$

where P is the load in Newtons, L is the span length in millimetres, b is the width of the beam in millimetres, and d is the thickness in millimetres. Immediately after testing, the samples were weighed and measured (density) to ascertain the exact moisture content at time of breaking (by using the oven-dried method as described in chapter 2).

3.5.2 Structural testing

3.5.2.1 Structural timbers acoustical testing

The dynamic MOE for the battens (47 X 100 X 3100 mm structural samples) was determined immediately prior to destructive testing. The stiffness was measured by first determining the density at a large-scale laboratory with battens having achieved a nominal MC of 12% as described previously then measuring the resonant log velocity with the Director HM200 (Fibre-gen NZ) as described in 2.3.1.1.

3.5.2.2 Structural batten testing

Using a Zwick Z050 universal testing machine (Zwick Roell, Germany), the 188 battens were tested for MOE and MOR (destructively) with four-point bending, according to the procedures described in EN408 (CEN 2003) and EN384 (CEN 2010). Global and local MOE and MOR were calculated from the data obtained during these tests using the equations given in EN408 (CEN,2003).

3.6 Heartwood/sapwood analysis

Each 5 cm disc (including a 5 cm slice from the top of the large 20 cm disc cut between 1.3 and 1.5 m along stem) was adjusted to be taken between whorls to avoid branches and the exact height from ground (*i.e.* distance along stem) recorded for all. They were then transported from site and stored at a minimum of -4° C in plastic bags to prevent drying/cracking and the growth of surface mould. All discs were then removed from freezer and allowed to thaw slightly and wetted to improve image quality where needed (wetting highlights the contrast between darker heartwood and lighter sapwood). Using a flatbed scanner (Epson 1640XL), all discs were optically scanned. Prior to scanning, the discs were marked for north and west.

The images were then analysed with both Image Pro Plus™ (Media Cybernetics, 2007; Bethesda, MD, USA) and Windendro™ (Regent Instruments Inc, 2004; Quebec, Canada). With Image Pro Plus™ the radius was measured in 4 directions (north, east, south and west) determining the heartwood area, the sapwood area, the total area and the disc diameter.

Figure 3-8. Showing the Image Pro Plus ™ (Media Cybernetics, 2007; Bethesda, MD, USA) which measures the length of the users chosen measurements, using a zoom function for accuracy. The disc ID (location, plot, tree and where it came from in stem) is recorded along with north, east, south and west.

3.7 Swelling analysis and preparation

The swelling rates of Douglas-fir were tested by using 20 mm x 20 mm x 20 mm samples. Each sample was taken from the same piece of wood as the clearwood samples (*i.e.* all information, including the radial position and ring numbers were known). Samples from PI-2-1 and PI-2-10 were used to highlight the difference between “inner”, “mid” and “outer” and between dominant and sub-dominant, in the radial and tangential directions.

Prior to swelling, all sample specimens were oven-dried to 0% MC. This was achieved using a BINDER™ chamber (BINDER KBF series– Constant Climate Chamber) at a constant temperature of >103° C for +24 hours. Each face (radial, tangential and longitudinal) was measured to the nearest 0.001 mm and weighed to nearest 0.001 g to ascertain density prior to swelling. The samples were then transported in a glass crucible (to keep the MC at 0%) to a purpose-built swelling rig.

The swelling rig consisted of a climate-controlled chamber, using fans to circulate air and kept at a constant temperature of 27° C. Inside, free-standing micrometers measuring to ±0.001 mm in the vertical direction were used independently of each other. Each sample was loaded into an empty container (which had been acclimatised inside the rig to maintain the conditions) with the direction in question facing upwards (*i.e.* to measure radially, the radial face would be pointing outwards as the swelling for the radial face would occur upwards in this manner) as this was the direction the micrometer measured. Each sample had a small piece of glass covering the top surface to evenly spread the slight weight of the micrometer. The micrometers were instantaneously zeroed once the filling of containers (sample included) with de-ionised water commenced. After 24 hours, the samples were removed and swelling rates calculated using the percentage change over 24 hours. This was undertaken for all samples before and after extraction (this was achieved by submerging all samples in an acetone bath 24 hours).

3.8 Adjustments, assumptions, corrections, limitations and transformations

Firstly, it is prudent to verify the discrepancies between percent difference (not "percentage of"), percent increase and percent decrease as various studies do not actually follow the same formula and some appear confused over the differences. Using the numbers 25 and 40 as an example, the three methods are:

$$\% \text{ difference} = ((40-25)/((25+40)/2))*100 = 46.15\% \quad [3\text{-}3]$$

This finds the difference between 25 and 40 (15) and then the average of the two (32.5) to negate order of numbers. This method is percent difference, not percent change.

$$\% \text{ increase} = ((40-25)/25)*100 = 60\% \quad [3\text{-}4]$$

This simply uses both numbers to find the increase from 25 to 40 (*e.g*. 60% of 25 would be needed to get 40).

$$\% \text{ decrease} = ((25-40)/40)*100 = -37.5\% \quad [3\text{-}5]$$

This simply uses both numbers to find the decrease from 40 to 25 (*e.g.* subtracting 37.5% of 40 would be 15, leaving 25).

Secondly, MOE values were adjusted to 12% MC as described in EN384 (CEN, 2010) and density values were also corrected to 12% MC using the equations developed by Simpson (1993), which also accounts for volumetric shrinkage (or expansion) with changes in MC by assuming a linear relationship between shrinkage and moisture content below the thought fibre saturation point (<30% MC) at the time (Stamm, 1964). The method set out in EN384 (CEN, 2010) indicates that a 1% change in value (*e.g.* MOE) shall occur for every 1% difference in MC, with values below 12% MC decreasing and values above 12% MC increasing. All values were converted to units of N/mm^2. The corrections to 150 mm depth for MOR and 95% reduction factor for target MOE or the reduction factor for MOR for grades less than C18 are described in chapter 4.

Thirdly, replication for silviculture did not occur. While silviculture likely affects timber properties, it was not tested for this project given the limited resources. Instead a small range of sites which happened to include some differing silvicultural regimes were tested. This is briefly discussed in the review chapter.

Fourthly, while it has been proven that genetics can influence wood properties, genetics were not tested for this study either as the exact provenance is often not known for all forest stands in the UK. This is also discussed briefly in the review chapter.

4 The properties of structural-sized Douglas-fir

4.1 Introduction

The aim of this chapter is to investigate the strength, stiffness and density of UK-grown Douglas-fir in structural-sized timber. It is vital to know these grade-determining properties to assign timber a strength class under the European Standard EN14081 (2005). This chapter examines these properties in order to quantify their variation and identify the influencing factors; facilitating the possibility of timber segregation throughout the supply chain. To do so, the relationship of known tree-level parameters (*e.g.* girth and height) to these properties is investigated. As the radial position of sawn timber at point of strength grading will most likely not be known, easily-measured variables (*e.g.* density or dynamic stiffness) which indicate the static bending strength and stiffness of Douglas-fir are investigated to determine their correlation.

Grading machines assign timber into these strength classes by using a measured “indicating” property (or properties). This is predominantly done in the UK by X-ray machines which use density and knottiness to predict strength. Bending-type machines can also measure stiffness by reaction force or deflection but these are being phased out. Likewise dynamic stiffness (which is positively correlated with strength) can be measured by stress wave speed (*e.g.* acoustic tools) if the sample density is known. Focusing on practical and advantageous approaches to predict strength classes in UK-grown Douglas-fir could prove extremely beneficial for the UK timber industry.

4.2 Aims and objectives

Specific objectives are: (1) to determine the strength, stiffness and density of Douglas-fir timber, (2) describe the population variability, (3) examine the strength and stiffness of structural-sized specimens between different growth regions and (4) to examine the distortion of structural-sized specimens.

4.3 Materials and methods

4.3.1 Methods

The five sites were chosen to give an overview of the UK-grown Douglas-fir resource (focusing on two distinct regions). For each of the five sites, three plots were randomly chosen and within each of these plots, three trees were selected for further processing (45 trees in total). Section 3.5.2.2 details the testing methods for structural-sized Douglas-fir battens. The 188 battens were subject to destructive testing. Properties are then predicted using explanatory variables (both tree-level and sawnwood). The chosen variables are given in Table 4-1 along with their tests for normality and Table 4-2 gives the range in values.

Name	Abbreviation	Shapiro-Wilk normality test[3]	
IML hammer	IML	w= 0.936,	p < 0.001
Crown ratio (%)	CR	w = 0.968,	p < 0.001
Slenderness	SL	w = 0.949,	p < 0.001
Lowest live branch	LLB	w = 0.922,	p < 0.001
Height to crown	HCB	w = 0.935,	p < 0.001
Diameter at breast height	DBH	w = 0.968,	p < 0.001
Tree height	HT	w = 0.972,	p < 0.001
Stem straightness score	SS	w = 0.878,	p < 0.001
Knottiness (X-ray)	Knots	w = 0.956,	p < 0.001
HM200	HM200	w = 0.978,	p < 0.004
ViSCAN	Viscan	w = 0.972,	p < 0.001
Local MOE	MOE.L	w = 0.982,	p = 0.013
Global MOE	MOE.G	w = 0.984,	p = 0.025
Shear-free MOE	MOE.S	w = 0.983	P = 0.025
MOR	MOR	w = 0.969,	p < 0.001
Density	DENS	w = 0.976,	p = 0.002

Table 4-1. Values for normality test. The *w* is the test statistic and the p-value shows significance of this. Values close to 1 are strong(er). The null hypothesis is that the data are normally distributed. Given *p*-values less than 0.05 it is rejected that it could be chance variation[3] (*i.e.* the data is not normally distributed). All units of measurement are in Chapter 3.

[3] While reasons for non-normality of data exists such as extreme values, an overlap of two or more process or insufficient data discrimination, the biological nature of wood (*e.g.* radial trends) would suggest either values close to a natural limit (or zero, such as age) may skew the data distribution, or the data follows a different distribution (*e.g.* length data, exponential distribution, or Poisson distribution).

Abbreviation	Min	Max	Mean	SD	CV[4]	5th PCTL	50th PCTL	95th PCTL
IML	7390	13300	9230	1390	15.1			
CR	23.3	56.6	41.3	8.4	20.4			
SL	54.1	115	77.3	12.4	16.1			
LLB	6.40	27.3	14.9	4.1	27.4			
HCB	12.6	28	18.2	3.5	19.3			
DBH	25.3	53.8	41.5	7.2	17.3			
HT	25.1	38.5	31.3	3.5	11.2			
SS	1	7	4.9	1.8	37.7			
Knots	1270	16800	6120	2630	42.9			
HM200	5030	16500	10500	2430	23			
Viscan	5910	16500	10600	2430	22.9			
MOE.L	4340	15400	9160	2260	24.7	5890	8850	13100
MOE.G	5380	14200	9100	1840	20.2	6290	8870	12400
MOE.S	4300	15700	9130	2390	26.2	5480	8840	13400
MOR	9.7	73.4	34.1	11.9	35.0	17.2	32.7	55.9
DENS	340	582	455	46.8	10.3	370	453	539

Table 4-2. Range in values for the chosen variables as described in Table 4-1. SD = standard deviation, CV = coefficient of variation. The 5th, 50th and 95th percentiles (PCTL) are also given for the four main dependant variables. All figures rounded to three significant places. All three MOE are given as their difference(s) is discussed later.

[4] CV = coefficient of variation (*i.e.* the ratio of standard deviation to the mean).

4.3.2 Statistical package

Using R, an open-source statistical programme (R Development Core Team, 2013), all non-linear analysis was carried out using functions within the nlme library. Various statistical tests were used for the analysis of both the tested samples and the corresponding information prior to testing (*e.g.* site/tree information, dynamic MOE).

4.3.3 Statistical methods

Interactions between variables were examined with a correlation coefficient (Pearson's) matrix, which measures the strength of a relationship between two variables (linearly, either positive or negative) as seen in Table 4-3. Multiple linear regression was used for prediction of structural properties. To determine differences in means between models or populations, ANOVA was used.

Variance components were examined to determine how much of the variability in branch number, size and angle was accounted for between sites, plots and trees, using a mixed-effects model with the basic form:

$$y = u + b0 + b1 + b2 + e \qquad [4\text{-}1]$$

where y is the parameter of interest, u is overall mean, b0 is the random effect of site, b1 the random effect of plot in site, b2 is the random effect of tree in plot in site and e is residual error.

4.4 Results

The following results give correlation tables and the limiting property (or properties) of these Douglas-fir samples for grading implications. Then density, MOR and MOE are investigated in detail, including predictive models. Following this, radial differences in properties are explored and finally distortion of these battens is examined.

	IML	CR	SL	LLB	HCB	DBH	HT	SS	Knots	HM200	Viscan	MOE.L	MOE.G	MOR	DENS
IML		-0.06	0.55	0.20	-0.12	-0.57	-0.30	0.04	-0.13	0.21	0.21	0.27	0.28	0.17	0.13
CR	-0.06		-0.18	-0.45	-0.78	0.27	0.20	0.10	-0.02	0.01	0.04	-0.03	-0.02	0.00	-0.15
SL	0.55	-0.18		0.34	0.01	-0.86	-0.26	-0.07	0.03	0.10	0.09	0.25	0.22	0.15	0.16
LLB	0.20	-0.45	0.34		0.23	-0.44	-0.30	0.01	-0.03	0.18	0.17	0.27	0.26	0.15	0.28
HCB	-0.12	-0.78	0.01	0.23		0.18	0.45	0.00	0.03	-0.08	-0.12	-0.08	-0.09	-0.09	-0.02
DBH	-0.57	0.27	-0.86	-0.44	0.18		0.68	0.12	-0.01	-0.14	-0.14	-0.28	-0.26	-0.18	-0.25
HT	-0.30	0.20	-0.26	-0.30	0.45	0.68		0.09	0.03	-0.14	-0.14	-0.18	-0.20	-0.15	-0.26
SS	0.04	0.10	-0.07	0.01	0.00	0.12	0.09		-0.15	0.18	0.13	0.05	0.10	0.03	0.05
Knots	-0.13	-0.02	0.03	-0.03	0.03	-0.01	0.03	-0.15		-0.77	-0.79	-0.61	-0.70	-0.56	-0.53
HM200	0.21	0.01	0.10	0.18	-0.08	-0.14	-0.14	0.18	-0.77		0.95	0.80	0.88	0.68	0.76
Viscan	0.21	0.04	0.09	0.17	-0.12	-0.14	-0.14	0.13	-0.79	0.95		0.83	0.91	0.71	0.74
MOE.L	0.27	-0.03	0.25	0.27	-0.08	-0.28	-0.18	0.05	-0.61	0.80	0.83		0.95	0.79	0.62
MOE.G	0.28	-0.02	0.22	0.26	-0.09	-0.26	-0.20	0.10	-0.70	0.88	0.91	0.95		0.81	0.70
MOR	0.17	0.00	0.15	0.15	-0.09	-0.18	-0.15	0.03	-0.56	0.68	0.71	0.79	0.81		0.54
DENS	0.13	-0.15	0.16	0.28	-0.02	-0.25	-0.26	0.05	-0.53	0.76	0.74	0.62	0.70	0.54	

Table 4-3. Correlation values between chosen variables. Significance was ascertained at $p<0.05$ using *cor.test(x,y)* for individual correlation coefficients. Only four sites ("PI", "LT", "MA" and "RU") were used in their totality for the IML values in this correlation matrix given these missing values (for site "LA", the IML readings failed).

Table 4-3 shows that both acoustic tools (HM200 and ViSCAN) are strongly correlated with global and local MOE. ViSCAN and HM200 are correlated with each other (0.95) to the same degree as global MOE and local MOE are correlated with each other (0.95). MOR is correlated strongly with both global MOE (0.81) and local MOE (0.79) but less so with the acoustic (0.68 and 0.71 for HM200 and ViSCAN respectively). There is a negative correlation between knots and the acoustical tools (ViSCAN -0.79 and the HM200 -0.77).

While there are numerous strong correlations between sawnwood variables, there are noticeably few between tree-level variables. IML is correlated with DBH and slenderness, while crown ratio is correlated with HCB. Slenderness is correlated with DBH as expected (given how slenderness is calculated) but surprisingly not height. LLB, HCB, DBH, HT and SS are not strongly correlated with anything apart from the above mentioned. Concentrating on sawnwood properties (due to their correlations with each other, together with few correlations between tree-level variables) can occur after examining multiple regression models to determine tree-level influences on these properties (*e.g.* global MOE) which will include tree means.

To predict density, while both MOE classifications were investigated (as they were for MOR as well), but global MOE was chosen. For the MOE, both acoustic tools alongside MOR and density should be investigated. While very few correlations between tree-level and sawnwood variables exist, the ones mentioned above warrant examination. The site "LA" had missing values for HCB, LLB and IML which for the correlation matrix the site were omitted. With the correlations above and the grade-determining property ascertained below, describing radial variation and predicting these properties can occur.

Property	C14	C16	C18	C20	C22	C24
MOR (N mm^2)	14	16	18	20	22	24
Mean MOE (kN/mm^2)	7	8	9	9.5	10	11
Density (*Pk*)	290	310	320	330	340	350

Table 4-4. Selected softwood strength classes showing characteristic values for bending strength (MOR), stiffness (MOE) and density (CEN, 2003a). *Pk* is the characteristic value of density (in kg/m^3). MOR and density are the 5-percentile values required for a certain grade.

All 188 samples battens were tested after conditioning to a target 12% moisture content to EN408 and results adjusted to 12% according to EN384.

Table 4-2 presents the results of testing. Local MOE (MOE.L) had a mean of 9160 N/mm^2 (SD = 2260, CV = 24.7%) with a 5th percentile of 5890 N/mm^2. The global MOE (MOE.G) was 9100 N/mm2 (SD = 1840, CV = 20.2%) and had a 5th percentile of 6290 N/mm^2. The shear-free MOE (MOE.S), a shear-free MOE calculated from global MOE (EN384, 1995) had a mean of 9130 N/mm^2 (SD = 2390, CV = 26.2%) with a 5th percentile of 5480 N/mm^2. Density ranged from 340-582 kg/m^3 with a mean of 455 kg/m^3 (SD = 46.8, CV = 10.3%) and MOR had a mean of 34 N/mm^2 (SD = 11.9, CV = 35%). The MOE to be used for all models is the shear-free MOE (MOE.S). The difference between mean MOE.L and mean MOE.S is minimal.

The mean MOE (local, global and shear-free) and 5th percentile MOR and density are used to assign grades. To attain a grade of C14-C16, none of these variables are limiting. The required mean batten stiffness required for a certain grade is shown in Table 4-4, while Table 4-5 shows what percent of all samples fall under these grades. Focusing on achieving C18, the shear-free stiffness (MOE.S) of all samples would need to average a minimum of 9 kN/mm^2. Given that the mean is 9,130 N/mm^2, the pass rate for C18 is 100%. Table 4-5 shows that a small percent (1.1%) fail on MOR, but this is within an acceptable grading reject rate for a sawmill. At the next higher grade it appears MOE (all) have lower pass grades than MOR, therefore MOE is very likely to be the limiting factor when assigning grades to UK Douglas-fir, particularly as more samples need to be removed in order to shift the population mean compared to the 5th percentile. For example 13.3% of all (lowest) battens would need to be removed (leaving 86.7%) for the mean of the rest to achieve C20 based on local MOE, whereas only 2 samples (1.1%) need to be removed for the MOR .

Property	C14	C16	C18	C20	C22	C24
MOE.L	100	100	100	86.7	68.6	37.2
MOE.G	100	100	100	91.0	76.1	48.9
MOE.S	100	100	100	91.0	77.1	50.5
MOR	100	100	98.9	95.7	88.8	79.3
DENS	100	100	100	100	100	100

Table 4-5. Showing batten percentage which achieved a characteristic value for a given grade. Abbreviations given in Table 4-1. For MOE.S, 50.5% of battens averaged C24 and above, meaning 49.5% (lowest valued) had to be removed.

4.4.1 Density

The overall mean density was 455 kg/m^3 (SD = 46.8, CV = 10.3%), while the 5th percentile was 370 kg/m^3. Examining variance components shows that 3.9% of the variation was between sites. The difference between plots was negligible, while the difference between trees explained 18.4% of the variation. The difference in residuals was high at 77.7% (variation within a tree).

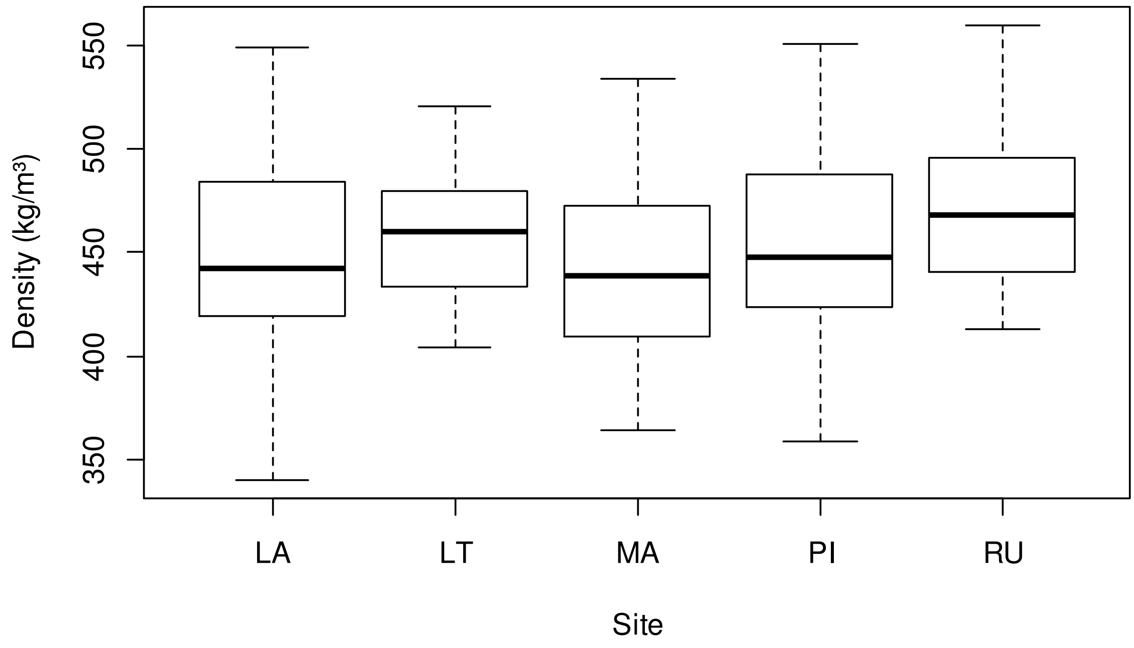

Figure 4-1. Showing the density for each of the five sites.

Visibly there were bigger differences in sample density within a site than between sites (Figure 4-1). Differences between sites for density were a mean of 447 kg/m^3 (SD = 51.1) for site LA, while PI had a mean of 454 kg/m^3 (SD = 50.9), RU a mean of 475 kg/m^3 (SD = 43.4), MA a mean of 441 kg/m^3 (SD = 45.4) and LT a mean of 460 kg/m^3 (SD = 37.0). There were no statistical differences between the two regions (North and Mid-range).

4.4.2 Strength (MOR)

MOR had a mean of 34 N/mm^2 and 5th percentile 17.2 N/mm^2. Given that MOR is correlated with density, knots, and MOE (both acoustic static, though only one will be used, a predictive model *(i.e.* multiple regression) to investigate these properties influence on MOR will present a prediction of strength allowing subsequent concentration on MOE for the remainder of this chapter. Tree-level variables are not correlated (using mean MOR per tree), thus examining all sawnwood variables correlated with MOR could potentially lead to their use in predicting MOR.

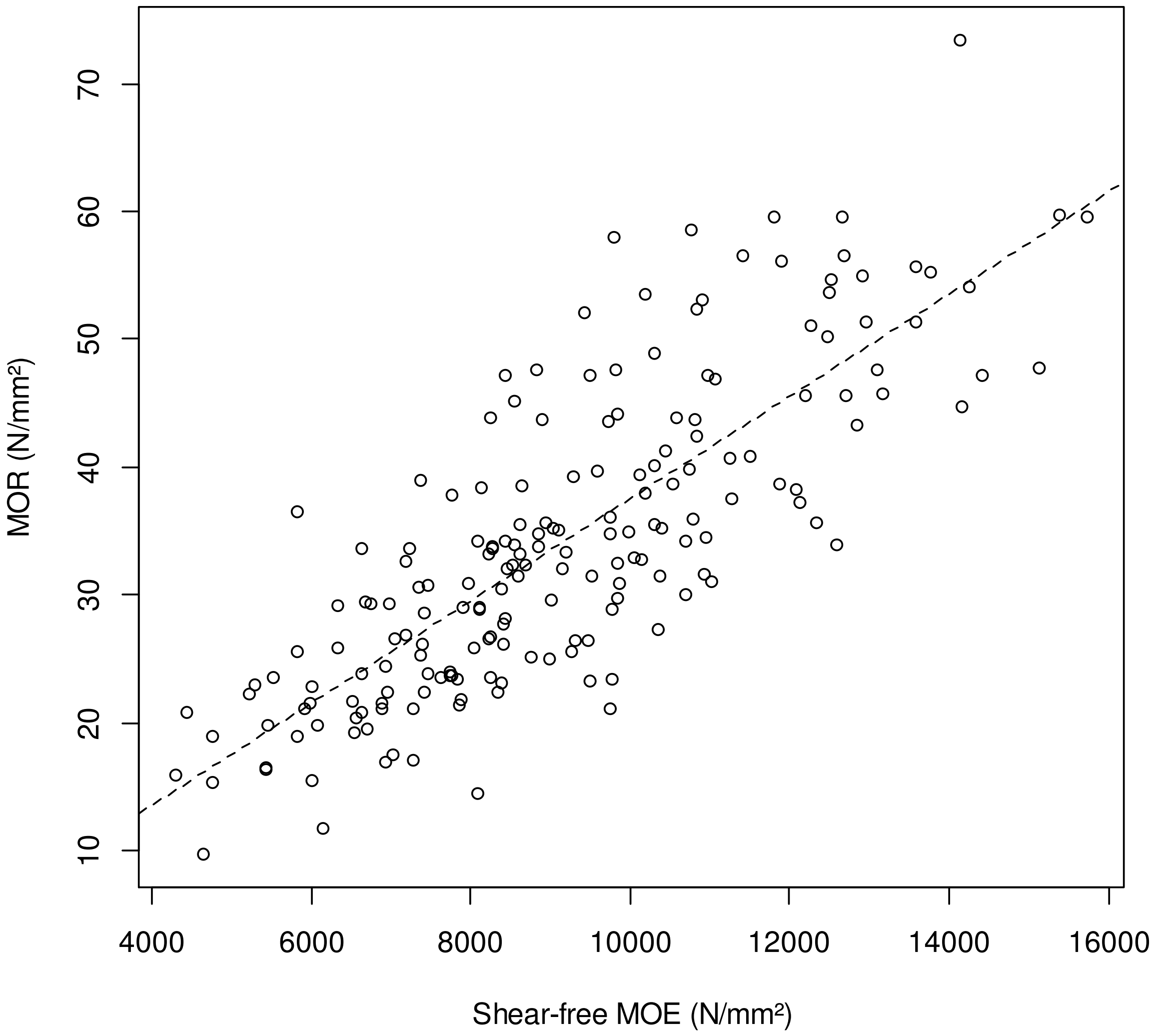

Figure 4-2. Showing the linear relationship between MOE and MOR (R^2 of 0.64).

Using linear regression, the coefficient of determination (R^2) explains the proportion of the variance (fluctuation) of MOR that is predictable from a sawnwood-level variable as shown in Table 4-6.

Variable	adj. R^2	RSE*	*p*-value
MOE.S	0.64	7.16	$p < 0.001$
HM200	0.47	8.72	$p < 0.001$
Viscan	0.50	8.39	$p < 0.001$
DENS	0.35	9.65	$p < 0.001$
Knots	0.32	9.86	$p < 0.001$

Table 4-6. Adjusted R^2, residual standard errors (RSE) and p-values for interactions with each variable and MOR (* = on 186 degrees of freedom).

Given the correlation coefficients shown in Table 4-3 and the coefficient of determination (regression) values in Table 4-6, a preliminary multiple regression model (MOR model 1) which included interactions between explanatory variables (MOE.S, DENS and Knots) showed only the variable MOE.S (F value 345) and interaction Knots:DENS (F value 8) to have any significant effects on the prediction of MOR. All other interactions were non-significant (*p*-value >0.05). MOR model 1:

MOR=MOE.G DENS *Knots* **[4-2]**

Given that static MOE (MOE.G, MOE.L and calculated MOE.L) and dynamic MOE (HM200, Viscan) are correlated (non-independent), the shear-free MOE (MOE.S) was chosen due to its correlation with MOR. The adjusted R^2 of MOR model 1 was 0.65 (RSE = 6.95) and thus no better than using MOE alone. Examining sum of squares shows MOE.G to explain most influence (64%), the interaction Knots:DENs negligible (1%) and residuals 33%. The numerous interactions showed little effects on the model thus rather than remove all non-significant interactions a secondary model (MOR model 2) which ignored interactions between variables was built. MOR model 2:

MOR=MOE.G+ DENS +Knots **[4-3]**

This showed MOE.G had the only significant influence (from ANOVA table, F value of 333) while Knots and DENS had no influence (F values <1) and were non-significant (*p*-values >0.05). The adjusted R^2 of this was 0.64 (RSE = 7.06). Sum of squares showed MOE.G to explain 64% of the variation with 35% unaccounted for (residuals). A model containing just density and knots had an R^2 of 0.43.

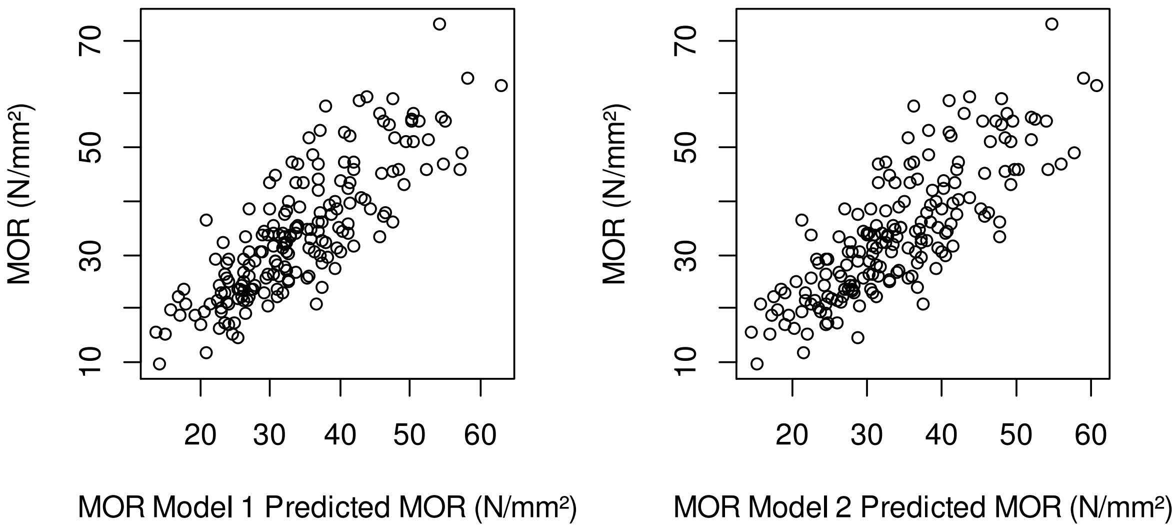

Figure 4-3. Predicted and observed values of MOR fitted against each other. MOR model 1 had an adjusted R^2 of 0.65 (RSE = 6.9) and MOR model 2 had an adjusted R^2 of 0.64 (RSE = 7.0).

It would be practical to use an individual sawnwood-level variable as shown in Table 4-6 to predict the strength (MOR) of Douglas-fir timber. As the data were nested (*i.e.* each sample was numerous within a tree, which was in a plot, which were in sites), hierarchal trends were investigated. Examining variance components shows the variation in MOR was accounted for between sites was negligible, there was an 8% difference between plots, 10% of the variation was explained by difference between trees and 82% was within the tree. Using ANOVA, there were no differences of MOR between regions (p-value=0.83), likewise MOR between sites was marginally non-significant (p-value=0.06).

4.4.3 Stiffness (MOE)

Local, global and shear-free MOE each had a mean of 9160, 9100 and 9130 N/mm^2 respectively.

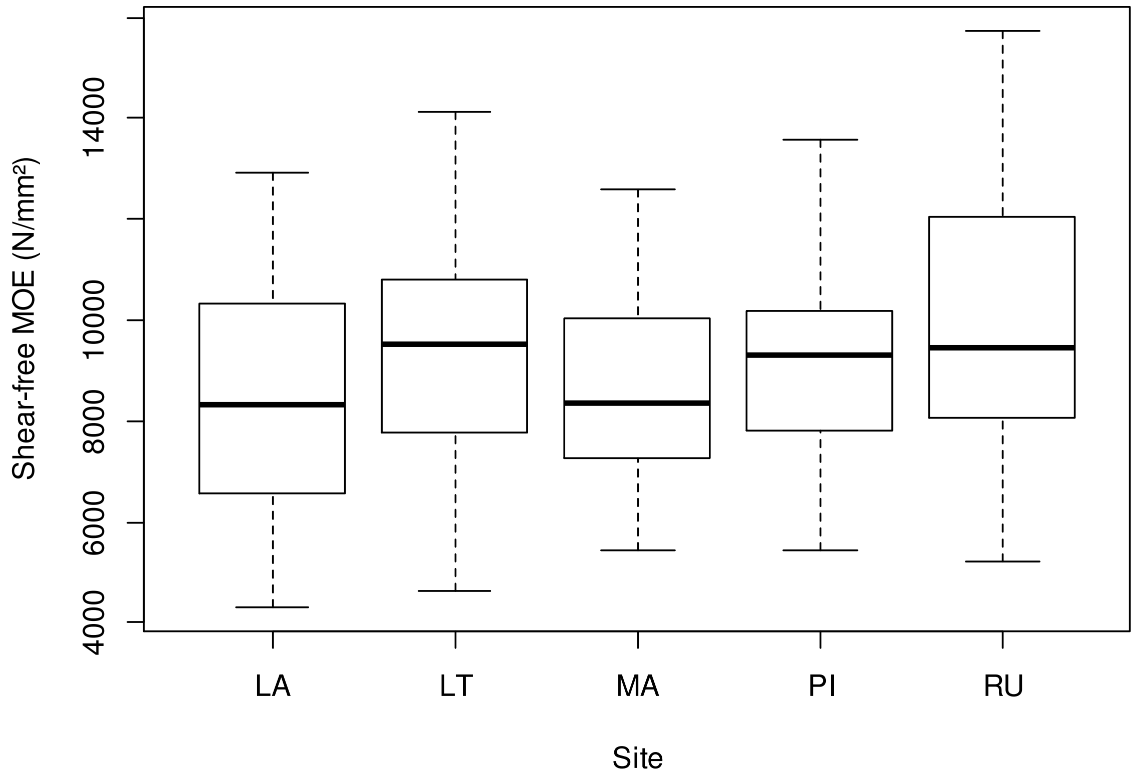

Figure 4-4. Showing MOE.S per site. The means are 8270, 9510, 8770, 9160 and 9940 respectively (left to right).

There was a difference between sites (*p* = 0.02) for MOE.G, but not between region (*p*-value = 0.22). Sites LT and RU were statistically larger than LA, while MA and LT were not. The median for each site is given in Figure 4-4

Initial prediction of MOE.S occurred using tree-level variables, then sawnwood-level variables. As the tree-level variables are measured per tree, MOE.S samples were averaged into a mean-tree value for these initial models. The chosen tree-level variables were IML, SL, LLB, DBH and HT. Both SL and LLB were non-significant (*p*-values >0.05). The rest were poorly correlated with MOE.S in individual regression with an R^2 of 0.02 (RSE = 1.04 on 146 degrees of freedom) for IML, while DBH had an R^2 0.09 (RSE = 1.10 on 186 degrees of freedom) and HT 0.13 (RSE = 1.08 on 186 degrees of freedom).

The initial multiple regression model which included interactions between the three variables (IML, DBH, HT) showed IML to have the most influence while HT also had some influence. The interactions *IML:DBH* and *IML:HT:DBH* were also influencing. All others had negligible effect (p-values >0.05). Mean MOE.S per tree:

*MOE.S=IML*HT*DBH* [4-4]

The adjusted R^2 was 0.28 (RSE = 0.983 on 140 degrees of freedom). Examining sum of squares showed IML to influence 19% of the variation, HT 3%, the two interactions above also 4% and 4% respectively, while the residuals accounted for 68% of the variation.

A second model ignoring interactions showed that IML had the most significant effect (F value of 36.6, *p*-value> 0.05) and HT less so (F value 6.3). IML accounted for 19% of the variation, HT 3%, DBH negligible and residuals 76%. The R^2 for this was 0.22 (RSE = 1.027 on 144 degrees of freedom).

Sawnwood-level variables were then examined for determination of MOE.S, given the tree-level variables were not highly significant. For the sawnwood-level variables, MOE.S was not averaged per tree as it was determined piece-by-piece. Given their correlation with MOE.S, the main sawnwood-level variables chosen were HM200, ViSCAN, density and knots. Their relationships were plotted in Figure 4-5 below to ascertain their predictive power for subsequent use in model building.

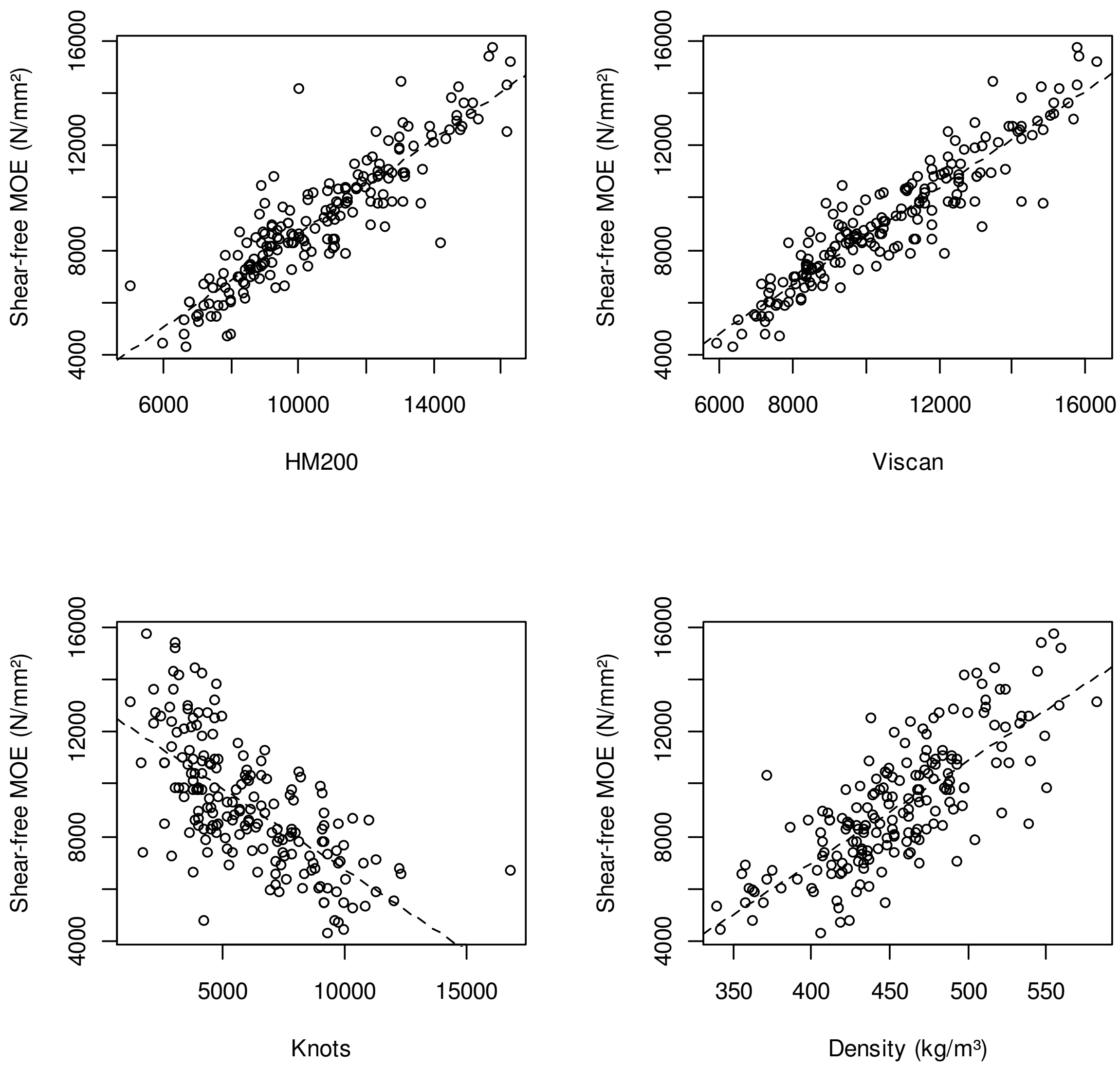

Figure 4-5. Showing the relationships between chosen variables and MOE.S. The coefficients of determination (R^2) are shown in table below for all interactions. The both HM200 and ViSCAN display a strong linear correlation with MOE.G while knots and density showed a weaker negative and positive correlation respectively.

Variable	adj. R^2	RSE*	*p*-value
HM200	0.80	1056	$p < 0.001$
Viscan	0.86	905	$p < 0.001$
DENS	0.59	1537	$p < 0.001$
Knots	0.46	1764	$p < 0.001$

Table 4-7. Relationships between variables and MOE.S (*on 186 degrees of freedom).

Table 4-7 shows ViSCAN to have the greatest prediction of MOE.S from the variables chosen, followed closely by HM200. The initial model had three independent variables where ViSCAN was chosen over HM200. While density is not truly independent of ViSCAN (it is included in the calculation of MOE) it is kept in the model(s) as it can still be interpreted as independent (*e.g.* while density is still needed to ascertain MOE, so is length or mass which are obviously independent to MOE). A model including interactions is given as MOE.S model 1:

*MOE.S=Viscan*DENS*Knots* **[4-5]**

For this MOE.S model 1, Viscan had the largest influence (F value 1120), while DENS had a negligible amount of influence (F Value 4, *p*-value>0.05), while Knots were non-significant (*p*-value>0.05). The interaction *Viscan:DENS:Knots* had an F value of 4 (*p*-value<0.05). The adjusted R^2 of this was 0.86 (RSE = 893) hence no better than using ViSCAN alone. Sum of squares shows while residuals account for 13% of the variation, Viscan accounted for 86% (all other interactions/variables were negligible). Reducing the model by removing all non-significant interactions leaves only ViSCAN and the above interaction (*Viscan:DENS:Knots).* This interaction becomes non-significant when used alone with ViSCAN, as assumed given the sum of squares above.

As with MOR, it would be prudent to just use one sawnwood-level variable to ascertain MOE.S (Table 4-7). For interests of both ease and availability for small-scale sawmillers, HM200 and density (both easily attainable variables) were also modelled but this model showed that DENS is not significant. The R^2 of a model containing both HM200 and DENS was 0.81, so again it would be prudent to just use the HM200 alone in terms of modelling, given that calculation involves density.

Variance components shows that for MOE.S, site accounts for 1.9% of variation, while the difference between plot and between tree account for 7.6% and 13.2% respectively. The residuals (in this case, within a tree) account for 77.2% of the variation.

4.4.4 Radial positioning

As the radial variation here refers to the difference in the properties radiating out from the pith, clear demarcation by using easily observed growth rings would be the most beneficial in determining specific characteristics at an exact (cambial) age. This was not possible for the structural samples but as described in section 3.4.2, the battens were classified into “inner”, “mid-range” and “outer” categories.

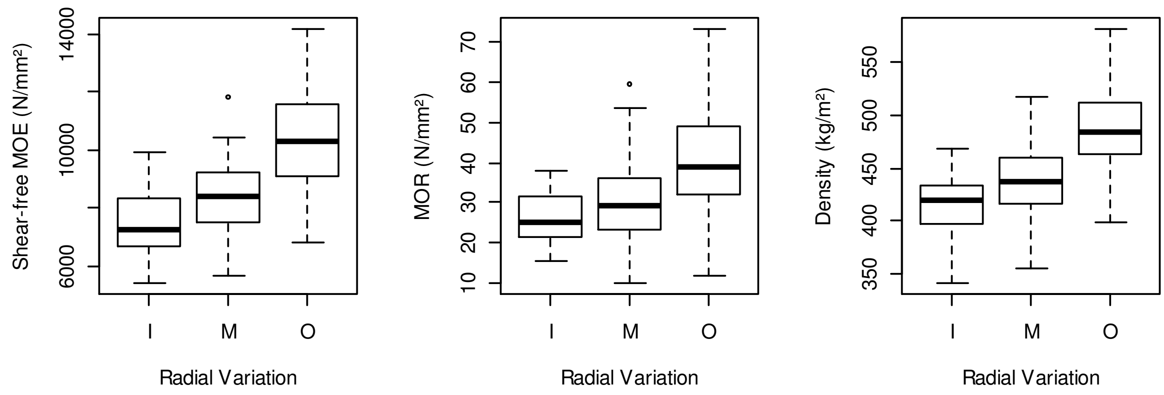

Figure 4-6. Radial variation for the main response variables. Showing the increases from “inner”, “mid-range” and “outer” for density, MOR, global MOE and local MOE. Values are given in Table 4-8.

All variables show an increase from pith (“inner”) to bark (“outer”). ANOVA shows there is a significant difference in means in MOE.S between radial positions (both p<0.005), similar to MOR and DENS (again, both p<0.005). The means and standard deviations for “inner” “mid-range” and “outer” properties are given in Table 4-8.

	“inner”		“mid-range”		“outer”	
Variable	Mean	SD	Mean	SD	Mean	SD
MOE.S	6980	1480	8160	1560	10700	2100
MOR	25.9	6.30	30.2	10.0	40.2	11.9
DENS	412	32.7	436	34.6	488	36.8

Table 4-8. Showing mean values for radial positions “inner”, “mid-range” and “outer”. All figures are rounded to 3 decimal places.

The largest difference was a 43% difference between “inner” MOR at 26 N/mm^2 and “outer” at 40 N/mm^2 (this is a 55% increase from “inner” to “outer”, or a 36% decrease from “outer” to “inner”). The difference in density was far less between “inner” and “outer” at 17%. Shear-free MOE had a 42% difference between “inner” and “outer” values (which is a 53% increase from “inner” to “outer” or a 35% decrease from “outer” to “inner”.

4.4.5 Distortion

EN 14081-1 (2005) presents the maximum permissible warp for each of the main types of distortion. This is done on a piece-by-piece basis, which does not assign timber to a grade yet sets out the limits for a specific grade; C18 and below, or above C18. For example, to achieve a pass rate in accordance with C18, spring cannot be above 8 mm for 2 m in length. Any piece >C18 with more than 8 mm spring is rejected. Distortion is additional criteria for the grade applied on each piece.

Strength classes according to EN 338		C18 and below	Above C18
Max warp in mm over 2m of length	Bow	20 mm	10 mm
	Spring	12 mm	8 mm
	Twist	2 mm/25 mm width	1 mm/25 mm width
	Cup	Unrestricted	Unrestricted

Table 4-9. Showing the maximum permissible warp according to EN14081 (CEN, 2005).

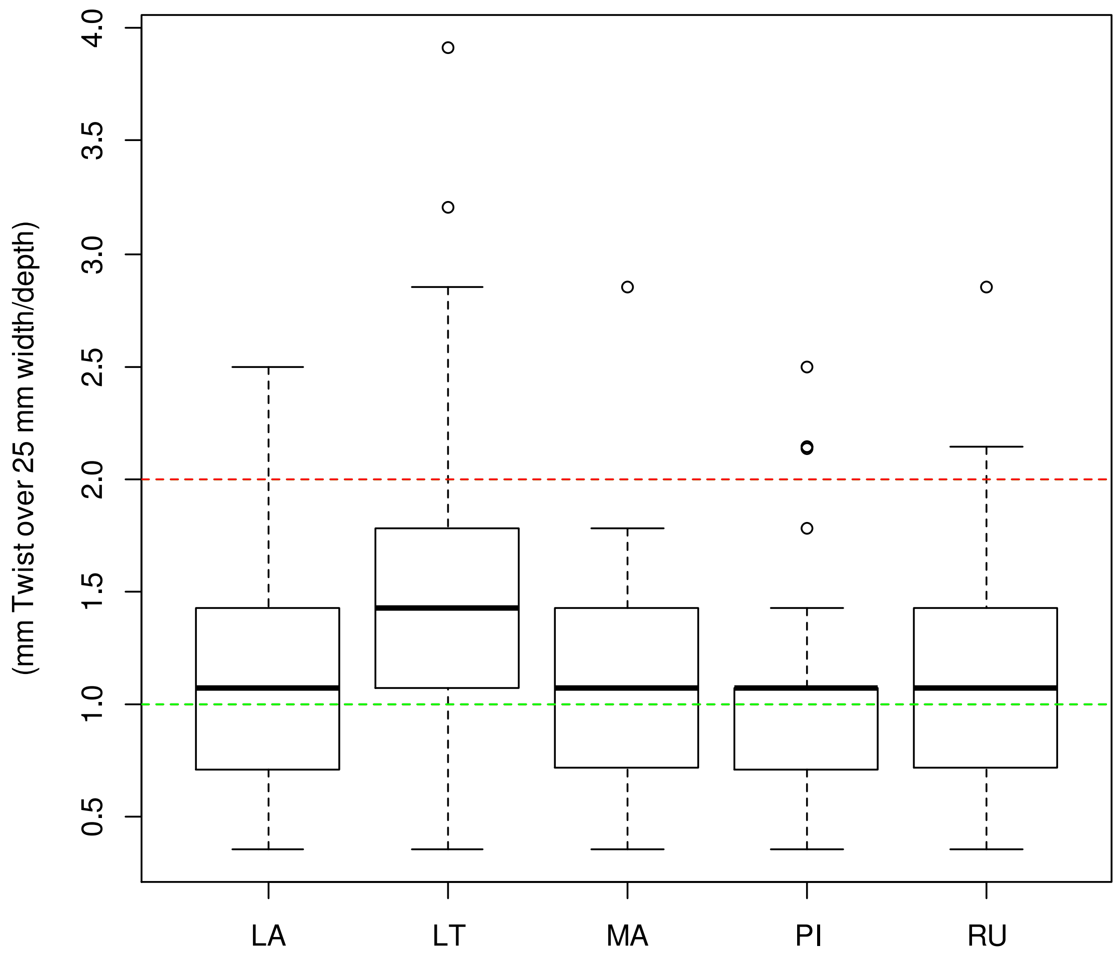

Figure 4-7. Showing twist per 25 mm width (EN 14081). Anything below the green line falls meets the twist criterion for grades above C18. Everything below the red line meets the twist criterion for C18 and below Anything above this is rejected. Note: these values are from unrestrained samples dried to 12% MC.

Figure 4-7 presents the main distortion (twist) for each site. These were taken from minimally unrestrained samples dried to 12% MC (as described materials and methods). Less than 10% was rejected as above 2 mm (red line in Figure 4-7) while the total mean (1.19 mm) was just below the cut-off for C18 as described in EN 14801 (2005). This equates to 31% (59 samples) having 1 mm or less (above C18) and 61% (114 samples) having greater than 1 mm but less than 2 mm twist (below C18) and 15 samples rejected. As distortion is regulated on a piece-by-piece basis, the mean is a valuable indicator of overall distortion. The amount of samples that pass or fail however is the fundamental issue.

While <10% of total samples failed due to twist according to BS: EN 14801 (2005), exactly 100% met the criterion for bow. For spring, 95% were above C18, 5% were below C18 and 0% was rejected. The permissible warp for cup is unrestricted. Using MOE.S (shear-free MOE) as an example, the pass rates in Table 4-5 were re-examined incorporating distortion.

Pass rates based on MOE Only		Distortion (based on MOE)		
		Reject	C18 and below	C18+
C24	50.5	54.3	28.7	17.0
C22	77.1	29.3	45.7	25.0
C20	91.0	16.5	53.7	29.8
C18	100.0	8.0	60.6	31.4
C16	100.0	8.0	60.6	31.4
C14	100.0	8.0	60.6	31.4

Table 4-10. The pass rates (%) for MOE.S on the left, and on the right re-examined incorporating distortion. While there are only three choices based on distortion (reject, C18 and below, or above C18), the required MOE.S for each batten had the percentage of pass/reject based on distortion occur. The columns on right are rates applied for both distortion (based on twist) and pass rates (based on MOE.S). For example, of the 100% that passed C18, 8% would then get rejected due to distortion (twist), whereas 92% would not be and of these, 61% would be C18 or below based on distortion (twist) and 31% would be above C18 (based on distortion)

The pass rates for a given grade reduce dramatically when re-examined with distortion. The pass rates at C18 are 100% based on MOE only, but with the added distortion requirements is lowered to 31%. These were assessed for distortion at a lower moisture content than is permissible, and the pieces were dried with no special restraint (freely loaded).

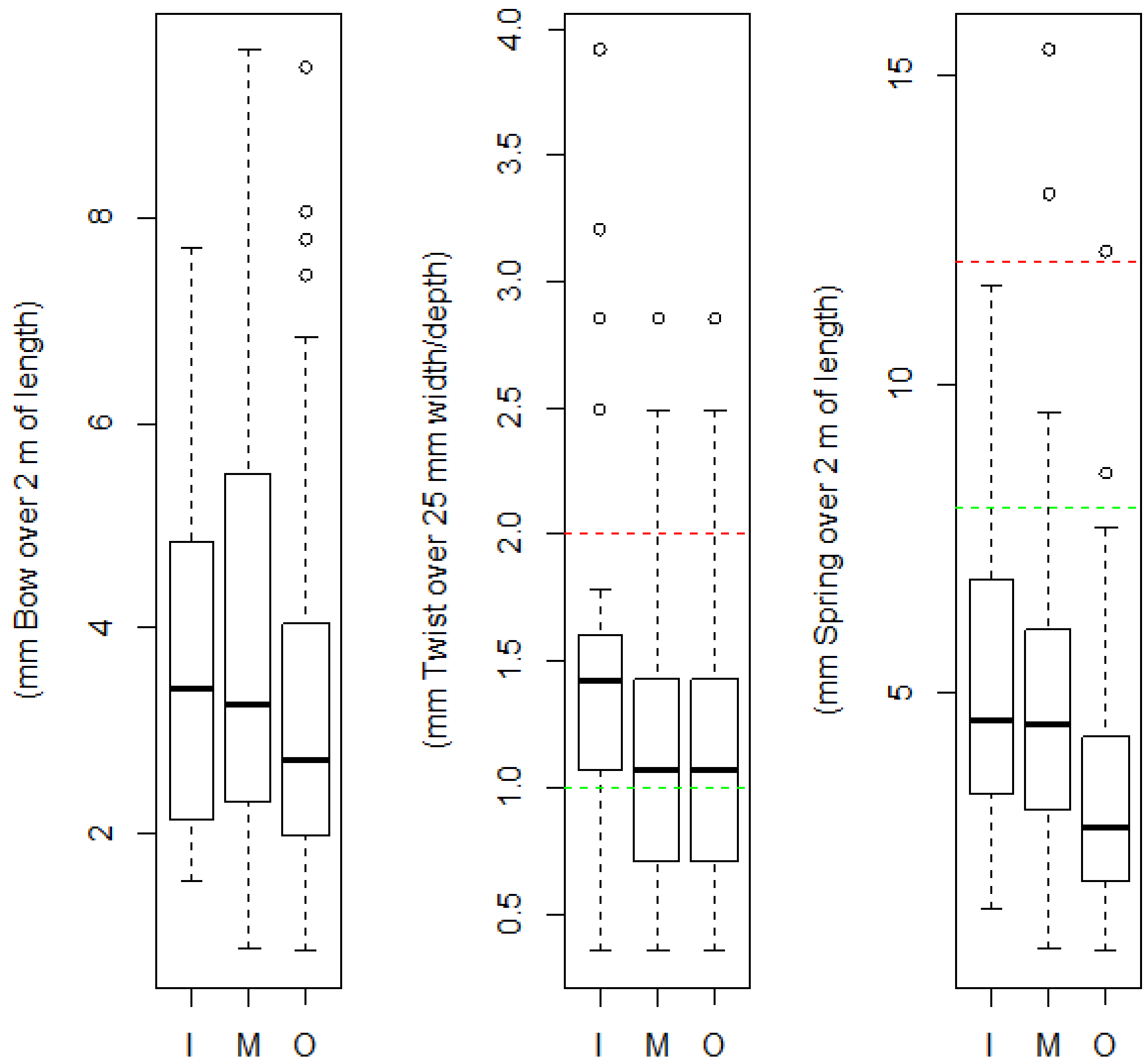

Figure 4-8. From left to right, the bow, twist and spring are displayed over the radial position. For bow, all samples fall below the C18 cut-off (10 mm) hence no green line is visible.

The mean values for "inner" "mid-range" and "outer" twist per 25 mm width/depth were 1.46 mm (SD = 0.79), 1.19 mm (SD = 0.52) and 1.09 mm (SD= 0.56) respectively.

4.5 Discussion

As presented in Table 4-2, the mean MOR was 34.0 N/mm^2 or 5th percentile at 17.2 N/mm^2. The mean MOE (shear-free) was 9130 N/mm2 and density was 455 kg/m3 (with a 5th percentile of 370 kg/m3). Density satisfied all requirements for the grades investigated (C14-24) whereas neither MOR nor Shear-free MOE did. Shear-free MOE as shown in Table 4-5 passed 100% at C18, but started declining from C20-C24 (91, 77, and 51% pass rates respectively). While the 5th percentile of MOR indicates at C18 that 99% will pass, the pass rates between C20 and C24 declines but not as greatly as MOE. This indicates that stiffness (MOE), rather than strength or density, may limit the use of Douglas-fir in higher-grade structural applications. However, it is strength (MOR) that is the first limiting factor.

As there is a likely difference between the MOR of defect-free samples and structural-sized ones but a far less obvious difference between MOE, it is reasonable to presume the presence of defects (*e.g.* knots or grain angle) can severely reduce strength (*e.g.* Zhou and Smith, 1991; Zhang *et al*., 2006; maybe another). Moore *et al.* (2009a/b) found Sitka spruce has strength of 36 N/mm^2 and 31 N/mm^2, with a stiffness of 7900 N/mm^2 and 7830 N/mm^2 respectively, much lower than the 34 N/mm^2 and 9130 N/mm^2 for strength and stiffness in Douglas-fir here. There is a large difference in MOR between Scots pine from clearwood samples Auty (2011) and Scots pine from structural samples (Macdonald *et al*., 2009). A multitude of tree characteristics directly affect MOE and MOR such as grain angle, density, MFA and knots (*e.g.* Brazier, 1986; Panshin *et al*., 1964; Zobel and Jett, 1995; Xu, 2002). Likewise factors affecting these tree characteristics include tree spacing (*e.g.* Brazier and Mobbs, 1993), thus allowing the postulation that silviculture will likely affect MOE and MOR.

For grading, Douglas-fir wood has potential to achieve C18 with minimum of reject (Table 4-5) before distortion is considered. Grading machines will not perfectly correlate with actual 4-point bending tests and therefore whichever indicating property is used should be well-correlated but will still ultimately be variable. In accordance with EN 338 and EN 384, a minimum of C18 is achievable for UK-grown structural Douglas-fir timber (based on an indicating property) and pass rates of >85% for C20 entirely plausible (EN384 CEN 2010, EN14081:1 CEN 2005, EN338 CEN 2003). Grading machines will allocate structural battens into their strength classes using a physically determined indicating property (*e.g.* knots or non-destructive results of reaction force), as discussed in detail in both Moore (2012) and Searles (2012). The pass rates for Douglas-fir here will be reduced when including distortion as per this chapter. However, these were assessed for distortion at lower moisture content than is permissible, and the pieces were dried with no special restraint (freely loaded) and therefore can be “ignored” as it was not the correct settings, rather this is a likely case of “worst-case scenario”.

For machine strength grading, these measured properties are generally related to the bending strength or stiffness (density is typically the least limiting factor). These properties must be taken not piece-by-piece but as a whole (*e.g.* a pack of timber) and this specific population has to match or exceed the required characteristics (with some allowance for uncertainty) which are the mean value of MOE and 5^{th} percentile values for MOR and density. Both MOE and density are frequently chosen as the indicating properties. Dynamic methods for determining structural MOE correlated well with static (both local and global) MOE. The HM200, in combination with density (while not technically a grading machine) displayed good potential as an indirect indicator of strength as the correlation with MOR was positive and its correlation with MOE was strong. Likewise, ViSCAN was a positive indicator of MOR and strong indicator of global MOE. Visual inspection (*e.g.* distortion) may reduce the total number of samples passed under a certain grade, as discussed above. For example, Roblot *et al*. (2008) suggest visually grading French Douglas-fir to EN 518 (CEN: 1995) gives rise to more boards being rejected than theoretical grading in accordance with EN 338 (CEN, 2003) and EN 384 (CEN, 2004). UK-grown Douglas-fir is higher in strength and stiffness that UK-grown Sitka spruce (as shown above).

Source	Density (12% MC)	Static MOE	Bending Strength
Fischer 1994	471	10.603	27,1
Glos *et al*. 1995	488	16.357	36,9
Sauter 1992	506	12.576	24,7
Pelz *et al.* 1998	438	9.158	18,1

Table 4-11. From Pelz, S; Sauter, U. H. (1998). European Douglas-fir from full-sized specimens (*e.g.* including knots). where MOE is kN/mm^2 and strength is N/mm^2.

Both USDA (2010) and Bawcombe (2013) which give mechanical properties of American, Canadian and British (region three “south”) are taken from defect-free “clearwood” and will be examined next, likewise it appears the Douglas-fir in this study is comparable to European Douglas-fir and higher in mechanical properties than UK-grown spruce thus examined in the following chapter.

Lachenbruch *et al*. (2010) found that MOE and MOR were better predicted by density and velocity then by either variable alone. This was however on small, defect-free samples from Oregon (which were also deemed mature wood). Acoustic velocity in small-clear Douglas-fir samples proved a poor predictor of MOR (Lachenbruch *et al.*, 2010), but its inclusion in models with density improved the model prediction compared to density alone.

The inclusion of variables not independent of each other (*e.g.* density and knots) in models for predicting MOR and MOE.S did not perform well in this study, yet the individual variables performed well at describing the data (Table 4-7).The adjusted R^2 of the sawnwood-level model for MOE.S was 0.86 (RSE = 893) hence no better than using ViSCAN alone. This is corroborated by examining sum of squares which shows residuals account for 13% of the variation and ViSCAN accounted for 86% (all other interactions/variables were negligible). It would appear prudent then, to only use one sawnwood-level variable to predict either strength or stiffness of fill-sized UK-grown Douglas-fir timber.

The radial positioning, where due to logistics in the field (*in situ*) they were assigned to either “inner”, “mid-range” or “outer” where the “inner” contained only juvenile wood and “outer” clearly had no juvenile present (everything undecided or in-between was deemed “mid-range”), showed large differences in strength, stiffness and density. As these radial differences were expected and profound, they form the basis of the following chapter (defect-free Douglas-fir) indicating variables. The juvenile region, which is the inner core, was discussed in chapter 2. It is clear from above that juvenile wood from this inner region has lower strength, stiffness and density which will be confirmed (or refuted) in the next chapter, specifically examining radial trends. Figure 4-8 shows that “inner” has a higher twist than “mid-range” or “outer”. This is likely to be exacerbated by the fact samples were dried to 12% MC in minimally restrained condition.

Sawmillers from Scotland (SIRT conference on timber quality, 2011) anecdotally indicated twist (as chief cause of distortion) to be a real concern for current and future timber production of Sitka spruce in the UK. Brazier (1985) indicates that juvenile wood (with low strength and stiffness compared to mature wood) is prone to distortion. Moore *et al*. (2009a) corroborate this, reporting mean values of Sitka spruce twist from inside and outside the juvenile wood zone being different (8.5 mm and 5.6 mm, respectively). Twist is also a major source of downgrade for other species such as Norway spruce, radiata pine or Sitka spruce (*e.g.* Cown *et al*., 1996; Johansson *et al*. 2001; Kliger, 2001; Searles, 2012). The Douglas-fir results here are comparable, as the difference between the means of “inner” (1.46 mm) and “outer” (1.09 mm) is 29% (alternatively the change from “inner” to “outer” would be a 25.3% decrease in twist, or from “outer” to “inner” representing a 33.9% increase in twist) and were much lower than Moore *et al*. (2009a) found in juvenile and mature Sitka spruce as above (8.5 mm and 5.6 mm, respectively). Avoiding timber containing juvenile wood (*i.e.* wood with pith or immediately adjacent to the pith) will maximise potential timber quality, as this will result in lower twist, higher MOE and MOR and denser wood (*e.g*. Cown *et al*., 1996; Kliger 2001; Johansson *et al*., 2001; Searles 2012). Wood from the juvenile section will ultimately have lower density, shorter tracheids, larger microfibril angle and spiral grain (Dinwoodie, 2000; Larson *et al.,* 2001; Macdonald and Hubert, 2002; Burdon *et al*., 2004), reduced strength (Megraw, 1986).

4.6 Conclusion

Specific objectives were: (1) to determine the strength, stiffness and density of Douglas-fir timber, (2) describe the population variability, (3) examine the strength and stiffness of structural-sized specimens between different growth regions and (4) to examine the distortion of structural-sized specimens.

The main limiting property for the UK-grown Douglas-fir sampled in this study is MOE. Given the importance of a machine to predict MOE and MOR (grade requirements), the variables that predicts the variation best (over 80%) is the acoustic tools tested here (ViSCAN, HM200). A model containing just density and knots had an R^2 of 0.43 so are still deemed important.

The exact strength and stiffness found are presented in Table 4-2. Twist is the most limiting of visual override grading for distortion. The majority of the models (two or more variables) explained a similar amount of variation as the chief variable alone. While Bawcombe (2013) investigated the mechanical properties of Douglas-fir growing in the UK (England and south Wales: “south region”), given the adjustment factors used (algorithm to adjust clearwood to structural) by the author, only indicative results could be produced. The work in this study compliments and progresses the work Bawcombe (2013) carried out by determining the limiting factor(s) for full-sized, structural samples of UK-grown Douglas-fir. While radial patterns have been examined in this chapter, the lack of knowledge on exact cambial age hindered utilising age as a primary explanatory variable. As it is assumed wood characteristics change in a radial fashion (*e.g.* pith-to-bark), a thorough investigation of clearwood samples (with a known cambial age and minimal influence of knots) is conducted in the following chapter, then a thorough examination of knots themselves (branching chapter).

5 The properties of defect-free Douglas-fir

5.1 Introduction

The aim of this chapter is to investigate and model the strength, stiffness and density of clearwood (small defect-free samples) UK-grown Douglas-fir. The structural-sized specimens allowed the limiting factor(s) of Douglas-fir (MOE and MOR) to be investigated but could only provide indicative results of radial variation. This is important as variance components analysis of structural-sized Douglas-fir data showed that most of the variation in density, strength and stiffness was within the tree. Therefore this chapter will again examine these properties in order to quantify their variation and identify the influencing factors, specifically concentrating on within-tree variation. The exact cambial age (*i.e.* ring number) of each clearwood sample is known thus facilitating age-related trends to be investigated and if possible, modelled. Clearwood properties are also easier to compare between studies as the confounding effect of knots is not present, hence the propensity of most academic studies to concentrate efforts on clearwood mechanical properties.

While linear models are simpler to interpret than nonlinear models, nonlinear models can follow trends more closely (*e.g.* Leban and Haines, 1999) as well as allowing the response variable predictions to be extrapolated outside the observed range of data (however, this would only generally work for asymptotic models with a response variable that is thought to be asymptotic also). Hence, both linear and nonlinear models will be investigated to determine under parsimony which models adequately describe and predict the response variables. Model comparisons will be made with other clearwood studies on economically important timber species in the UK (*e.g.* Auty, 2010) and on Douglas-fir growing in other countries under different management scenarios (*e.g.* Auty and Achim, 2008).

5.2 Aims and objectives

Specific objectives are: (1) to determine the strength, stiffness and density of Douglas-fir clearwood specimens, (2) examine the influence sawnwood-level variables have on these means across a range of sites, (3) investigate the influence of tree-level variables on clearwood properties and (4) develop age-related models which predict individual values for strength, stiffness and density.

5.3 Materials and methods

5.3.1 Methods

A wide range of sample sources are needed to fully determine the extent of variability within a species (*e.g.* Moore *et al.*, 2009). Consequently, the five sites were chosen to give an overview of the UK-grown Douglas-fir resource (focusing on two distinct regions, which will be comparable to a third region as examined by Bawcombe, 2013). For each of the five sites, three plots were randomly chosen and within each of these plots, three trees were selected for further processing (45 trees in total). For each sample tree, one flitch was cut longitudinally and clearwood specimens were taken from these and their cambial ages (pith to bark) were recorded. While all 272 clearwood samples were aimed to be defect free, certain samples did contain trace amounts of grain deviation or small knots, thus ranked from one (perfectly defect-free) to three (some deviations) as described in section 3.4.1 in detail. Individual age(s) for each sample is known but for comparative examination with structural battens, the samples were also categorised into 3 age groups; “inner” which were cambial ages 0 - <15 (n=121), “mid-range” which were cambial ages 15 - <30 (n=100) and “outer” which had cambial ages of 30 + (n=51). All specimens were subject to tests including distortion testing and bending tests in accordance with the correct standard (*i.e.* BS 373, EN 14081). MOE and MOR are given as flexural values unless stated otherwise.

Abbreviation	Min	Max	Mean	SD	CV	Shapiro-Wilk normality test	
Crown ratio	23.3	66.5	41.6	9.3	22.4	w = 0.9721	$p < 0.001$
Slenderness	54.1	115.1	77.0	12.5	16.3	w = 0.9344	$p < 0.001$
Lowest live branch	6.4	27.3	14.8	4.0	26.8	w = 0.9403	$p < 0.001$
Height to crown base	11.2	28.0	18.2	3.6	19.8	w = 0.9665	$p < 0.001$
Diameter at breast height	25.3	53.8	41.8	7.1	16.9	w = 0.9653	$p < 0.001$
Tree height	25.1	38.5	31.4	3.4	10.7	w = 0.9772	$p < 0.001$
Stem straightness	1.0	7.0	5.0	1.8	36.3	w = 0.8754	$p < 0.001$
MOE (N/mm^2)	2940	14300	8540	2230	26.2	w = 0.9868	$p =$ 0.013
MOR (N/mm^2)	7.7	129.9	79.1	18.5	23.4	w = 0.99	$p = 0.06$
Density (kg/m^3)	265	628.0	488	63.6	13.0	w = 0.9928	$p = 0.212$
Rings per sample	0	9	2.3	1.3	56.4	w = 0.8515	$p < 0.001$
Cambial age	2	46	18.2	11.7	64.3	w = 0.9465	$p < 0.001$
Flexural dynamic MOE	3870	18100	10500	2930	27.9	w = 0.9836	$p = 0.003$
Long. dynamic MOE	4100	20500	11400	3400	29.8	w = 0.9862	$p = 0.010$

Table 5-1. Showing the range of values for all data. The *w* is the test statistic and the p-value shows significance of this. W values close to 1 are strong(er). The null hypothesis is that the data are normally distributed. Given *p*-values less than 0.05 it is rejected that it could be chance variation (*i.e.* the data are not normally distributed). All units of measurement are given in chapter 3 (materials and methods). SD = standard deviation, CV = coefficient of variation.

5.3.2 Statistical methods

Using R, an open-source statistical programme (R Development Core Team, 2013), all non-linear analysis was carried out using functions within the nlme library. Various statistical tests were used for the analysis of both the tested samples and the corresponding information prior to testing (*e.g.* site/tree information, dynamic MOE), including ANOVA to determine difference between the means, linear and non-linear regression and interactions between variables were examined with a correlation coefficient (Pearson's) matrix, which measures the strength of a relationship between two variables (linearly, either positive or negative) as seen below.

5.4 Results

The following correlation table indicates which variables to investigate further.

	CR	SL	LLB	HCB	DBH	Height	SS	MOE	MOR	Density	Rings	Age	MOE.fx	MOE.In
CR		-0.36	-0.59	-0.83	0.34	-0.01	0.14	0.00	0.03	-0.02	-0.15	-0.03	-0.05	-0.03
SL	-0.36		0.56	0.35	-0.80	0.07	-0.14	0.05	0.15	0.08	0.43	-0.02	0.02	0.03
LLB	-0.59	0.56		0.62	-0.39	0.21	-0.03	-0.04	-0.01	0.04	0.19	0.03	-0.04	-0.05
HCB	-0.83	0.35	0.62		-0.01	0.56	0.01	-0.10	-0.12	-0.07	-0.03	0.03	-0.06	-0.07
DBH	0.34	-0.80	-0.39	-0.01		0.51	0.24	-0.16	-0.25	-0.16	-0.52	0.03	-0.12	-0.14
Height	-0.01	0.07	0.21	0.56	0.51		0.18	-0.18	-0.19	-0.17	-0.27	0.02	-0.17	-0.17
SS	0.14	-0.14	-0.03	0.01	0.24	0.18		-0.01	-0.04	0.01	-0.19	0.00	0.00	-0.01
MOE	0.00	0.05	-0.04	-0.10	-0.16	-0.18	-0.01		0.89	0.80	0.44	0.70	0.93	0.92
MOR	0.03	0.15	-0.01	-0.12	-0.25	-0.19	-0.04	0.89		0.81	0.49	0.65	0.79	0.79
Density	-0.02	0.08	0.04	-0.07	-0.16	-0.17	0.01	0.80	0.81		0.39	0.73	0.79	0.77
Rings	-0.15	0.43	0.19	-0.03	-0.52	-0.27	-0.19	0.44	0.49	0.39		0.47	0.39	0.41
Age	-0.03	-0.02	0.03	0.03	0.03	0.02	0.00	0.70	0.65	0.73	0.47		0.72	0.71
MOE.fx	-0.05	0.02	-0.04	-0.06	-0.12	-0.17	0.00	0.93	0.79	0.79	0.39	0.72		0.99
MOE.In	-0.03	0.03	-0.05	-0.07	-0.14	-0.17	-0.01	0.92	0.79	0.77	0.41	0.71	0.99	

Table 5-2. Correlation values between chosen variables, where values closer to 1 are strong. Significance was ascertained at $p<0.05$ using *cor.test(x,y)* for individual correlation coefficients. Only four sites ("PI", "LT", "MA" and "RU") were used in their totality for the IML, HCB and LLB values in this correlation matrix given these missing values (for site "LA", all samples in plot 3 were removed) are not allowed. This is for all values (not mean per tree) in all cases.

As density is a direct measurement on each sample it will be a good predictor of the properties (MOE, MOR) as seen in Table 5-2. However, the clearwood mechanical (MOE, MOR) and physical (density) properties of interest are known (Table 5-1), thus their variability within the tree are of main interest. To achieve growth models, MOE and MOR (and density) are each examined to see how age fares as a predictor, and then the amount of rings per sample is added to the models to investigate its effect on these properties. Before the models, the relationships between the mechanical and physical properties are explored (as well as differences between sites (in the appendix 10.2).

Table 5-2 shows poor correlation between values for individual tree-level variables (crown ratio, slenderness, lowest live branch, height to crown base, diameter at breast height, total tree height and stem straightness) and individual sawnwood-level variables (MOE, MOR, density, rings per sample, cambial age, flexural dynamic MOE and longitudinal dynamic MOE). Given that the correlation table is for individual samples and as such the relationships are affected by the variability, the main properties of interest were again investigated with Pearson's correlation by using average per tree.

Certain tree-level variable are correlated with each other, such as height to crown base with crown ratio (HCB, CR) or diameter at breast height with slenderness (DBH, SL). However, MOE, MOR and density taken as mean per tree are better correlated with tree-level attributes as seen in Table 5-3.

	MOE	MOR	Density
DBH	-0.22	-0.39	-0.21
HT	-0.34	-0.35	-0.33
SL	-0.0087	0.18	0.030
SS	-0.035	-0.084	0.032

Table 5-3. Showing correlation values between chosen variables with values close to 1 as strong. All were significant, ascertained at p<0.05 using *cor.test(x,y)* for individual correlation coefficients. Only four sites ("PI", "LT", "MA" and "RU") were used in their totality for the IML, HCB and LLB values in this correlation matrix given these missing values (for site "LA", all samples in plot 3 were removed) are not allowed.

Table 5-3 shows that stem straightness (SS) and slenderness are not correlated with MOE, MOR and density, while DBH and height are correlated slightly better with sawnwood-level variables but not enough to be strong. Many more exist between the sawnwood-level variables, noticeably so between the longitudinal and flexural dynamic MOE (0.99). These are both correlated strongly with static MOE (0.92 and 0.92 respectively). As given in Table 5-1 the mean MOE is 8540 N/mm^2 and MOR is 79 N/mm^2, while density is 488 kg/m^3.

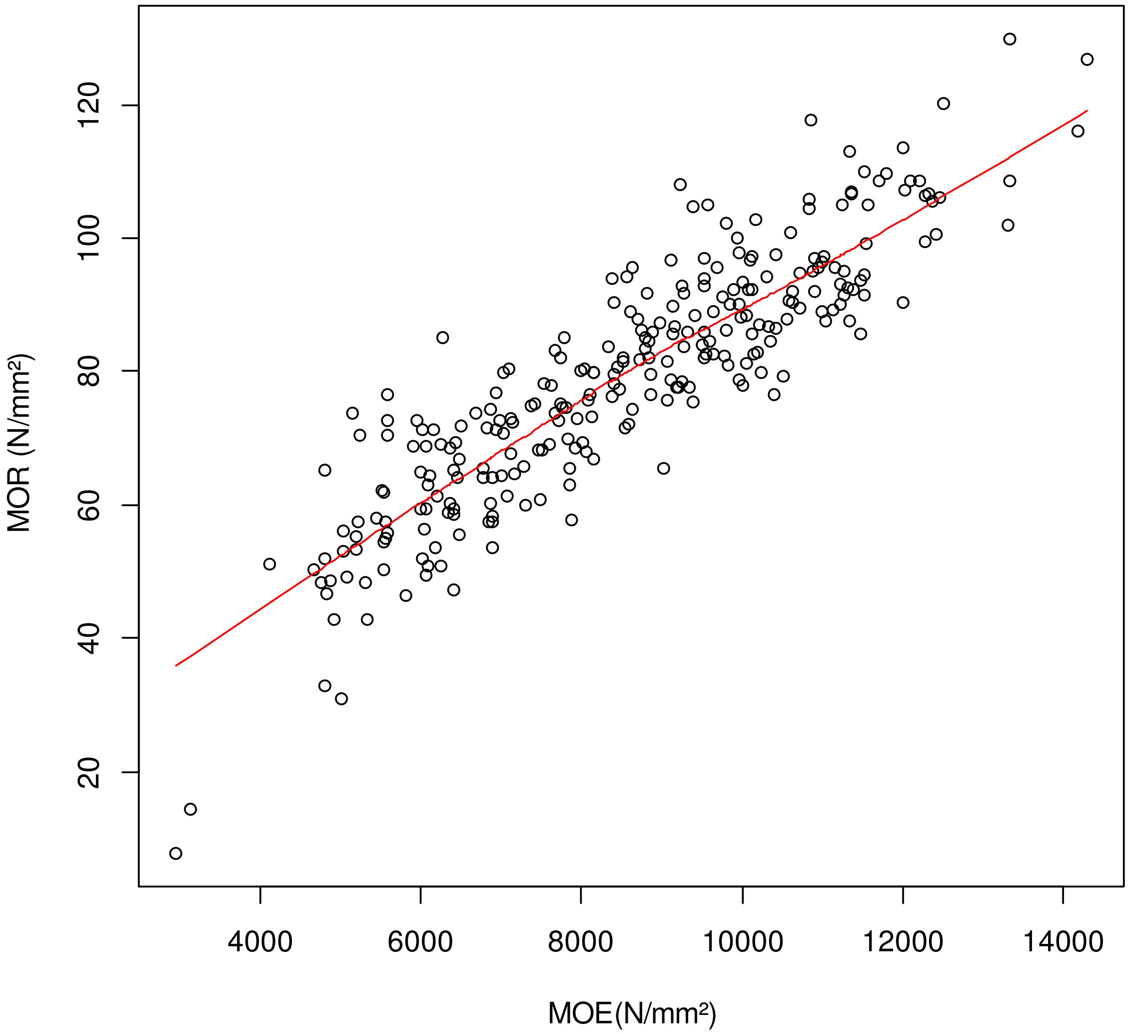

Figure 5-1. Showing the strong relationship between MOE and MOR (R^2 0.80), with the equation MOR=0.0074*MOE+15.827. The red line here is a loess line (locally weighted regression).

MOR and MOR are correlated (r 0.89) and using linear regression, the coefficient of determination (R^2) explains the proportion of the variance (fluctuation) of MOR predictable by MOE is 0.80 (RSE = 1010 on 270 degrees of freedom, p<0.005).

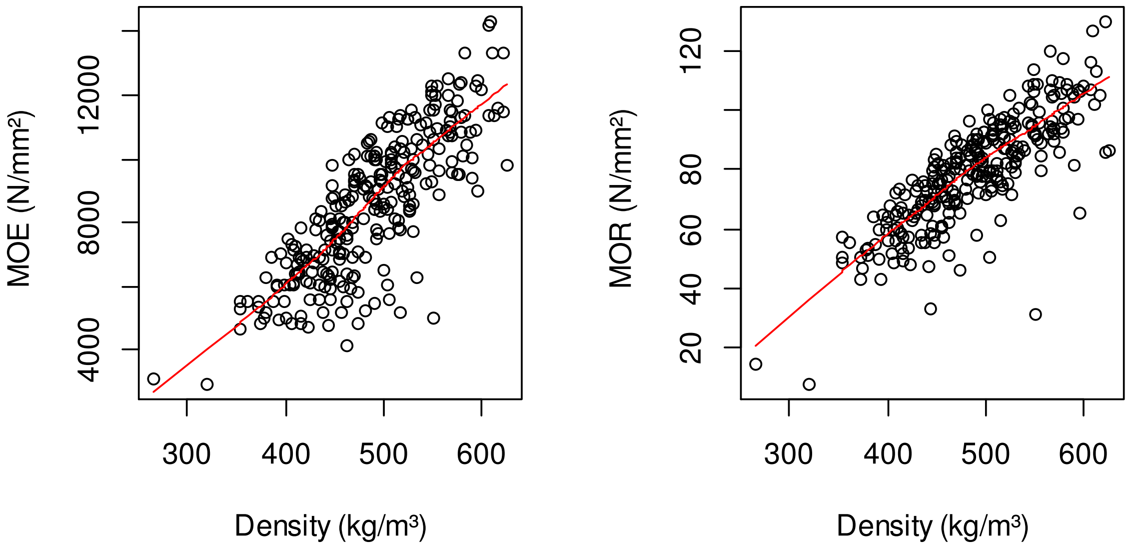

Figure 5-2. Showing the positive relationships between MOE and MOR with density. The lower value of some MOE and MOR that still have high density values may be due to radial position (*e.g*. near the pith) but this is inconclusive as of yet.

The linear relationship between density and MOE is positive (R^2 of 0.66, RSE = 37 on 270 degrees of freedom). Density is also correlated with MOR and has a similar relationship (R^2 of 0.66, RSE = 36 on 270 degrees of freedom).

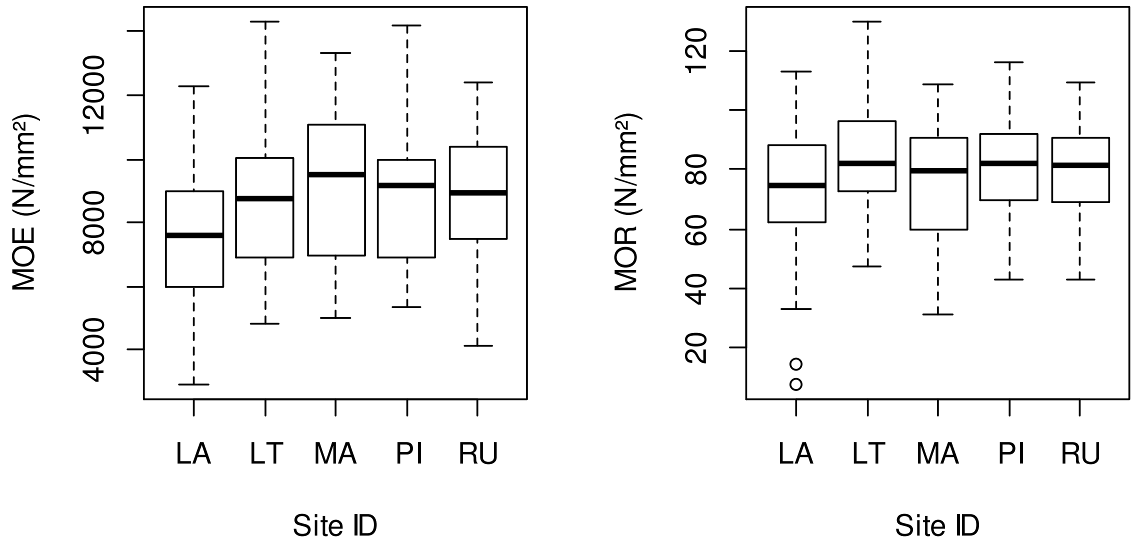

Figure 5-3. Showing the range of MOE and MOR for each site (LA, LT, MA, PI and RU). LT and PI have individual higher values (top end of range). 95% of data is shown (along with median line) in the boxwhisker plot (upper and lower quartiles can be seen within box).

The MOE (total population mean 8540 N/mm^2) is different for each site as confirmed by doing a single ANOVA to determine if the sites are different (Pr(>F) 0.00522). MOR had a total mean of 79 N/mm^2. For both MOE and MOR, the variation within a site appears to be greater than the variation between sites. Investigating age-related trends will allow for models which predict individual values for strength, stiffness and density to be made.

		MOE		MOR	
Site	Replications	Mean	SD	Mean	SD
LA	55	7570	2230	74	21.6
LT	51	8670	2120	85	18.5
MA	63	9070	2310	76	17.8
PI	43	8670	2100	82	16.0
RU	60	8690	2140	79	16.3

Table 5-4. The MOE and MOR per site (mean and stand deviation), with the amount of samples per site given (replications).

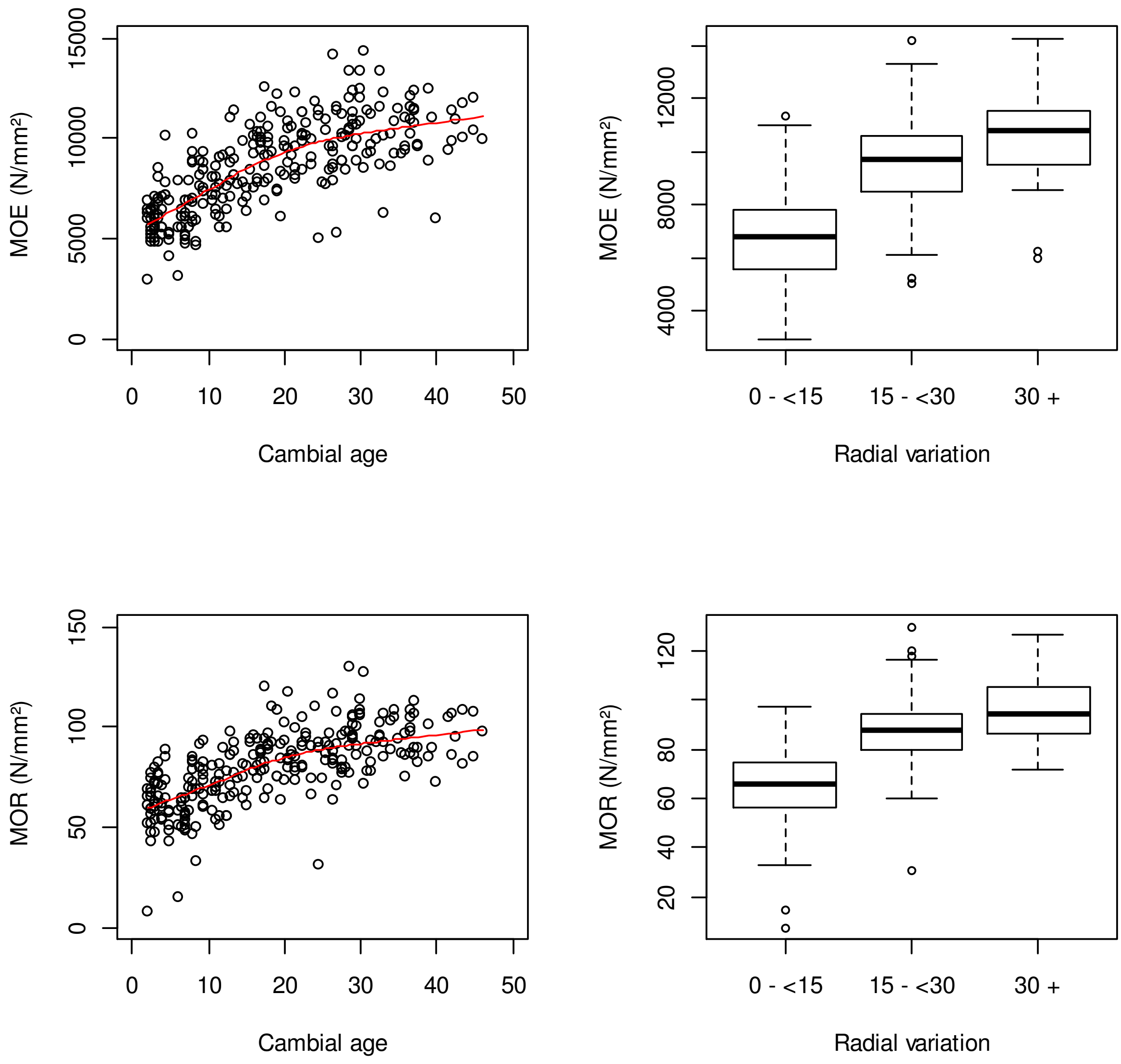

Figure 5-4. Showing radial change in both MOE and MOR. Individually, MOE and MOR appear non-linear as cambial age increases (left). This trend is also seen in the radial variation groupings (right).

Figure 5-4 shows an increase in MOE and MOR with age as seen for individual values (cambial age) and together in their groupings (radial variation, which are the age-groups as discussed above in materials and methods). The red line represents a smoothed function trend line (a LOWESS line, *i.e.* a locally weighted regression line), which imply the age-related trends are not linear. For MOE, the asymptote of the curve cannot clearly be defined as it extends beyond the dataset. However, it appears to be above 10,000 N/mm^2 indicating that for older samples (higher cambial ages), MOE is likely to increase (to an asymptotic point). It is reasonable to assume given the data that older wood (higher cambial age) will be stiffer, stronger (and denser) but this could not feasibly continue in perpetuity; it would eventually reach a maximum value (and either continue along a straight line or decline).

Using linear regression, the coefficient of determination (R^2) explains the proportion of the variance of MOE and MOR that is predictable from a given sawnwood-level variable as shown in Table 5-5.

	(Predictable) relationship with MOE			(Predictable) relationship with MOR		
Variable	adj. R^2	RSE*	*p*-value	adj. R^2	RSE*	*p*-value
MOE	N/A	N/A	N/A	0.80	8.38	$p < 0.001$
MOR	0.80	1010	$p < 0.001$	N/A	N/A	N/A
Density	0.66	1310	$p < 0.001$	0.66	10.75	$p < 0.001$
Rings	0.19	2006	$p < 0.001$	0.24	16.14	$p < 0.001$
Age	0.51	1565	$p < 0.001$	0.44	13.89	$p < 0.001$
MOE.fx	0.87	804	$p < 0.001$	0.65	11.01	$p < 0.001$
MOE.ln	0.86	840	$p < 0.001$	0.64	11.15	$p < 0.001$

Table 5-5, (Predicative) relationships between MOE and MOE and the given variables (density, rings per sample, age, flexural dynamic MOE and longitudinal dynamic MOE). * RSE on 270 degrees of freedom.

Given the correlation coefficients shown in Table 5-2 and the coefficient of determination in Table 5-5, while the main response variables (MOE, MOR and density) are all correlated with each other (signifying non-independence), they all a have a clear relationship with age, therefore age shall be the primary indicator (independent predictor) variable for model-building.

For each parameter, there will be three types of model examined; linear, logarithmic and exponential, which will be done twice. Firstly they will be modelled with age then as explained above, the number of rings per sample will be included (thus 18 models in total for the three parameters).

5.4.1 MOE models

The MOE for each tree and differences between sites is seen in the appendix (10.2).

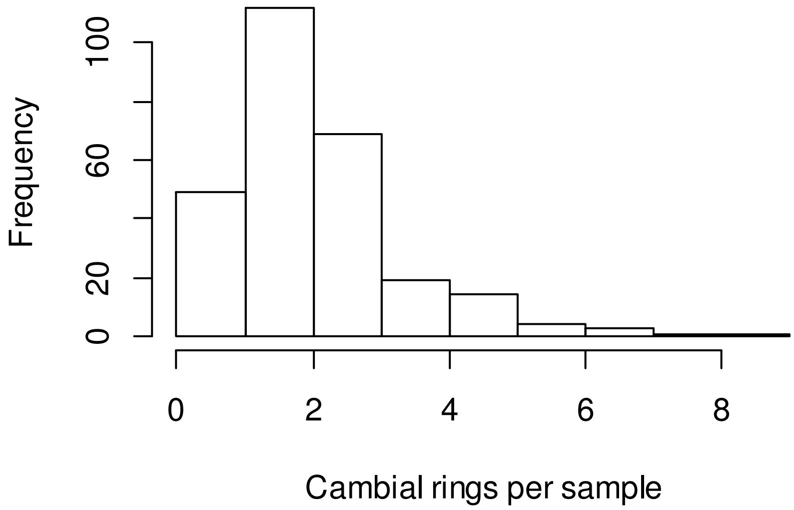

Figure 5-5. Examining MOE samples for use in predictive modelling, with a histogram for amount of rings per sample. There are no samples with "0" rings.

Firstly we can see the histogram of rings per sample to determine if the amount (as biologically assumed based on previous literature that a higher proportion of LW would mean higher strength and stiffness) is a factor. The Shapiro-Wilks test (Table 5-1) indicates the normality (or lack of) and Figure 5-5 above shows the expected the histogram of rings per sample (samples cannot have a cambial age of “0”).

As already stated, it appears the relationship between age and MOE is non-linear. However, the simplest form of model would be to use only age as the independent variable (thus rendering the model as a simple linear regression). Model 1 (linear):

MOE ~ Cambial age [5-1]

This estimates the intercept at 6058 and gives an adjusted R^2 of 0.51 (RSE: 1565).

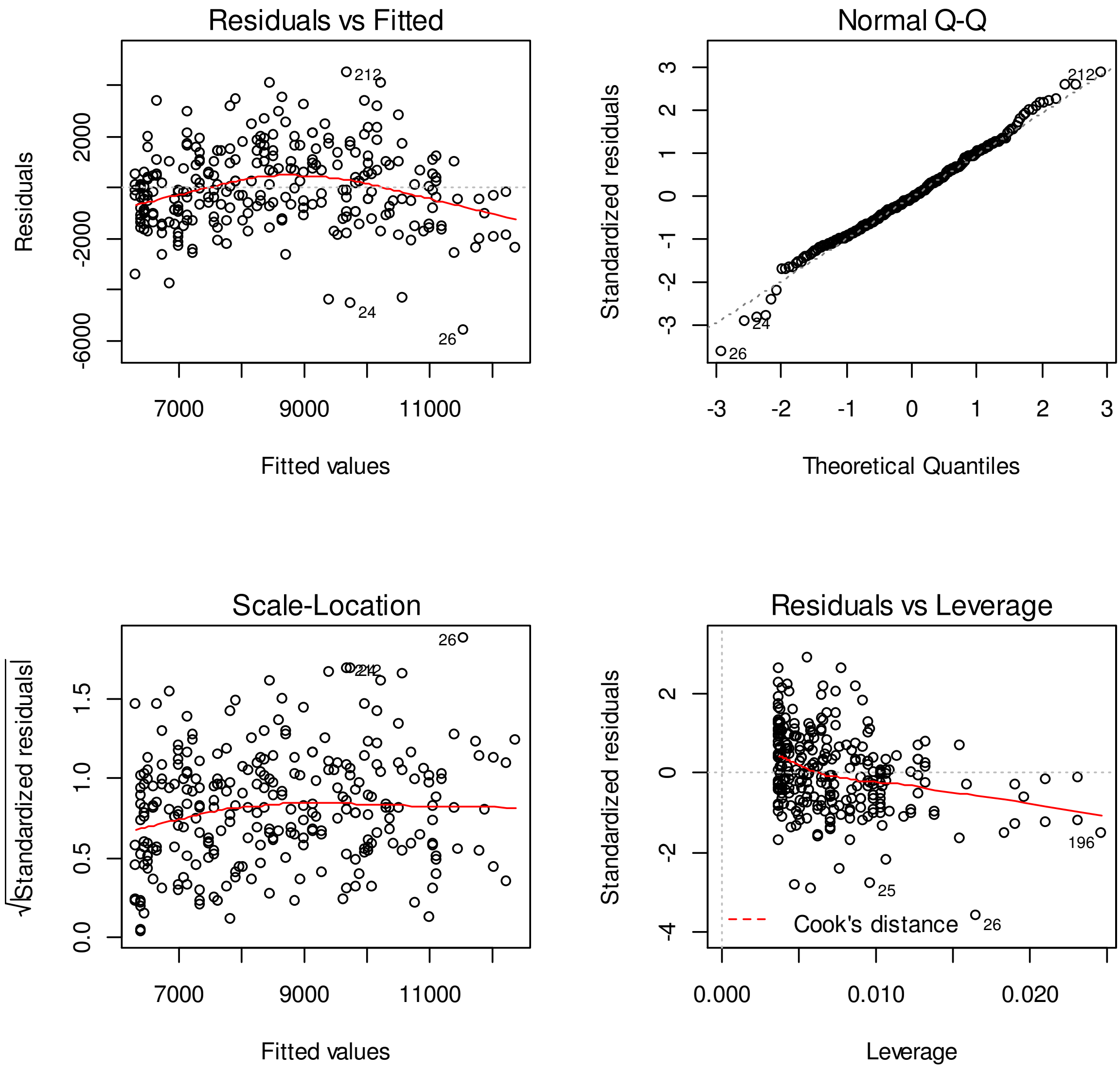

Figure 5-6. Showing model 1 and the residual v fitted values. The residuals show the model is not adequate, while the Q-Q plot confirms lower and top end skew of data not fitting to model.

For this simple version above, while not entirely homoscedastic, the residuals v fitted (where points should be randomly scattered around the centre line) suggest non-linearity but variance does not massively increase or decrease and the Q-Q plot (*i.e.* whether the distribution of residual error is normal or not) corroborates this. The residuals v fitted plot suggests the model is not as accurate at higher fitted values, or put simply the model is not adequate (due to the non-linearism of the data). The residuals account for 49% of the variation. Model 2 (logarithmic):

MOE ~ ln.Cambial age **[5-2]**

Model 2 is slightly better, giving a higher R^2 value (0.54) and lower RSE value (1516). The model explain more of the variation, consequently residuals counted for slightly less (46%) compared to model 1. Model 3 (exponential model):

MOE ~ -a/exp(Cambial age * b) + d [5-3]

where a is the estimated starting value (intercept), b is the rate (ratio of line change) and d is the asymptote for MOE (assumed maximum average value). The RSE value for the exponential model was the lowest of the three (and R^2 of 0.56 was highest). Given that Douglas-fir in the UK is given as 10,500 mm^2 by Lavers (1983), the upper limit was indicated at over 10,000 N/mm^2.

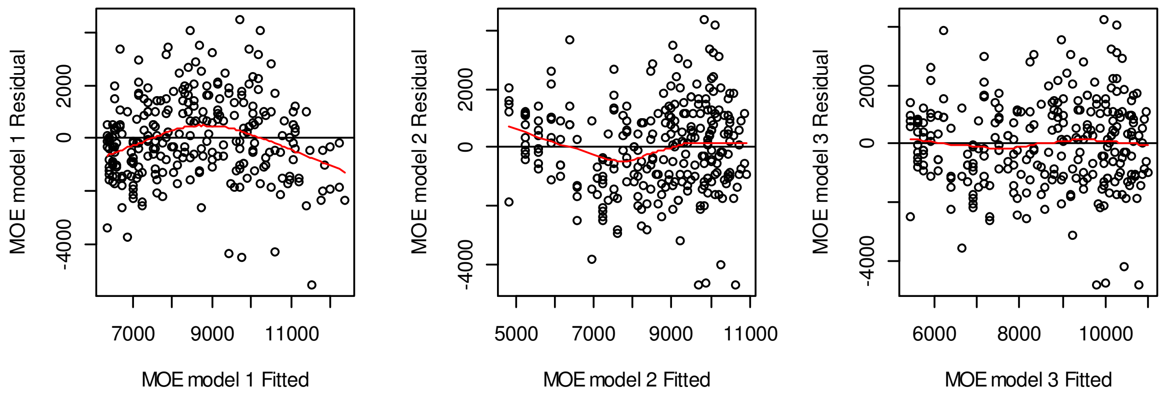

Figure 5-7. Residuals v fitted for models 1 – 3. Model 3 appears to be the most homoscedastic fit, while the red line for models 1 and 2 deviate from the centre, suggesting the model do not adequately fit the data.

For this residual v fitted values for model 3, it suggests an unbiased and homoscedastic fit. The red line does not deviate from the centre thus suggesting the model is adequate and continues to fit at higher values.

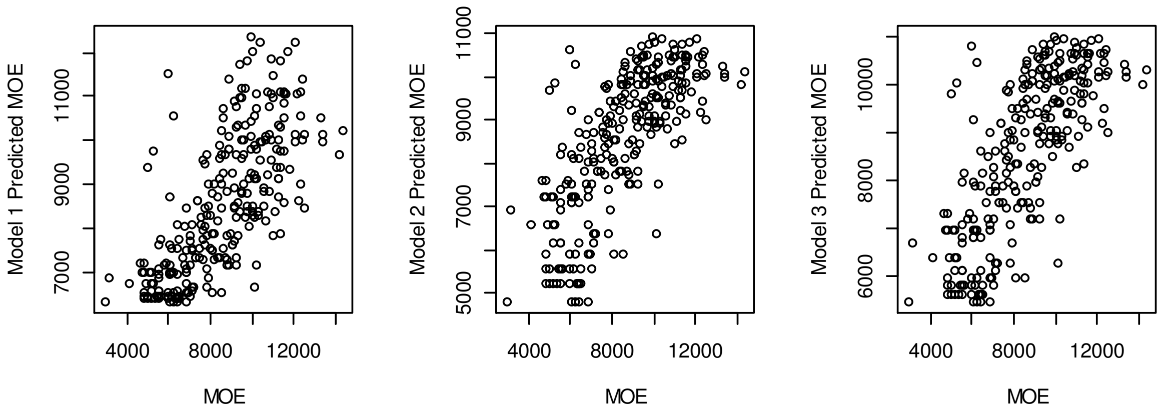

Figure 5-8. Observed and predicted values for the three models using only age as the predictor variable. All three are generally equally adequate in predicting MOE using only age to predict MOE.

As seen in Figure 5-8, the predicted MOE for all three models indicate positive but not strongly fit values compared to observed values. Table 5-6 shows the adjusted R^2 (coefficient of determination) for these models. The exponential model (model 3) had the lowest residual standard error and highest value for fit (R^2 of 0.56).

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Signif.	RSE	Adj. R^2
Model 3 (exponential)							
a	6.75E+03	4.44E+02	15.199	< 2e-16	***	1482	0.56
b	5.66E-02	1.23E-02	4.621	5.92E-06	***		
d	1.15E+04	5.64E+02	20.346	< 2e-16	***		
Model 2 (logarithmic)							
(Intercept)	3434.8	300.7	11.42	<2e-16	***	1516	0.54
log.age	1952.8	109.5	17.84	<2e-16	***		
Model 1 (linear)							
(Intercept)	6057.953	175.726	34.47	<2e-16	***	1565	0.51
SampleAge	136.765	8.141	16.8	<2e-16	***		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1							

Table 5-6. Showing parameter estimates for the linear, logarithmic and exponential models using only age as the indicator. The exponential model (3) has the highest R^2 and lowest RSE.

The first models were determined using age as the explanatory variable. Adding rings (but not the interaction between age and rings) to the models gave the following updated versions:

Model 1A is the linear model with density added as secondary variable:

$$MOE = SampleAge + rings \quad [5\text{-}4]$$

Model 2A is the logarithmic model with density added as secondary variable:

$$MOE = \ln.age + rings \quad [5\text{-}5]$$

Model 3A is the exponential model with density added as secondary variable:

$$MOE = -a/\exp(SampleAge * b) + d + (e * rings) \quad [5\text{-}6]$$

The same models as before had rings per sample added given their likelihood of influencing the prediction of MOE. All three models barely increased in their ability to predict MOE (*i.e.* the models fit the data only slightly better than before). These are given below (Table 5-7).

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Signif.	RSE	Adj. R^2
Model 3A (exponential)							
a	6.116e+03	4.418e+02	13.843	<2e-16	***	1456	0.58
b	6.163e-02	1.367e-02	4.510	9.69e-16	***		
d	1.050e+04	5.815e+02	18.055	<2e-16	***		
e	2.422e+02	7.844e+01	3.088	0.00223	***		
Model 2A (logarithmic)							
(Intercept)	3296.6	298.12	11.06	< 2e-16	***	1489	0.56
log.age	1777.9	119.54	14.87	< 2e-16	***		
Rings	262.80	78.68	3.34	0.0009	***		
Model 1A (linear)							
(Intercept)	5747.7	205.59	27.957	< 2e-16	***	1545	0.52
SampleAge	124.55	9.136	13.633	< 2e-16	***		
Rings	234.76	84.445	2.814	0.0052	**		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1							

Table 5-7. Showing parameter estimates for radial MOE models with added. As the previous table, the exponential model (3A) has the highest adjusted R^2 and lowest RSE. The logarithmic model has a marginally lower R^2.

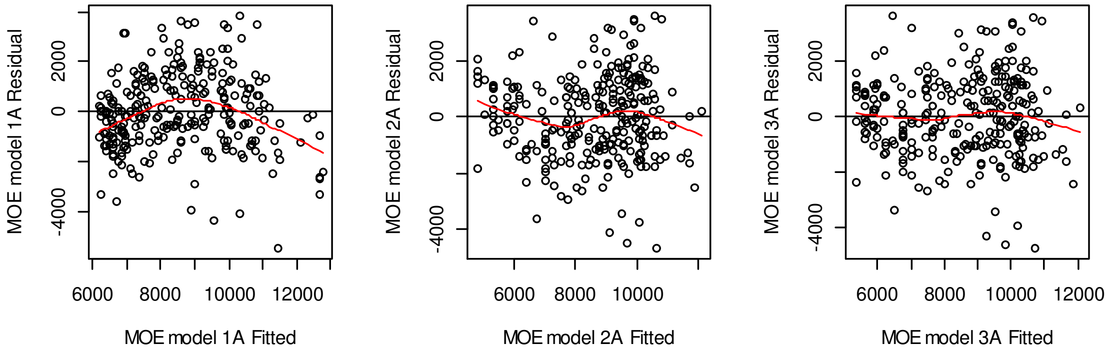

Figure 5-9. Showing fitted v residuals for models 1A – 3A (rings included). Model 3A appears to have a better fitted v residuals range, with the red line not deviating as much from central point as 1A and 2A, indicating model 3A has a better fit than model 2.

As model selection can be based on a visual analysis of the normalised residuals plotted against fitted and explanatory variables (Pinheiro and Bates, 2000), model 3A appears to adequately describe the data trend. Figure 5-10 shows the predicted values for the three models. Models 2A and 3A appear to predict MOE better than model 1A.

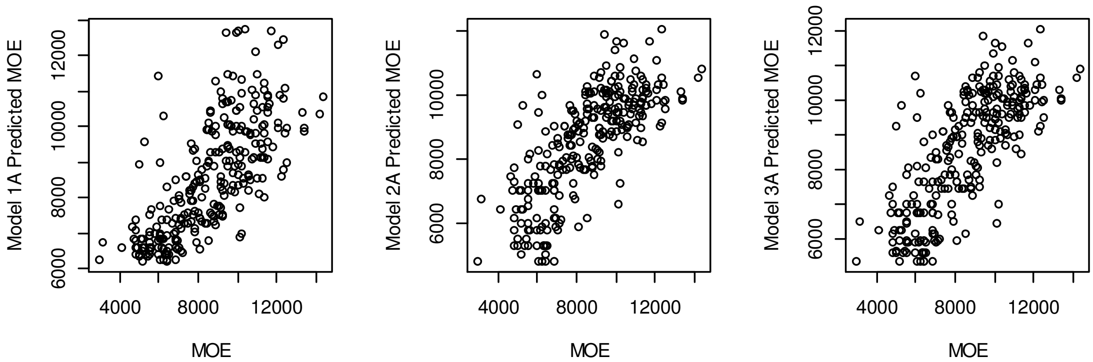

Figure 5-10. Predicated and observed values for models 1A – 3A. Model 2A and 3A appear to fit the data better than model 1.

As the data were nested (*i.e.* each sample was numerous with a tree, which was in a plot, which were in sites), hierarchal trends were investigated. Examining variance components, 4.3% of the variation in MOE was accounted for between sites, there was no difference between plots, 6.5% of the variation was explained by difference between trees and 89.2% was within the tree. This is to be expected as MOE varies greatly within the tree (as seen, MOE changes with age, which is an increasing ring number from pith, *i.e.* radial position).

Using cambial age as a fixed effect (as previously seen that age is correlated with MOE), 13.5% of the variation was explained between sites, plot still had no effect, yet between trees there is a 40.8% difference and the residual variance is now 45.7%, this suggests a separate relationship of MOE to AGE by tree might be required in further analyses.

5.4.2 MOR models

MOE and MOR have a strong relationship; accordingly the same models above for MOE were tested for MOR. Similar to MOE, age was used as the primary variable for MOR and both linear and non-linear models were explored. MOR can be predicted due to its correlations with age (R^2 0.44). The differences between sites can be seen in appendix 10.2.

As with MOE modelling, age was the primary explanatory variable. The same types (1: linear, 2: logarithmic, and 3: exponential) of models were tested. Using age as the only predictor variable, the linear model had the highest RSE and lowest R^2 while again as with MOE, the exponential model had the highest R^2 and lowest RSE for MOR, but these all described less than half of the variation (R^2 of 0.44, 0.45 and 0.47 respectively). Rather than reporting all the steps taken for MOR which are the same as for MOE, only the chosen set is detailed here. Fitting the data to the same models for MOE, including density as a secondary variable again increased the predictive power of the three model types (now 1A, 2A and 3A) as seen in Table 5-8.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Signif.	RSE	Adj. R^2
Model 3A (exponential)							
a	43.63204	4.43647	9.835	< 2e-16	***	12.97	0.56
b	0.05571	0.01672	3.332	0.000983	***		
d	90.53156	5.88656	15.379	< 2e-16	***		
e	3.38551	0.69700	4.857	2.03e-06	***		
Model 2A (logarithmic)							
(Intercept)	38.6262	2.6405	14.628	< 2e-16	***	13.2	0.49
log.age	12.3359	1.0588	11.651	< 2e-16	***		
Rings	3.6033	0.6969	5.171	4.55e-07	***		
Model 1A (linear)							
(Intercept)	55.5136	1.7822	31.148	< 2e-16	***	13.4	0.48
SampleAge	0.8786	0.0792	11.093	< 2e-16	**		
Rings	3.3465	0.7234	4.626	5.79e-06	***		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1							

Table 5-8. Showing parameter estimates for radial MOR models using age and rings as predictor variables. As before, the exponential model has the highest R^2 and lowest RSE, with the linear logarithmic model having only a slightly lower R^2 than each other

MOR "A" models (using rings and age as predictor variables) were not much better than using age alone. MOR model 3A (exponential) fit the data better than model 2A or 1A did, but only by a small percentage.

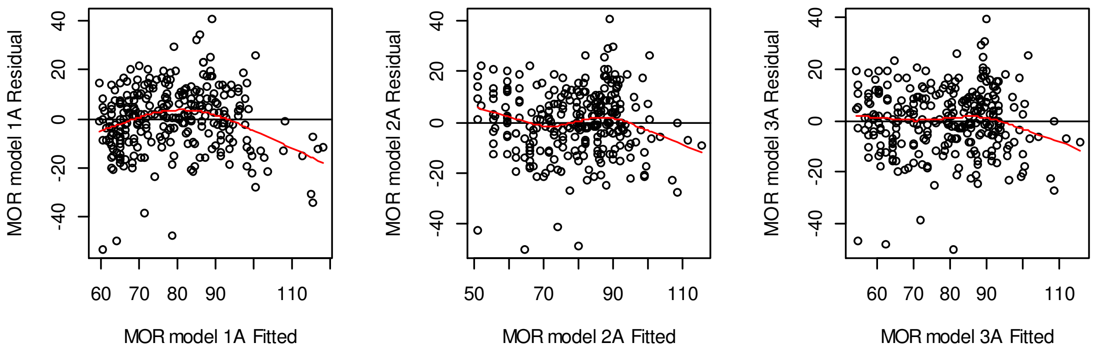

Figure 5-11. Showing residuals v fitted for models 1 – 3. Model 1 appears to have a slightly less homoscedastic fit compared to 2 and 3, while the red line for models 1 also suggests at lower values the models do not fully describe the data (not perfectly adequate).

The fitted v residuals show that for MOR model 1A, the data is not as adequately described compared to models 2A or 3A, which appear to be slightly better. In this instance, MOR model 3A seems to be the better fit. The line deviates at lower ends suggesting the models do not accurately describe the data for samples with the lowest MOR results. Figure 5-12 shows the predicted MOR for “A” models. Model 2A and 3A appear to predict better than model 1A by a small margin.

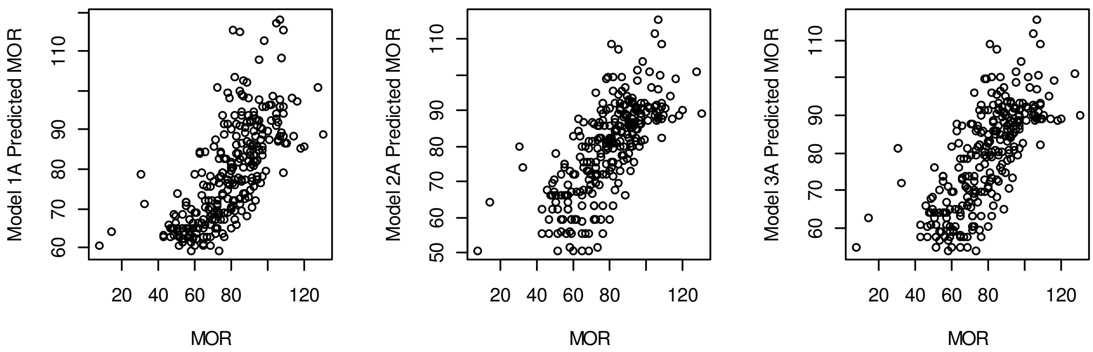

Figure 5-12. Predicted and observed MOR for the models 1A, 2A and 3A. All appear to predict MOR well.

For MOR, adding rings per samples for the three models (*i.e.* 1A, 2A and 3A) gave little difference in their predictive power. Under parsimony, it would be prudent to use model 3A for MOR (exponential with just age and rings as the predictor variables).

Examining variance components, 3% of the variation in MOR was accounted for between sites, 2% between plots, 7% of the variation was explained by difference between trees and 88% was within the tree. This is expected as MOR is so closely related to MOE which also varies greatly within the tree (radially). As with MOE, using a fixed-effect (in this case, age), the balance shifted towards explaining more of the difference between sites. 9% of the variation was explained between sites, plot explains 4% of the variation, yet between trees 32% of the variation is explained. The residuals (in this case within-tree not described by a single relationship of MOR to age) explain 55%.

5.4.3 Density models

The density models, as with MOE and MOR, were fit to the data for density (linear, logarithmic, and exponential with age as primary predictor variable and rings per sample secondary).

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Signif.	RSE	Adj. R^2
Model 3A (exponential)							
a	295.3819	122.8865	2.404	0.0169	*	43.41	0.55
b	0.0184	0.0113	1.629	0.1046			
d	696.6815	129.1119	5.396	1.5e-07	***		
e	3.4088	2.3454	1.453	0.1473			
Model 2A (logarithmic)							
(Intercept)	350.402	9.252	37.874	< 2e-16	***	46.2	0.47
log.age	47.509	3.710	12.806	< 2e-16	***		
Rings	5.972	2.442	2.446	0.0151	*		
Model 1A (linear)							
(Intercept)	412.013	5.8047	70.9980	< 2e-16	***	43.63	0.53
SampleAge	3.7948	0.2579	14.712	< 2e-16	***		
Rings	3.1984	2.3560	1.358	0.176			
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1							

Table 5-9. Showing parameter estimates for radial density models using age and rings as predictor variables. As before, the exponential model has the highest R^2 and lowest RSE, with the linear model in this instance having only a slightly lower R^2.

For density, the only model which had all interactions significant was the logarithmic, but this was the lowest R^2. The linear was able to predict desnity better than logarithmic (unlike MOE and MOR) and the exponential was the better of the three again, despite its non-significance of half the variables. In this instance, it would seem prudent to suggest the linear model is better than logarithmic, but the exponential is still the best predictor which is corroborated by Figure 5-13.

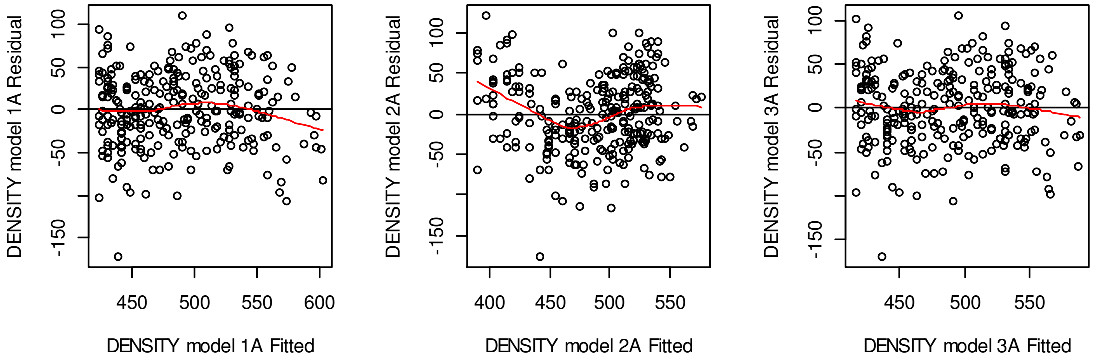

Figure 5-13. Residuals v fitted for the three models. Model 3A is the best fit, while model 1A (linear) is better than model 2A (logarithmic).

The values for models 1A and 3A appear to predict density better than model 2A (Figure 5-14), but adding rings per sample again did not highly change the results.

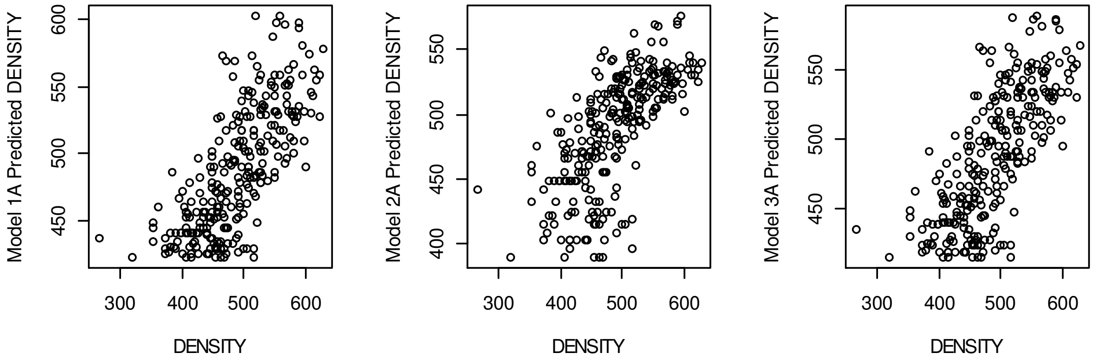

Figure 5-14. Showing the predicted models for density, where model 2A is less appropriate.

Examining variance component again shows 6% of the variation in density was accounted for between sites, 2% between plots, 10% of the variation was explained by difference between trees and 82% was within the tree. Again using age as a fixed-effect, 8% of the variation was explained between sites, plot explains 5% of the variation, yet between trees 49% of the variation is explained. The residuals (in this case within-tree not described by a single relationship of density to age) explain 39%.

5.4.4 Using density to predict MOE and MOR

Despite age-related trends (variation within the tree) being of primary interest for this chapter, given the fact MOE and MOR are more highly correlated with density than age, the linear, and logarithmic and exponential models were tested, using density as primary predictor variable then age and rings per sample secondary and tertiary. The full working is not presented here (as age-related trends remain primary focus), rather just the final chosen model(s) for MOE and MOR. While the exponential model again predicted the variation more than logarithmic, it was marginal and under parsimony (Occam's razor) the logarithmic model(s) was chosen.

MOE model: y=density+ln.age [5-7]

MOR model: y=density+ln.age+rings [5-8]

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Signif.	RSE	Adj. R^2
Model 2 (logarithmic) for MOR							
(Intercept)	-26.7242	5.0390	-5.303	2.38e-07	***	9.999	0.71
DENSITY	0.1865	0.0132	14.133	< 2e-16	***		
Log.age	3.4755	1.0187	3.412	0.000746	***		
RINGS	2.4896	0.5343	4.659	5.00e-16	***		
Model 2 (logarithmic) for MOE							
(Intercept)	-3744.074	596.113	-6.281	1.35e-09	***	1187	0.72
DENSITY	20.306	1.549	13.108	< 2e-16	***		
Log.age	907.395	117.050	7.752	1.87e-13	***		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1							

Table 5-10. Parameter estimates for MOE and MOR models using density, age and rings as predictor variables

By investigating sum of squares, the density accounted for 66% of the variation, the natural logarithm of age 6% and 28% was unexplained (residuals) in the MOE model. For the MOR model, again 66% of the variation was accounted for by density, age (logarithm) accounted for 2%, rings per sample 2% and 29% was unaccounted for.

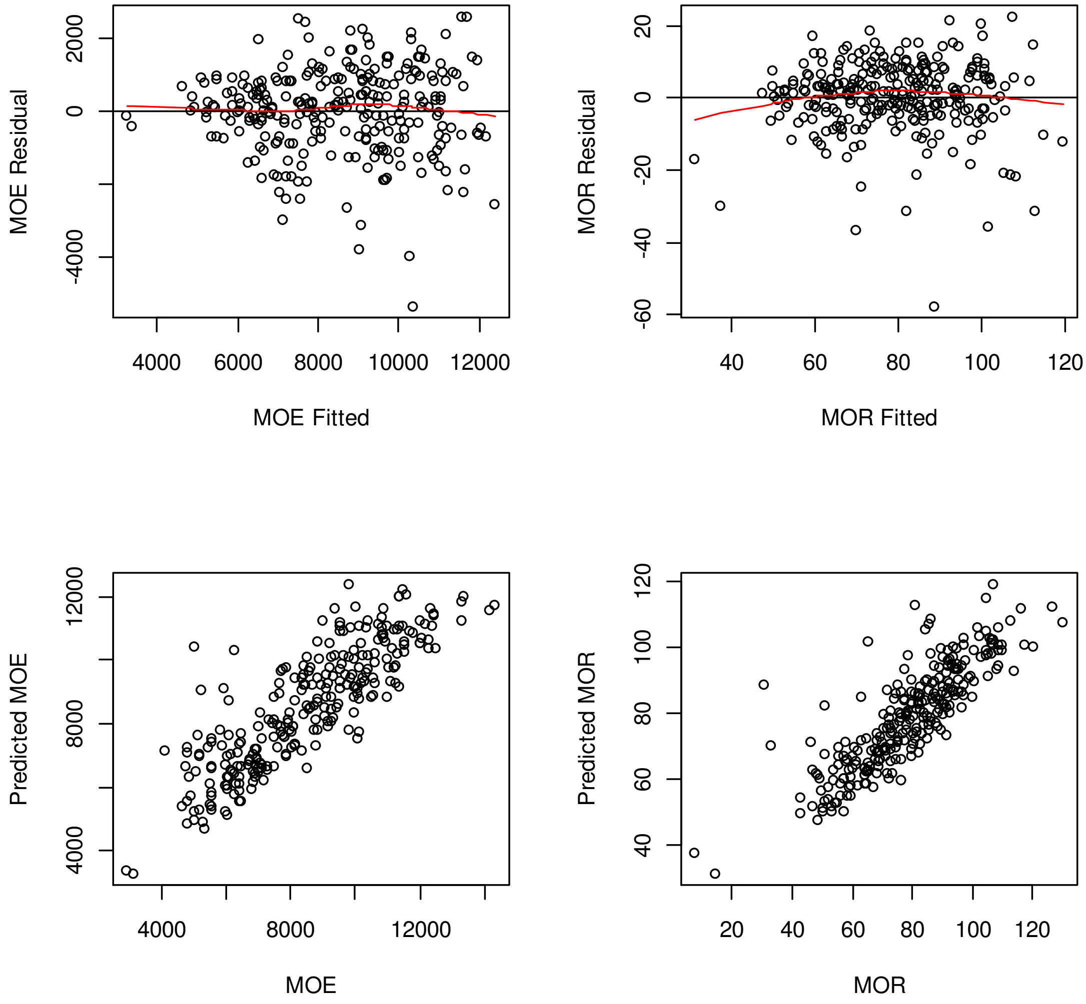

Figure 5-15. Showing the residual v fitted for both models. MOE fits well as does MOR (but slightly less so). The predicted MOE and predicted MOR are similar, showing an increase (logarithmic model) in predicted values for an increase in observed values.

The residual v fitted is presented for both MOE and MOR models using density as main predictor variable. The MOE model appears to be a good fit while the MOR is slightly more skewed than the MOE model. The MOR model however demonstrates is ability to predict MOR values based on observed values, similar to the MOE model.

5.4.5 Including the Bawcombe (2013) data to examine regions

As Bawcombe (2013) explored clearwood data for the south of UK (Table 3-1), investigating that region and the differences with the two presented for this study was possible. The only data available from the author consisted of clearwood MOE and MOR for a given age (the exact cambial age was known, akin to this study). Using the author's breast height samples only, the means of these regions was given and a linear relationship between the parameters (MOE and MOR) and age was examined.

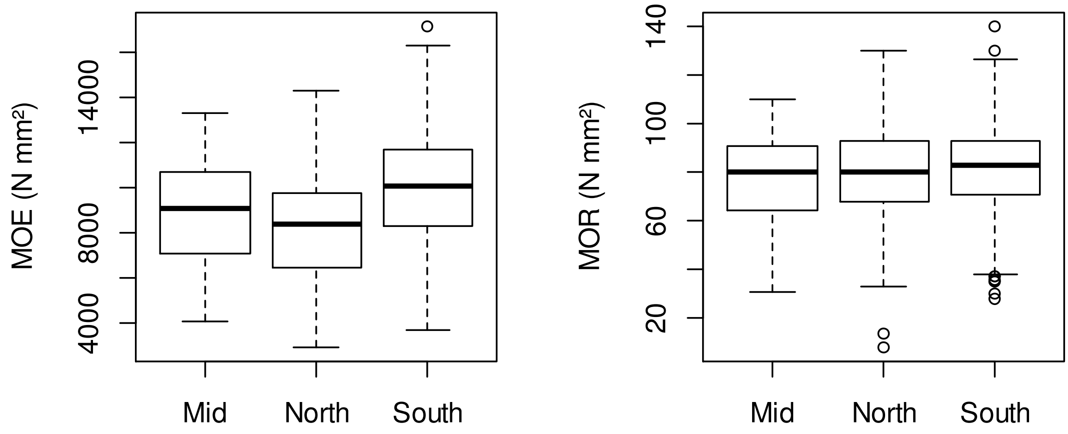

Figure 5-16. Showing the means for MOE and MOR per region (north, mid and south).

As seen above, there was a difference in means (across the regions), as north had a mean of 8263 N/mm^2 (SD = 2209), mid 8882 N/mm^2 (SD = 2226) and south had a mean of 9924 N/mm^2 (SD = 2494).

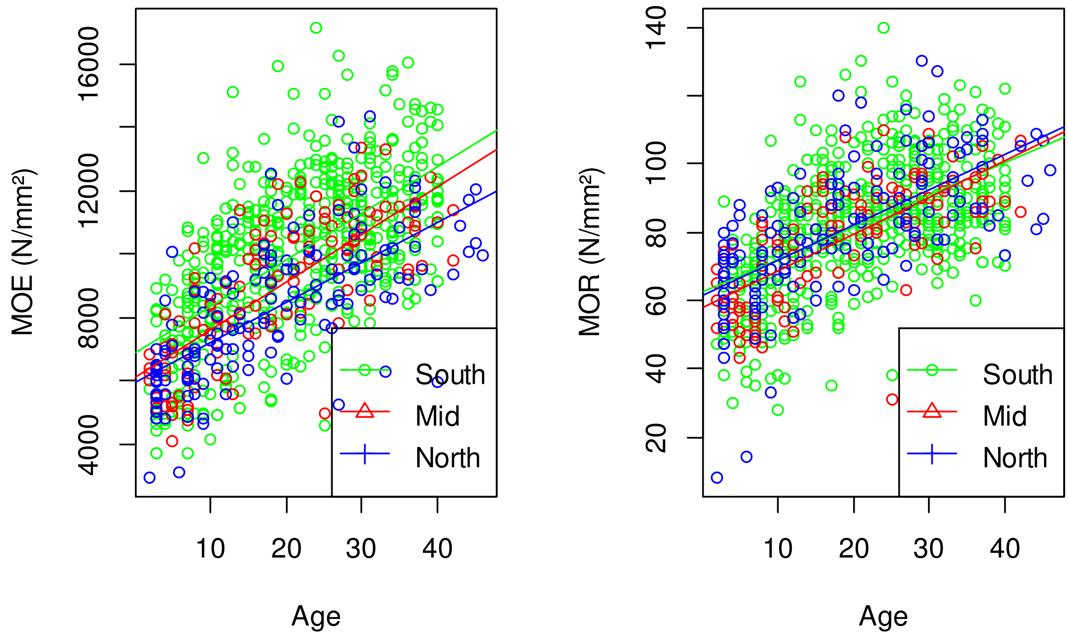

Figure 5-17. Showing the linear relationships between MOE and age, and MOR and age. The three regions are examined to ascertain their slope, intercept and R^2. The south data has a higher overall mean for MOE (and intercept).

Examining a linear model (Figure 5-17) for each region gives a higher R^2 for the mid region over the north and south having the lowest of thee three. This lack of variability explained by age in Bawcombe's (2013) is likely a result of the number of sample compared to the ones presented for this study (north n=149, mid n=123 and south n=516). The R^2 and intercept are given for MOE and MOR per region below (Table 5-11).

	MOE			MOR		
	Intercept	Slope	R^2	Intercept	Slope	R^2
North	5938	126	0.48	61	1.03	0.40
Mid	6084	151	0.57	57	1.08	0.50
South	6872	147	0.38	62	0.95	0.30

Table 5-11. Table showing the slope, intercept and R^2 for each of the three regions (for MOE and MOR).

5.5 Discussion

The aim of this chapter was to investigate and model the strength, stiffness and density of clearwood (small defect-free samples) UK-grown Douglas-fir, specifically examining both tree-and-sawnwood-level variables to ascertain their influence on MOE and MOE then develop age-related models which predict these mechanical properties. Clearwood properties without the confounding effect of knots being present offered a chance for age-related trends to be modelled using age as the primary indicator variable, given its correlation with MOE and MOR. It is also easily definable, as each cambial ring represents one year of growth (excluding lammas growth).

Cambial age was thus selected to be the primary explanatory (predictor) variable. The correlation was positive (r = 0.70 and r = 0.65 for MOE and MOR respectively) and age was predominantly positive in predicting MOE and MOR (R^2 of 0.51 and 0.44 respectively) and could be described as adequate, alone in predicting these mechanical properties. While density was correlated with stiffness and strength (r = 0.80 and r = 0.81 for MOE and MOR respectively), the aim of the chapter was to model radial trends (pith-to-bark). However, it is worth noting that if one wishes to explain as much variability as possible (and does not solely care about radial trends), including density increased the predictive power of the models (better fit to the data). For example, age predicted MOE positively (R^2 of 0.51) but age and density together in a logarithmic model predicated MOE by more than 20% (R^2 of 0.72) than age on its own. Brazier (1967) highlights density is the parameter that is most closely associated with timber performance (mechanical). Bowyer *et al.* (2007) also suggest density is the most important wood quality factor given its relationship with MOR.

Leban and Haines (1999) developed both linear and nonlinear models to predict the MOE of small clearwood specimens of hybrid larch, using the same three predictor variables (mean cambial age, density and rings per centimetre) but by dynamic (flexural) testing. Their linear regression model (multivariate) for MOE using all three parameters had an adjusted R^2 of 0.66, which while an improvement over models for each of their parameters taken individually, is lower than the model presented here using density, age and ringers per sample. For the non-linear model, the authors assumed a zero MOE at an age of zero and included maximum attainable MOE, the ring age for maximum MOE growth rate vs. age, and the shape parameter of the model as their parameters. The model fit the data well, but as McLean (2008) points out that while it is agreed nothing living can have an age of zero, therefore unlikely that wood at the centre of the tree would have zero MOE.

Other studies included explanatory variables not investigated here, such as MFA (*e.g*. Alteyrac *et al*., 2006), but typically age (cambial) and density are often used as predictor variables (*e.g.* Cown *et al*., 1999; Leban and Haines, 1999; Verkasalo and Leban, 2002, Lachenbruch *et al*., 2010) in linear regression models predicting MOE and MOR (in clearwood properties). Lachenbruch *et al.* (2010) investigated density, MFA and acoustic velocity in the mature (outer) wood of Douglas-fir. They showed MFA to have more influence than density on the MOE and MOR of Douglas-fir, but this was only analysed in mature samples. Given the known differences in mechanical properties between juvenile and mature wood it may be that the results do not describe the whole picture. They also examined differences between earlywood and latewood and found a large difference in density between the two (as expected) signifying the likelihood that latewood proportion in Doulas-fir bears a significant influence on the mechanical properties. This trend where juvenile wood has less desirable properties than mature is the reason for not using density to describe the radial trend; rather, describe MOE, MOR and density with age.

To be parsimonious, models should use readily available and easily extractable data with as few parameters as possible (within reason). For example in Scots pine, Auty and Achim (2008) explained 58% and 54% of the variation in MOE and MOR respectively using only age (cambial) as the sole predictor variable (without consideration for inter-tree variation). The models presented here are simple in their design (linear, logarithmic and exponential with two predictor variables). Adding rings per sample did not particularly increase the predictive power and warranting its inclusion is difficult given the fact that for MOE it explained only an extra 1%, 2% and 2% for the linear, logarithmic and exponential models respectively, which are similar figures for both MOR and density also.

There were 272 clearwood samples, with 121 (44%) “inner” samples, 100 (37%) “mid-range” and 51 (19%) “outer” compared to 188 battens, with 32 (17%) “inner”, 70 (37%) “mid-range” and 86 (46%) “outer”. While the structural battens were categorised into their classes based on estimation in the field, it is indicative that by human error more samples could be placed into “mid-range” or “outer” wood, given the different percentages observed between the amount of “inner” estimated in the field and laboratory (17% estimated for structural, but 44% observed with clearwood to an age of 15). This could either suggest a lower number of rings were classed as juvenile (obviously less than a cambial age of 15) in field estimation, or it could also be the size as shown in Figure 5-18 below within each structural batten, it would be expected a minimum of two or three clearwood samples would be taken, thus a higher amount of “inner” coming from the clearwood dataset. Structural battens used bark to pith to bark (full central cant) while clearwood only used pith to bark. Figure 5-18 shows that if estimation in-field were to correspond with clearwood samples, there would be far less “inner” clearwood samples, thus rendering the juvenile age of <15 as too high. The higher percentage of “outer” battens may also arise from the fact many of these may have had some small amounts of deviation, bark or wane (which would have signified failure in clearwood thus rejected) but were still visually acceptable for further testing.

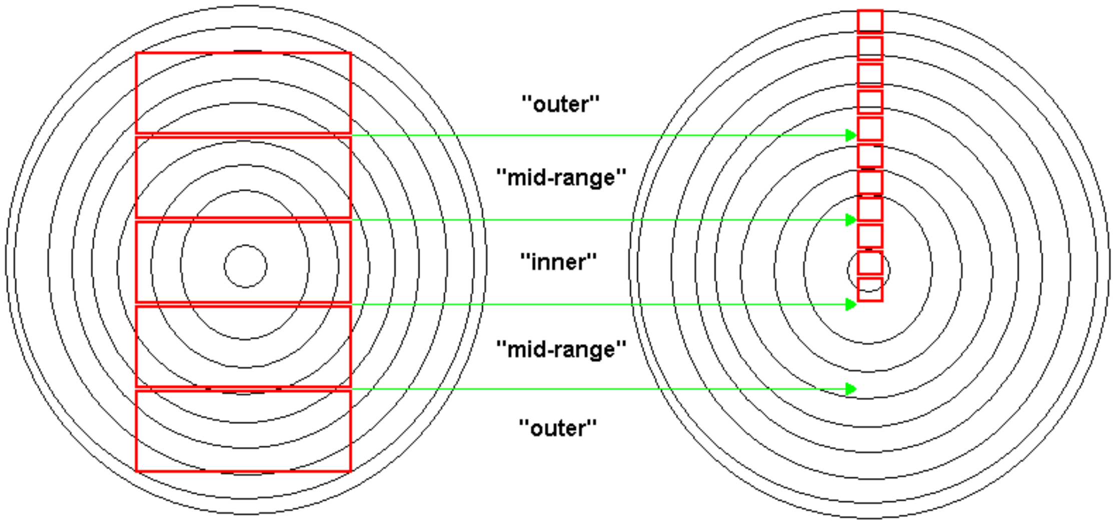

Figure 5-18. Showing a representation (only) of the range of sample differences between structural and small, clearwood samples from the same piece of timber (transverse stem).

In **Error! Reference source not found.**, both MOE and MOR show an increase (N/mm^2) from “inner” wood to “outer” wood (*i.e.* moving from pith to bark). MOE increases (from 6823 N/mm2) by 55% (to 10565 N/mm2) when going from “inner” to “outer”. Likewise MOR increases (from 65 N/mm2) by 46% (to 95 N/mm2) when going from “inner” to “outer”.

There is little to no peer-reviewed information on Douglas-fir mechanical properties correlated with cambial age (radial changes). As evidenced in this study, there is an obvious change in MOE and MOR over the radius, observed as a function of increasing ring numbers (cambial age). A recent, semi-parallel to this study by Bawcombe (2013) has examined clearwood properties of Douglas-fir growing in southwest England and found a similar trend; MOE and MOR do increase with increasing age as seen in Figure 5-17. The southern data (Bawcombe, 2013) had the highest mean MOE and MOR but the lowest R^2 with age, given the higher sample numbers (greater variance).

Barrett and Kellogg (1991) noted that the amount of juvenile wood in Douglas-fir affected the modulus of elasticity (decreased stiffness with increased juvenile wood) for structural battens. The study by Lavers (1983) is limited due to the requisite basic background information of clearwood being unavailable (*e.g.* age of sample) but a useful indicator that UK-grown Douglas-fir may be lower in strength and stiffness compared to Canadian or American Douglas-fir.

On felled trees (sawn timber as per chapter 4 or clearwood properties in this chapter) non-destructive evaluation methods (*e.g.* acoustical testing) are quick, cheap and efficient when compared to destructive sampling and are now becoming widespread (*e.g.* Auty and Achim, 2008; Haines *et al*., 1996; Lachenbruch *et al*., 2010) due to dynamic wood stiffness being highly correlated with static bending stiffness and moderately correlated with strength. The strong correlation between dynamic testing of MOE and destructive testing indicates that "time and effort" can be reduced by only using the dynamic method(s) if the goal is to determine a mean MOE (or MOR) for a sample population.

5.6 Conclusions

Specific objectives were: (1) to determine the strength, stiffness and density of Douglas-fir clearwood specimens, (2) examine the influence sawnwood-level variables have on these means across a range of sites, (3) investigate the influence of tree-level variables on clearwood properties and (4) develop age-related models which predict individual values for strength, stiffness and density.

This chapter demonstrates the difference in Douglas-fir clearwood properties taken for this study, to the UK-grown but unknown background of Lavers (1983) Douglas-fir samples. USDA (2010) presents American Douglas-fir MOR as 82 - 90 N/mm^2 and MOE as 10,300 - 13,400 N/mm^2 at 12% MC, and Canadian Douglas-fir as 88 N/mm^2 for MOR and 13,600 N/mm^2 for MOE (also at 12% MC) for clearwood specimens. For clearwood samples presented here, the mean MOE was 8,500 N/mm^2, MOR was 79 N/mm^2 and density was 490 kg/m^3 (all rounded to two significant figures). Radial differences in Douglas-fir indicate that wood from the juvenile part of the tree (adjacent to pith) is likely to be the weakest, becoming stronger and stiffer the higher the cambial age. Using age alone as predictor variable will generally explain around half of the variation. If age-related models are not the sole interest, including density as primary indicator variable will increase the models predictive abilities. As the Pearson's table also suggests, dynamic methods for testing MOE are strongly correlated with static MOE thus destructive testing (breaking) samples is not always a necessary step to determining MOE.

6 Branching properties of Scottish-grown Douglas-fir

6.1 Introduction

In Douglas-fir, knots cause the greatest economic degradation (or loss) when grading structural timber (McKimmy, 1986) and are the chief cause of reduced strength as highlighted between chapters 4 and 5 (structural and clearwood chapters). Douglas-fir's persistent and vigorous branching (Cahill *et al.,* 1986; Oliver *et al.,* 1986) affects timber and veneer grade recovery (Fahey *et al*., 1991), and of the four main characteristics it is typically branch size that is of greatest importance (*e.g.* Maguire 1994; Weiskittel *et al*., 2007b).

Various tree-level attributes such as height to crown base, total tree height or diameter, alongside branch-level attributes, *e.g.* branch height or growth unit position will often relate to and influence branch characteristics (*e.g*. Maguire *et al.,* 1999; Ishii and McDowell, 2002; Hein *et al.,* 2008; Auty, 2011). Models of branching habits have not been undertaken for UK-grown Douglas-fir and existing studies and models (both destructive and concurrent) have been developed mainly in the Pacific N.W. (*e.g.* Hann 1999; Maguire and Hann 1987; Maguire *et al.,* 1991; Maguire *et al.,* 1994; Maguire *et al.,* 1999; Weiskittel *et al.,* 2007 A/B) and Central Europe (Hein *et al.,* 2008) where climatic conditions and silvicultural techniques are decidedly different, or for other species such as Norway spruce (*Picea abies* (L.) Karst *e.g.* Colin and Houlier, 1991), Scots pine (*Pinus sylvestris* L. *e.g.* Auty, 2011; Makinen and Colin, 1998) and Sitka spruce (Achim *et al.,* 2006). In order to maintain comparability with the UK forest resource, it is proposed to focus initially on branching models built to describe trees grown in the UK.

6.2 Aims and objectives

This chapter aims to describe the branching characteristics of Douglas-fir trees grown in Great Britain through empirical models. Branches are essential for tree growth and survival and can be highly variable in size and shape. This sample set allows investigation of models that describe branching of Douglas-fir trees grown in Britain for comparison with other species. The factors that most influence timber properties are those that will be focused upon here, with the emphasis on branch diameter:

1 – Branch diameters at point of insertion

2 – Angle of insertion

3 – Probability of mortality

4 – Frequency

6.3 Materials and methods

6.3.1 Materials

The three sites in Scotland were used for this part of the study. The three even-aged stands had different initial spacing and different final densities are detailed in chapter 3. All trees selected for branching analysis were felled and sampled between June and October 2010. Resources did not permit the time-consuming branching assessments also to be made at the sites in Wales. These three sites are typical of Douglas-fir sites in Britain. Differences in sites are not tested as they are not replicated, but the variability in branch characteristics between sites, plots and trees were examined.

6.3.2 Methods

The full field methodology of plot layout and sample tree selection and preparation is shown in chapter 3. A list of abbreviations used in this chapter can be found below in Table 6-1. From each site, three plots were investigated and within each plot, a Dominant, Co-Dominant and Sub-dominant tree were sampled, equalling 24 trees over the three sites (original number of 27 was reduced to 24 due to unforeseen circumstances in which one plot had to be abandoned).

Only branches >5 mm in diameter were measured in this study, thus discounting an abundance of small (1 - 4 mm) branches generally located near the top of the canopy as these are assumed to have a negligible effect on timber. The full protocols are outlined in chapter 3.

After felling the sample trees and snedding branches (to approx. 25 cm from stem), the stem apex was noted and the height to crown base and height to lowest live branch were recorded. For each whorl, the distance to the bottom of whorl was recorded and every single branch position within the whorl was recorded (also determining whether it was a whorl branch or interwhorl branch). Within each whorl, the status, size (diameter in 2 directions) and angle of insertion were recorded, similar to Achim *et al*. (2006), as seen in Figure 3-3.

From the original 7561 branches, only a complete dataset were used (*e.g.* azimuth, angle, vertical and horizontal diameters, status, distance from stem apex *etc.*) thus from three sites (24 trees) the total number of branches was 7202, from 1129 growth units (a mean of 47 whorls per tree). A summary of tree-level, GU-level and branch-level attributes can be found in Table 6-1.

Variable	Definition	Min	Max	Mean	SD*
CL2	Crown length (LT-HCB) (m)	8.02	22.2	13.2	2.94
CR2	Crown ratio (CL2/LT)	0.28	0.66	0.42	0.09
DBH	Diameter of stem measured 1.3 m from ground level (cm)	25.3	50.4	37.7	7.3
HD	Height to diameter ratio (LT/DBH)	0.66	1.19	0.85	0.13
HCB	Height to base of crown (from ground) (m)	11.2	28	18.1	3.94
LLB	Lowest live branch (from ground) (m)	6.2	27.3	15.5	4.75
LT	Length of tree (measured post-felling) (cm)	24.6	38.8	31.3	3.76
GU	Growth unit defined as whorl and interwhorl branches in an annual height increment section	n/a	n/a	n/a	n/a
GUL	GU length (cm)	11	163	69	22.2
D.top	Distance from top (stem apex) to bottom of GU (m)	0.53	37	13.7	8.85
Z	Relative distance from stem apex to base of annual growth unit (D.top/LT)	0.02	1	0.44	0.27
BD	Branch diameter (mm)	5	78	19.4	10.4
BHREL	Relative BHT (BHT/LT)	0.03	0.99	0.58	0.27
BHT	Height of each branch (m)	0.63	38.3	18.2	8.79
BRA	Branch insertion angle (to nearest 5°)	10	140	73.5	13.5
Max.bd	Maximum branch diameter per GU (mm)	5	78	29.4	10.9
NBR	Number of branches per GU	1	18	8.1	3.05
Rank	Branch rank in a whorl (1=Max.bd, 2=second-thickest branch, *etc.*)	1	17	4.17	2.57
Status	Branch status (living=1, dead=0)	n/a	n/a	n/a	n/a

Table 6-1. Showing chosen variables (tree-level, GU-level then branch-level) for this chapter. A full list including differences between sites can be found in the appendix 10.4. * = standard deviation.

6.3.3 Statistical analysis

The distribution of branch sizes and angle of insertion are examined and compared to various studies (*e.g.* Achim *et al.*, 2006; Hein *et al.*, 2008) then variation within a tree is described via modelling, predominantly using general linear models (GLM's) which are linear regressions that allows response variables to have error distributions (*i.e.* not normally distributed).

Branch characteristics are highly variable and consequently branching models are not always entirely successful in terms of predicting a lot of the variability and will have a low R^2. The main aim is to visualise the data to allow conclusions to be drawn from them. The primarily non-orthogonal dataset contains discrete (*e.g.* counts of branches per whorl) and continuous data (*e.g.* branch diameter per whorl).

6.4 Results

The branch size, angle, status and frequency were examined in order, specifically looking at differences between dominance classes, variability between sites, plots and trees, and correlations between tree-level variables (*e.g*. DBH). Then these four parameters will be plotted against their respective positions (*e.g*. height in stem) and following Achim *et al*. (2006), they will be modelled to allow prediction of their behaviour.

	CL2	CR2	DBH	HD	HCB	LLB	LT	GUL	Dtop	Z	BD	BHREL	BHT	BRA	max.bd	NBR	Rank	Status
CL2		0.87	0.71	-0.63	-0.43	-0.51	0.33	0.30	0.07	0.00	0.23	-0.01	0.07	-0.05	0.35	0.07	0.02	0.16
CR2	0.87		0.39	-0.61	-0.81	-0.73	-0.16	0.20	-0.05	-0.02	0.16	0.02	-0.03	-0.08	0.26	0.06	0.02	0.20
DBH	0.71	0.39		-0.78	0.10	-0.26	0.66	0.28	0.12	0.00	0.26	-0.01	0.16	-0.01	0.42	0.06	0.03	0.10
HD	-0.63	-0.61	-0.78		0.40	0.63	-0.07	-0.17	0.02	0.03	-0.24	-0.03	-0.05	0.06	-0.40	-0.05	-0.03	-0.17
HCB	-0.43	-0.81	0.10	0.40		0.80	0.71	0.00	0.16	0.03	-0.04	-0.03	0.15	0.07	-0.09	-0.03	0.00	-0.17
LLB	-0.51	-0.73	-0.26	0.63	0.80		0.44	-0.12	0.09	0.01	-0.13	-0.01	0.10	0.06	-0.27	-0.09	-0.04	-0.17
LT	0.33	-0.16	0.66	-0.07	0.71	0.44		0.23	0.22	0.04	0.13	-0.04	0.22	0.04	0.18	0.02	0.01	-0.05
GUL	0.30	0.20	0.28	-0.17	0.00	-0.12	0.23		0.40	0.37	0.17	-0.35	-0.29	0.11	0.33	0.32	0.18	-0.27
Dtop	0.07	-0.05	0.12	0.02	0.16	0.09	0.22	0.40		0.98	0.22	-0.98	-0.91	0.20	0.22	-0.11	-0.04	-0.79
Z	0.00	-0.02	0.00	0.03	0.03	0.01	0.04	0.37	0.98		0.20	-1.00	-0.96	0.20	0.19	-0.13	-0.05	-0.80
BD	0.23	0.16	0.26	-0.24	-0.04	-0.13	0.13	0.17	0.22	0.20		-0.19	-0.15	0.02	0.57	-0.14	-0.58	-0.01
BHREL	-0.01	0.02	-0.01	-0.03	-0.03	-0.01	-0.04	-0.35	-0.98	-1.00	-0.19		0.96	-0.21	-0.19	0.13	0.04	0.80
BHT	0.07	-0.03	0.16	-0.05	0.15	0.10	0.22	-0.29	-0.91	-0.96	-0.15	0.96		-0.19	-0.14	0.13	0.04	0.77
BRA	-0.05	-0.08	-0.01	0.06	0.07	0.06	0.04	0.11	0.20	0.20	0.02	-0.21	-0.19		0.30	0.03	0.21	-0.16
max.bd	0.35	0.26	0.42	-0.40	-0.09	-0.27	0.18	0.33	0.22	0.19	0.57	-0.19	-0.14	0.30		0.08	0.11	-0.03
NBR	0.07	0.06	0.06	-0.05	-0.03	-0.09	0.02	0.32	-0.11	-0.13	-0.14	0.13	0.13	0.03	0.08		0.47	0.16
Rank	0.02	0.02	0.03	-0.03	0.00	-0.04	0.01	0.18	-0.04	-0.05	-0.58	0.04	0.04	0.21	0.11	0.47		-0.01
Status	0.16	0.20	0.10	-0.17	-0.17	-0.17	-0.05	-0.27	-0.79	-0.80	-0.01	0.80	0.77	-0.16	-0.03	0.16	-0.01	

Table 6-2. Pearsons correlation table for tree, growth unit and branch level variables.

6.4.1 Branch diameter

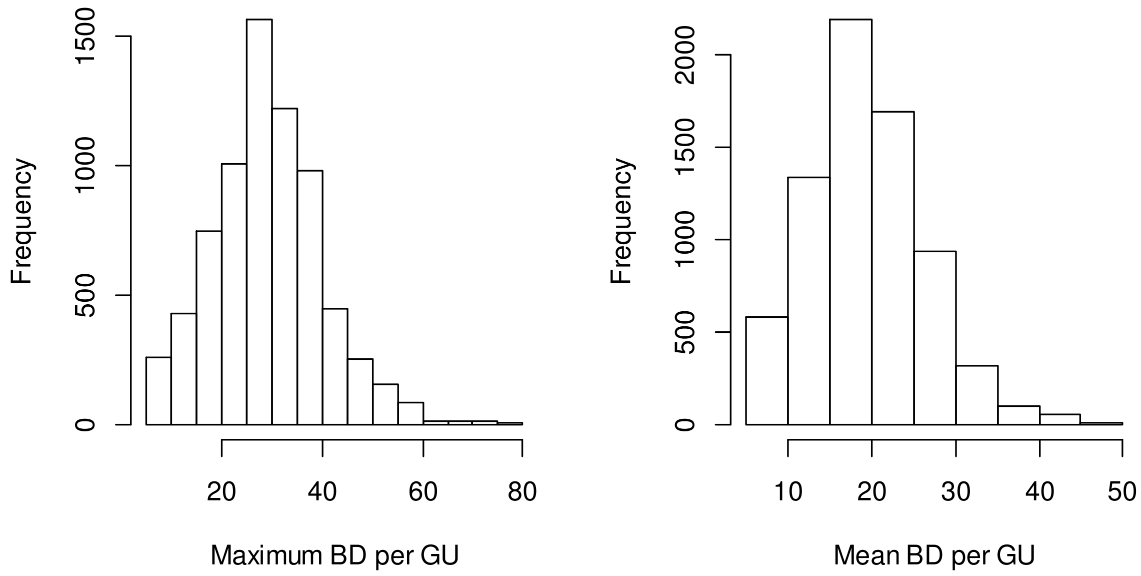

Figure 6-1. Histograms for maximum (left) and mean (right) branches per GU.

For branch diameter, variance components shows the variation in number of branches was accounted for between sites was negligible (0.8%), nil between plots, while 9.6% explained by difference between trees and 89.7% within the tree**.** The range was 5 – 78 mm, with the average being 19.4 mm (SD = 10.4 and CV = 53.6) for the entire population. Each branch was measured to give total mean per tree, total mean per GU, maximum branch size per tree and maximum branch size per GU. The maximum BD per GU (predominantly whorl) was 29.4 mm and similar to the maximum BD per whorl in Hein *et al.* (2008) for Pacific NW trees, and slightly smaller than the German (which were widely-spaced). The mean and maximum branch diameters per growth unit were related (R^2 of 0.75). To ascertain mean and maximum branch diameters (*e.g.* per GU) two measurements were taken for each branch (horizontal and vertical). A paired t-test will reject the null hypothesis (equality of the averages) but as the mean of the differences is -0.08 mm, the measurements were taken to an accuracy of 1 mm (for all branches over 5 mm) and therefore practicality dictates that only one diameter is necessary as the branch can be viewed as circular for statistical purposes. This was corroborated by conducting regression analysis on vertical and horizontal branch diameters which showed a highly significant relationship (R^2 0.99, RSE = 1.239 on 7200 degrees of freedom) in Figure 6-2 below.

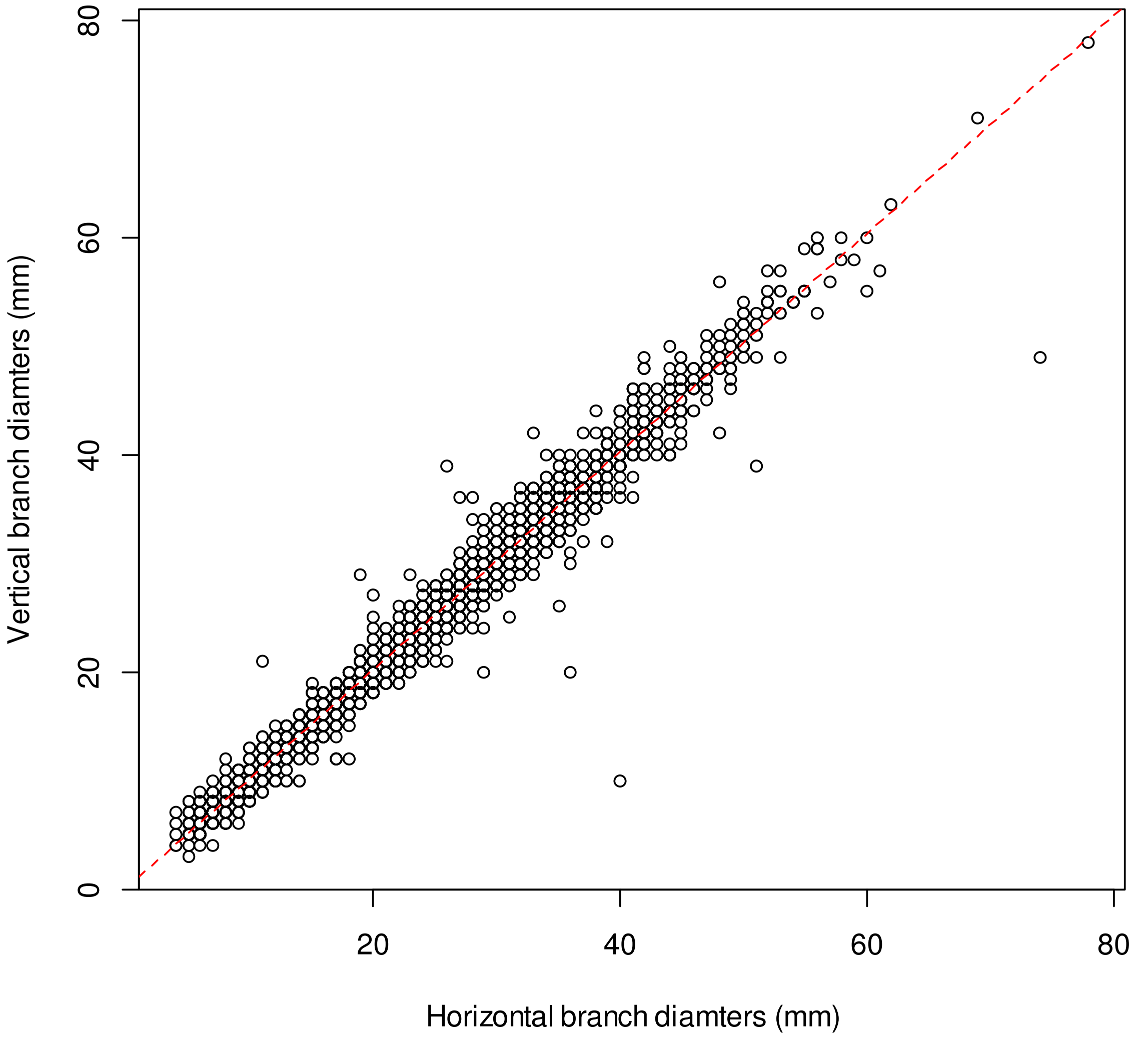

Figure 6-2. Showing regression (R^2 of 0.99) of vertical and horizontal branches and highlighting the non-necessity of measuring both for future studies in UK-grown Douglas-fir. The n=7202, yet much are overlapped given that they were measured to the nearest mm.

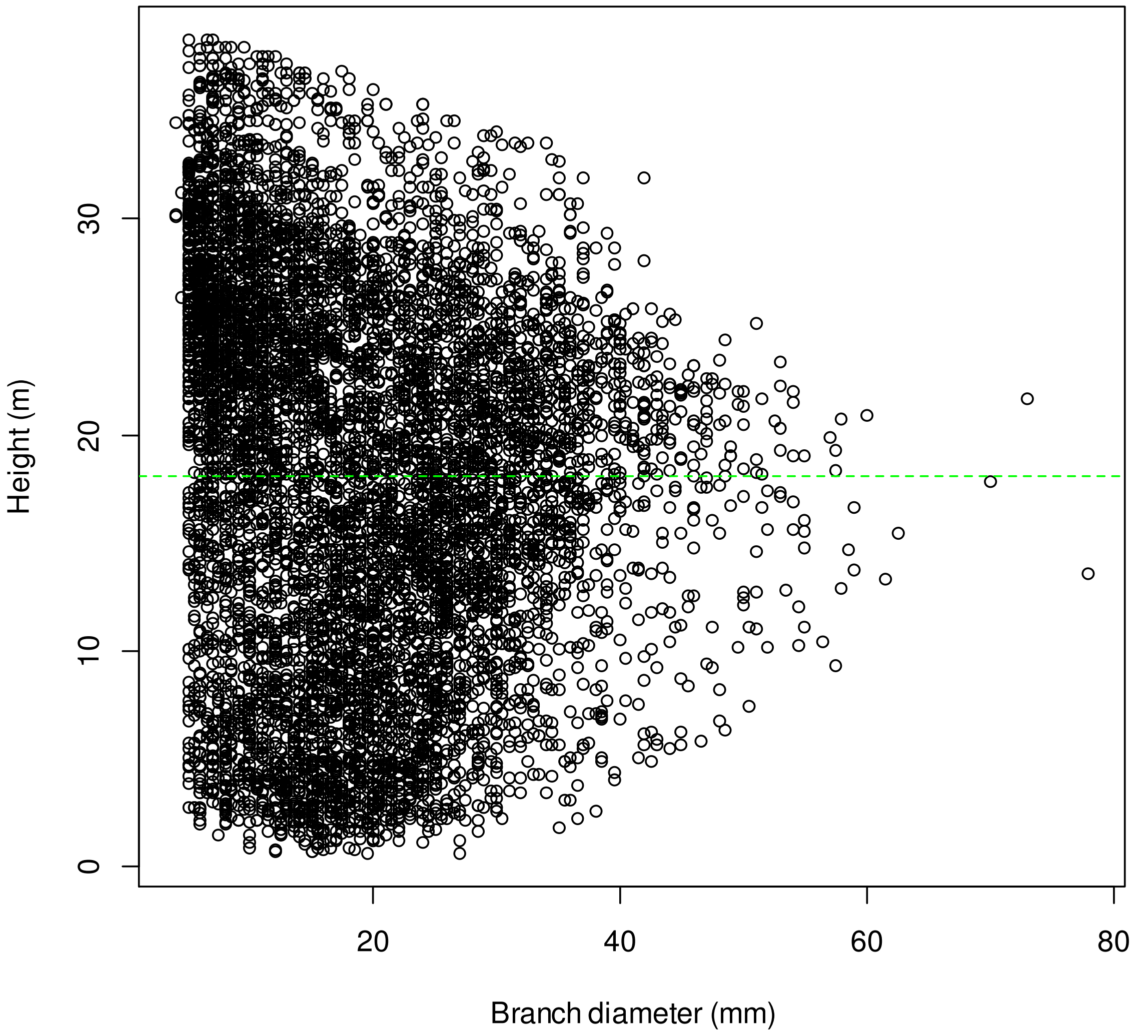

Figure 6-3. Showing the large number of branches and their diameter at a given height. The green line represents mean crown base (18.1 m). At live crown base the diameters appear to peak and then reduce in size again.

Figure 6-3 shows every branch (n=7202) and its point of insertion in tree (BHT). The green line is mean crown base, showing that as distance from stem apex increases, so too does the size of the largest branch (per GU), as indicated by plotting the maximum branch diameter with distance along stem from apex. However at a certain position the maximum branch size peaks at which point the trend then shifts to mainly reducing in size. This generally happens near live crown base.

The largest branch per tree (not to be confused with maximum branch per GU) occurred on average at 93% DINC (*i.e.* 7% above crown base). PI occurred at

82%, LT at 84% DINC while LA maximum branch diameter per tree occurred at 119% DINC (alternatively, this is 19% beyond/below crown base). For example with a crown height/length of 10 m, a DINC of 120% would represent the largest branch per tree occurring at 2 m below live crown base (along stem).

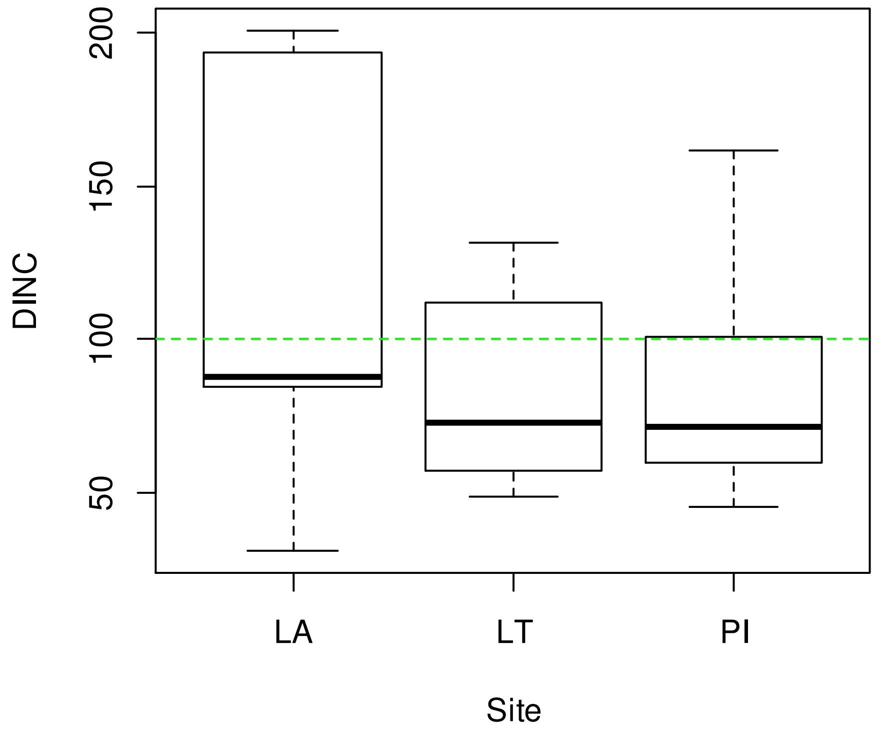

Figure 6-4. Showing depth into crown (DINC %) from stem apex for the largest branch per tree. The green line again represents a theoretical crown base (live). 100% represents bottom of the crown for a given tree, and not 0%, given how 50% of the depth should represent halfway between stem apex and crown base.

For the entire population, dominance played an integral part. The largest individual branches (per tree, taken as mean for all trees) were 58.6 mm for Dominant, 45.8 mm for Co-Dominant and 44.1 mm for Sub-Dominant trees. The difference between Dominant and Co-Dominant is 24.7% (or a 22 % decrease). This is similar to the mean maximum branch diameter per GU, which for Dominant is 34.6 mm, 28.3 mm for Co-Dominant and 25 mm for Sub-Dominant (Figure 3.3.4), with the difference between Dominant and Co-Dominant being 19.7% (or an 18% decrease). The difference between Dominant and Sub-Dominant is 28.2 % and 32% for largest individual branch per tree (for all tree means) and average maximum branch diameter per GU respectively.

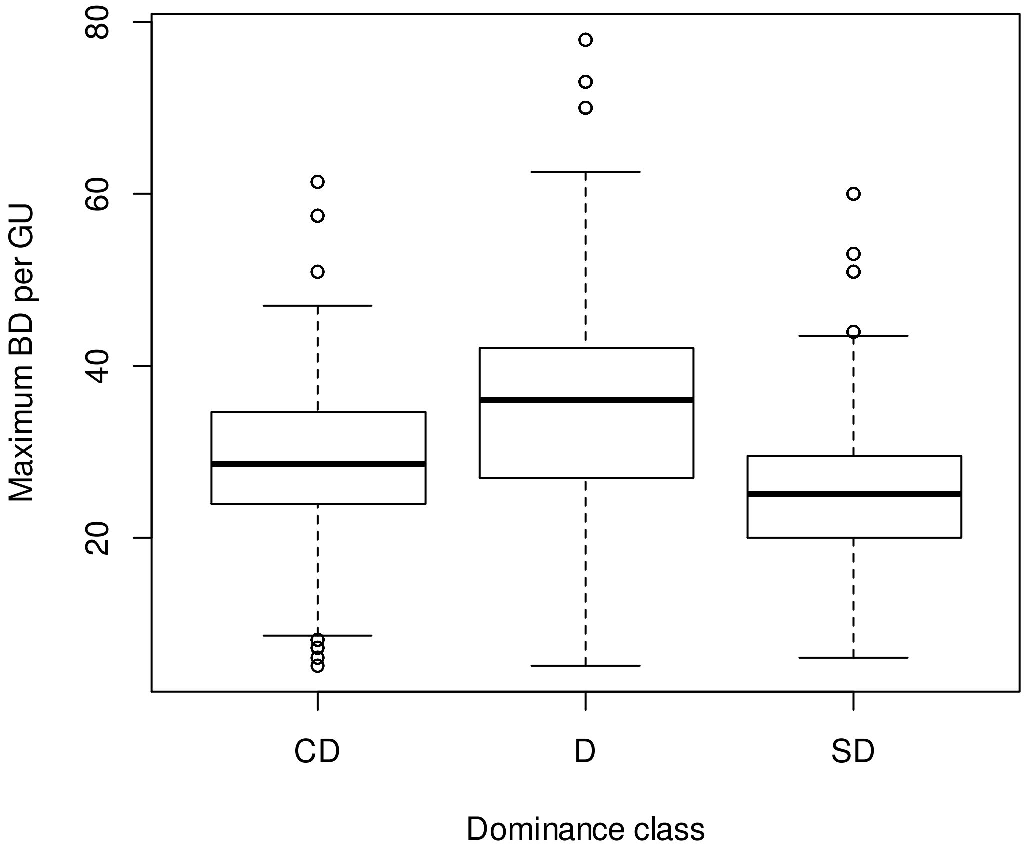

Figure 6-5. Maximum branch diameter per GU for each dominance class, showing that dominant trees appear to have bigger branches.

Figure 6-5 (above) shows that the larger tree (dominants) had larger branches on average compared to the co-dominants and sub-dominants. The means are given above from both largest branches per tree (mean) and maximum BD per GU (mean). The largest individual branch of entire population was 78 mm for dominants, 62 mm for co-dominants and 60 mm for sub-dominants.

Previous studies (*e.g.* Auty, 2011) determined that the maximum branch diameter was positively related to relative depth in the stem (among other variables such as DBH and crown ratio). The response variable here (BD) was not highly correlated with any variable and the chosen predictor variable for position in stem (BHREL) does not have a linear relationship with BD. Following Achim *et al.* (2006) which describes the average branch size (not maximum) per

GU for Sitka spruce grown in the UK, the following model was fitted using the nls (non-linear least squares) package in R (R core development team, 2014):

$y = \text{a}1 + \text{i}[1-x].\ \text{e}^{-\text{b}.x}$ **[6-1]**

where a, i and b were empirically determined parameters based on the estimates in Achim *et al.* (2006) and x is relative branch height as described in Table 6-3. Running the model for all branches (n=7202) gives an R^2 of 0.47 (RSE = 5.4 on 7190 degrees of freedom). Including the HD ratio decreased the R^2 to 0.46. The model was re-run for both whorls (subset to n=4777) and interwhorls (subset to n=2409) which gave an R^2 for all whorl branches (all dominance classes) of 0.32 and 0.12 for interwhorls. As dominance earlier shown an effect on the maximum branch size, they were modelled also. For each class of dominance run individually, the following coefficients are given.

Coefficients		a	i	b
Whorl	Dominant	4.16887	12.80877	-2.69347
	Co-dominant	2.34121	13.05438	-2.70156
	Sub-dominant	4.88472	13.00339	-2.47672
Interwhorl	Dominant	6.0585	6.2130	-1.6969
	Co-dominant	4.1987	8.0079	-1.8877
	Sub-dominant	4.4447	7.7001	-1.9891

Table 6-3. Coefficients for the branch diameter model (based on Achim *et al.*, 2006). The model was tested for dominant, co-dominant and sub-dominants (a, i and b were empirically determined parameters)

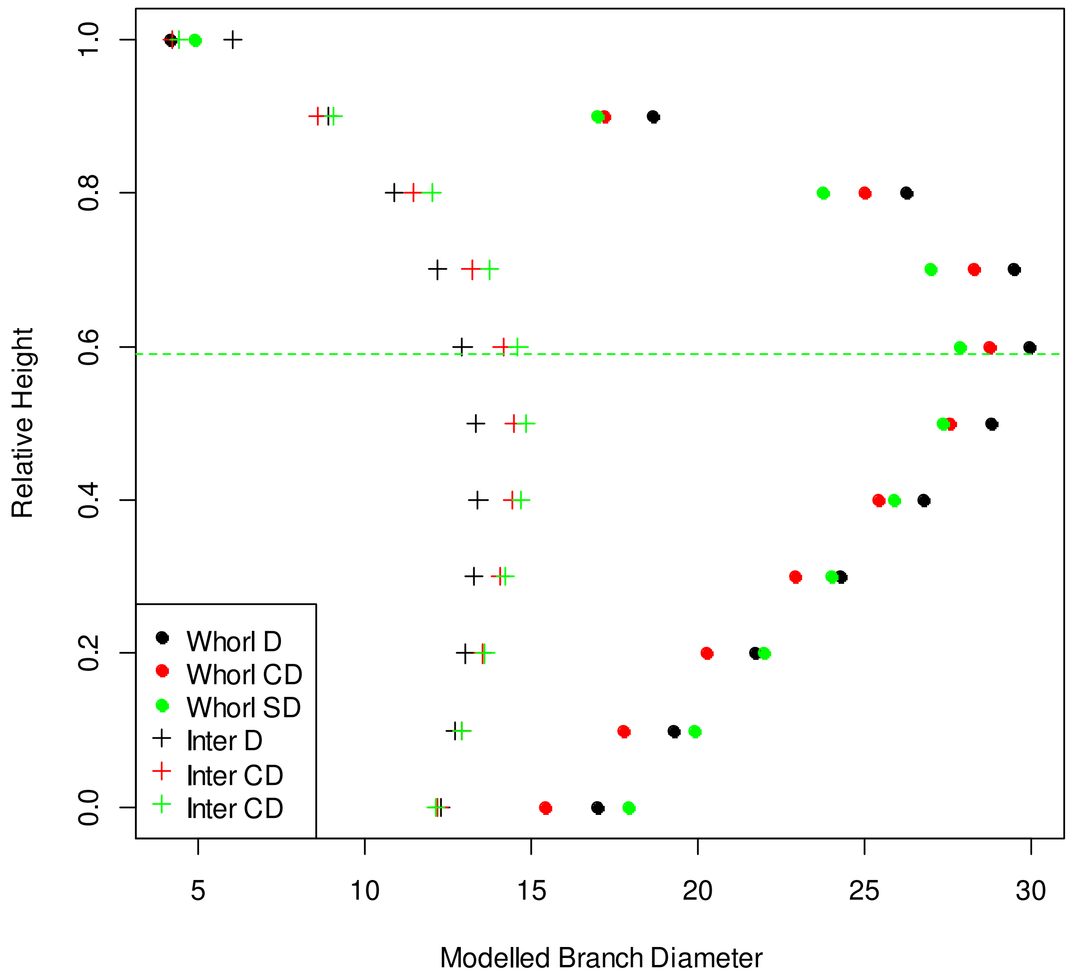

Figure 6-6. Plot of the model for branch diameter, based on Achim et al. (2006). The whorl branches on dominant trees have the largest predicted diameter for a given height in the stem, followed closely by co-dominant and then sub-dominant. For interwhorl branches, the dominant trees actually had the lowest predicted diameters. The whorls appear to peak around crown base (mean) whereas the interwhorls peak slightly under live crown base.

Figure 6-5 shows that the initial branch diameter for whorl and interwhorl is similar but the predicted average whorl branch (regardless of dominance class) increases at a far greater rate than interwhorl, to a much largest diameter. Around 60% from ground (or 0.6 of relative height) whorl diameter peaks, very close to the mean HCB (relative) for all samples (an average of 18.1 m HCB to an average of 30.8 m height) which is 59% from ground. These models demonstrate an overview of the average Douglas-fir tree for the age range given.

6.4.2 Branch angle

The mean angle of insertion (BRA) ranged from 10-140° with a mean of 73.5° (SD = 13.5). Examining variance components shows the insertion angle of Douglas-fir trees changed in variation between sites by 2.9%, negligible variation occurred between plots (0.4%) and 13.9% between trees, with the residuals (within-tree) explaining 82.7% of the variation.

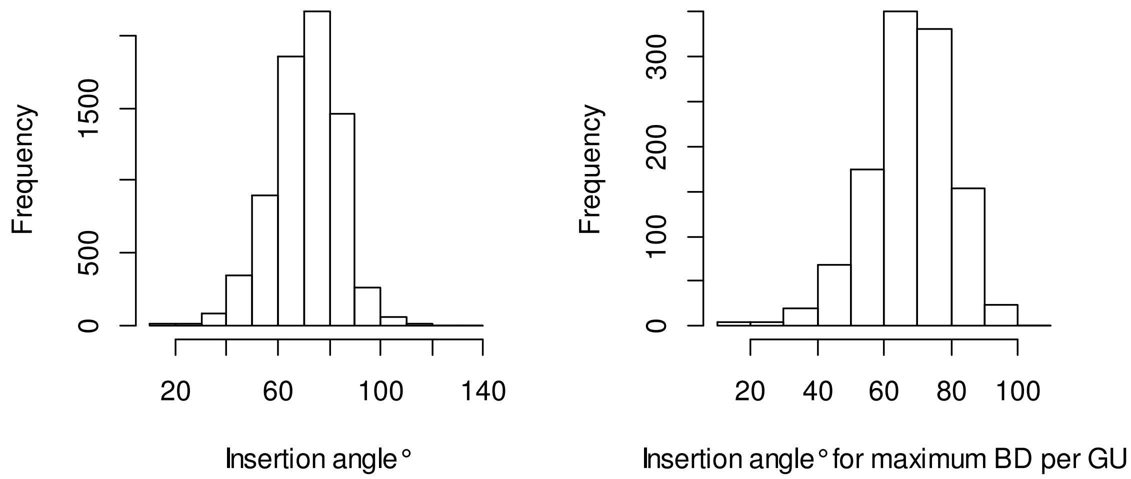

Figure 6-7. Histogram for all branches insertion angle and for the largest branch per GU.

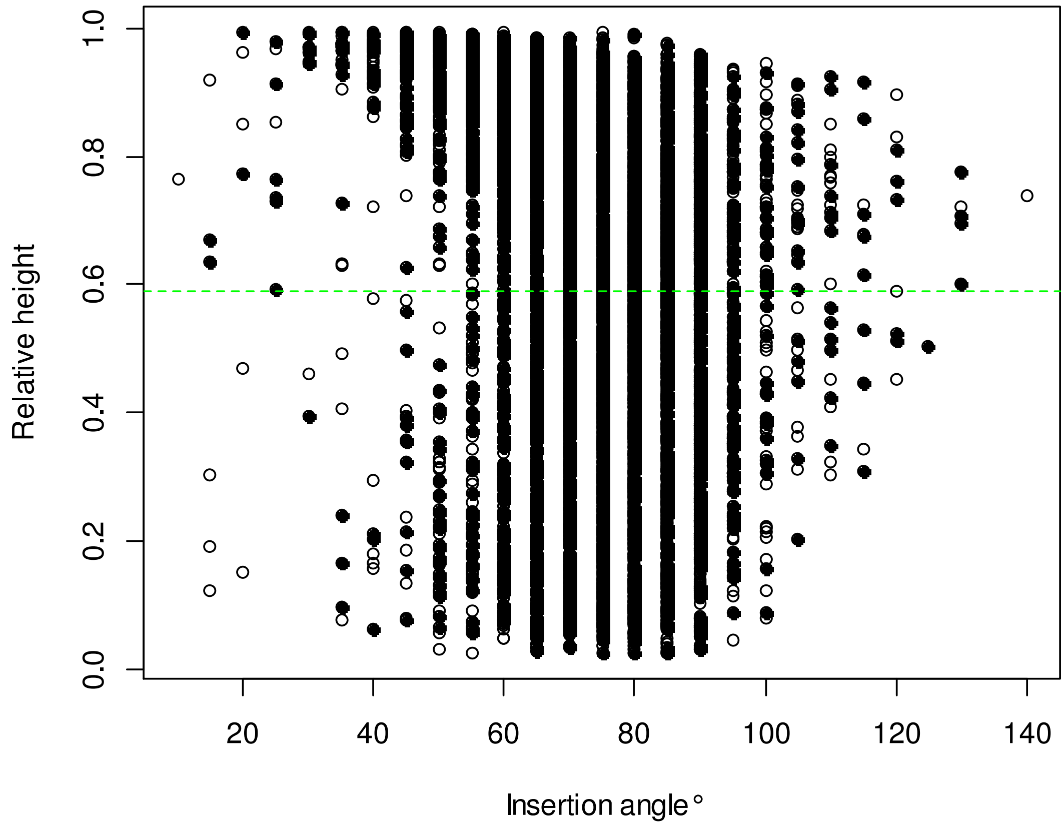

Figure 6-8. Showing the angle of insertion for every branch (n=7202) and its relative position within the tree. The live crown base is represented by the green line.

The insertion angle appears to start sharply at top of the tree (low angle, ~20°) then broadly increases to around live crown base, whereupon it starts to decrease again. This is generally given as the branches "point up" in the higher portions of canopy before approaching a horizontal angle (~90°) and then declining slightly towards a "pointing down" angle.

There were some differences between sites (site LT had a mean of 70.4°, LA had 76.7° and PI had a mean of 74.0°) but the difference in dominance classes were small, with the mean dominant angle being 74.0° (with a range of 10 – 140°) and the mean co-dominant angle being 74.7° (range 15-125°), whereas the sub-dominant was smaller with a mean of 71.7° (range 15-130°). The insertion angle was similar for only the largest branch per GU (n=1129) as seen below in Figure 6-9.

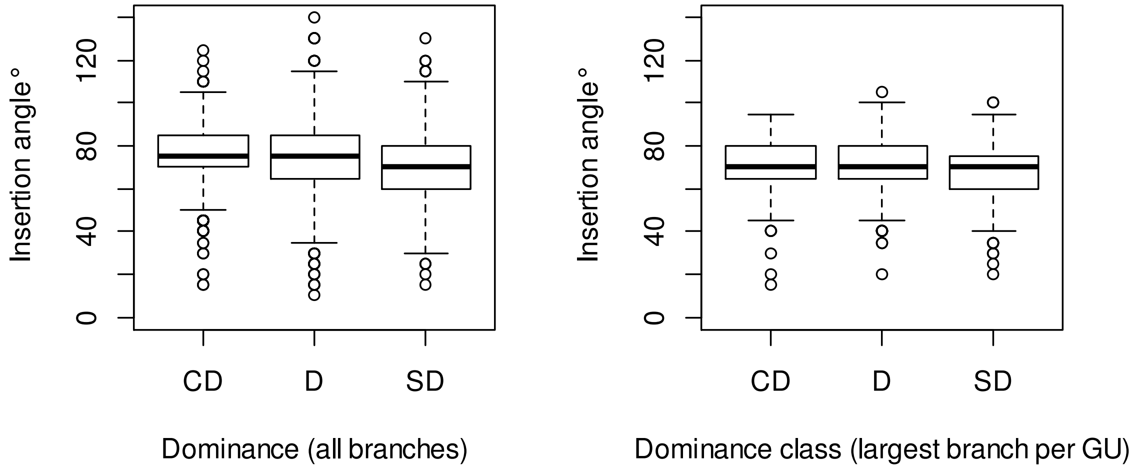

Figure 6-9. Dominance classes and insertion angle for all branches and largest branch per GU.

The correlation coefficient and coefficient of determination values were low for all tree-level variables, as seen in the Pearson's correlation table (Table 6-2) branch angle is not highly correlated with anything. Branch angle's position in the stem is the highest explanatory variable (*e.g.* BHT, BHREL, Z) alongside the largest branch per GU. Accordingly, the branch angle model by Achim *et al.* (2006) which used relative height was tested:

$$BRA=i*\exp(-((a)/(b-hr))) \quad [6\text{-}2]$$

where BRA is branch angle, hr is BHREL and a, b and i are parameters to be estimated from the data. Using all branches the adjusted R^2 was 0.17 (RSE = 5.033 on 7190 degrees of freedom). The data was then subset to whorl or interwhorl, giving an R^2 of 0.12 and 0.10 respectively. The coefficients are given below.

Coefficients	i	a	b
All	78.627905	0.015134	1.015814
Whorl	76.932053	0.014610	1.017110
Interwhorl	82.966088	0.019036	1.017057

Table 6-4. Table of coefficients for the branch angle model. The full dataset coefficients are given, and the data subset to whorl only and interwhorl only also.

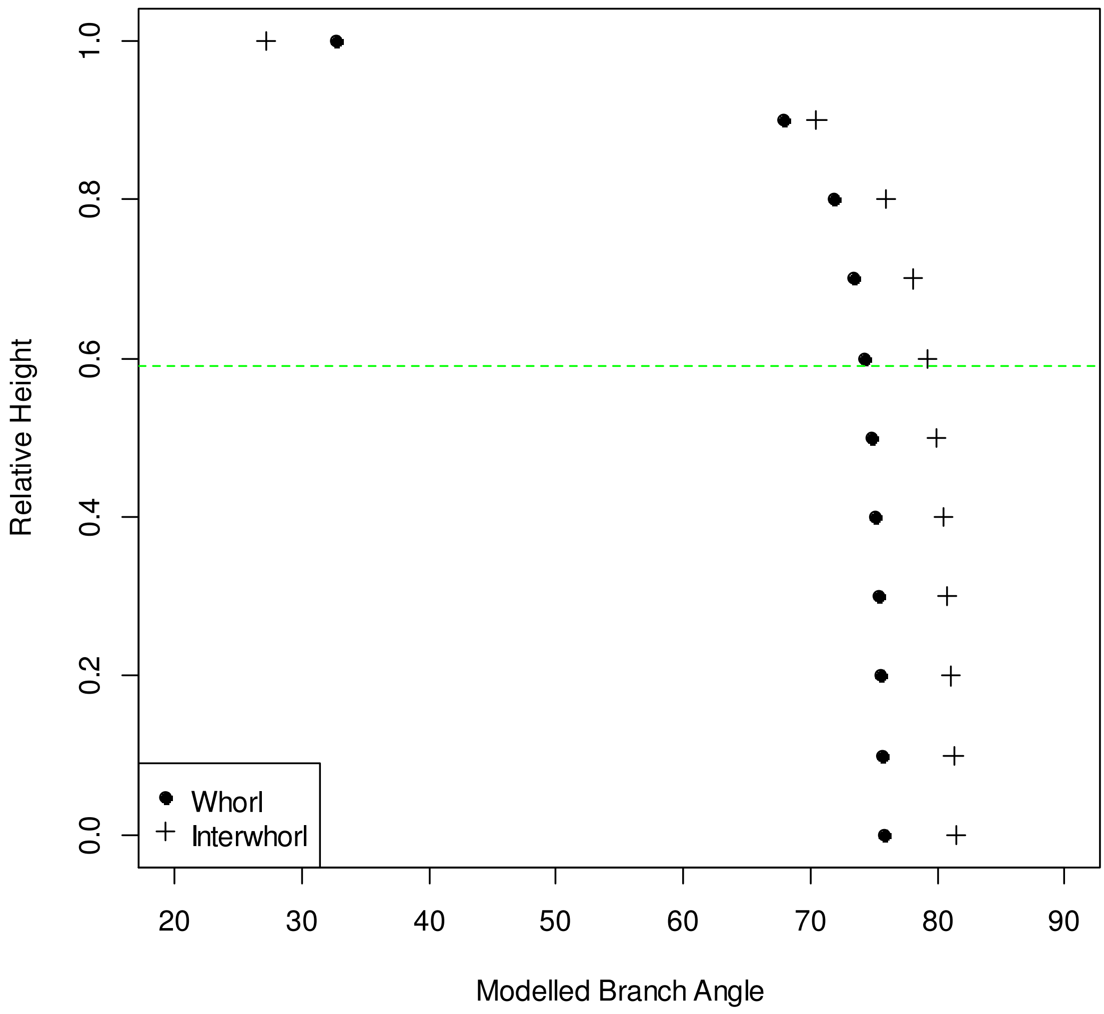

Figure 6-10. Modelled branch angle based on Achim *et al*. (2006) plotted for whorls and interwhorls. The green line represents mean crown base (live)

The predicted branch angle based on Achim *et al*. (2006)'s model and re-parameterised to the data here shows a low insertion angle (steep) towards top of the tree and rapidly increases to a higher angle (more horizontal) before halfway down the crown. From the live crown base (the green line) towards the bottom of the tree, the predicated angle does not particularly increase by any significant amount. The interwhorls were predicted to have a higher angle of insertion than whorls, except for the very top of the relative height.

6.4.3 Status

The status (alive or dead) is important to timber properties. From a total of 7192 (10 NA's were removed from the 7202) there were more live branches (n=3813) than dead (n=3379) with a diameter of 5.0 mm or greater in the dataset (from 24 trees). There was an average of 4.5 live branches and 3.6 dead branches (from a mean of 8.1 branches) per growth unit. Similarly to branch angle, Table 6-2 shows that the status is not highly correlated with any other variables other than vertical position in the tree (BHT, BHREL, Z).

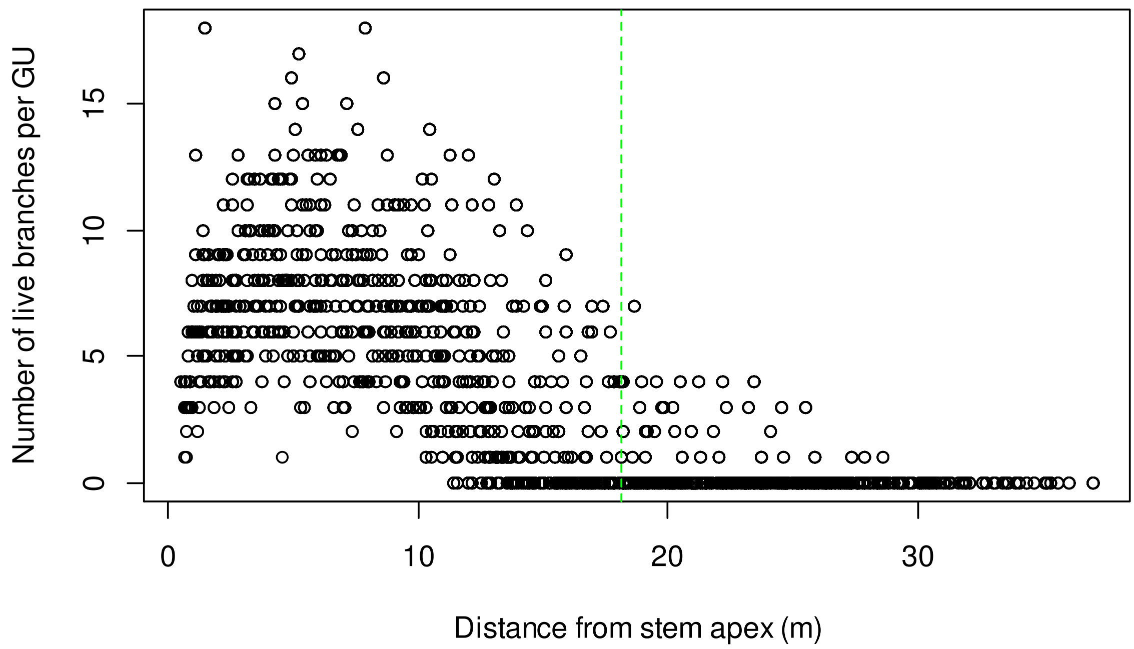

Figure 6-11. The distance from top and number of live branches per GU. This shows the number of live branches increases to around 50% in the crown and then decreases to crown base (mean of 18.1 m) with the number of live branches per GU decreasing even further past HCB. Outside of the crown, the average number of live branches is <5 per GU.

The number of live branches per GU decreased further down the stem (from apex). Once past crown base, the number of live branches lowered. While there was a lowering of total branches (live and dead) it must be noted the plot above only shows lives branches per GU, hence 0 being valid as distance from apex increases. To highlight the difference, both live branch and dead branches per GU are plotted below.

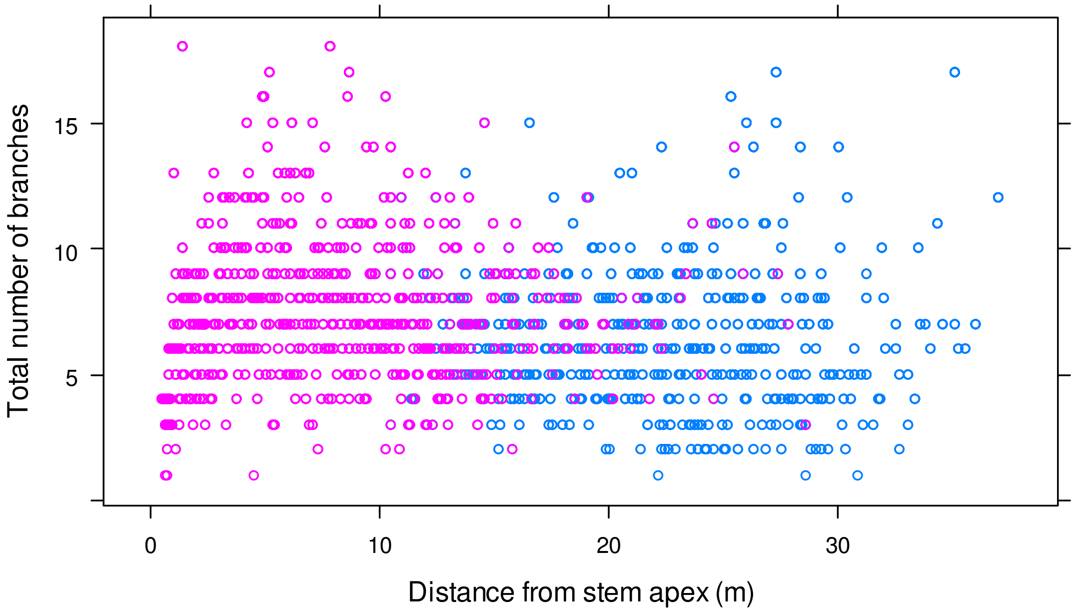

Figure 6-12. Showing both all live branches (purple) and dead branches (blue) similar to above.

Branch status was not correlated highly with tree-level attributes (*e.g.* DBH) but was with certain branch or growth unit-level such as the branch height or relative branch height and growth unit number (an association with height in stem, r = -0.82, R^2 of 0.67). These form the basis for predictive modelling.

The status of a branch can only be described as either dead or alive, which is a binary phenomenon (where live = 1 and dead = 0). The correct approach is to use logistic regression (a binomial general linear model used for predicting a binary outcome from a set of continuous predictor variables). Based on Achim *et al.* (2006), the model for branch status is:

SP=((1)/(1+exp(-(a1+b1*GuNo)))) [6-3]

where SP is the status probability, a1 and b1 are to be estimated from the data, and GuNo is the number of growth units (0 being apex, 54 being lowest in tree). The coefficients are given in Table 6-5 below.

Coefficients	a	b
All	8.988933	-0.386026
Whorl	10.35676	-0.42988
Interwhorl	8.98985	-0.4211

Table 6-5. Coefficients for the model of branch status probability (based on Achim *et al.*, 2006), where a and b are parameters to be estimated from the data. The model was also subset to both whorl and interwhorl.

The Achim *et al.* (2006) model used growth unit number as primary covariate. Similar results can be found by using relative branch height (as both are branch distance from stem apex) as shown below.

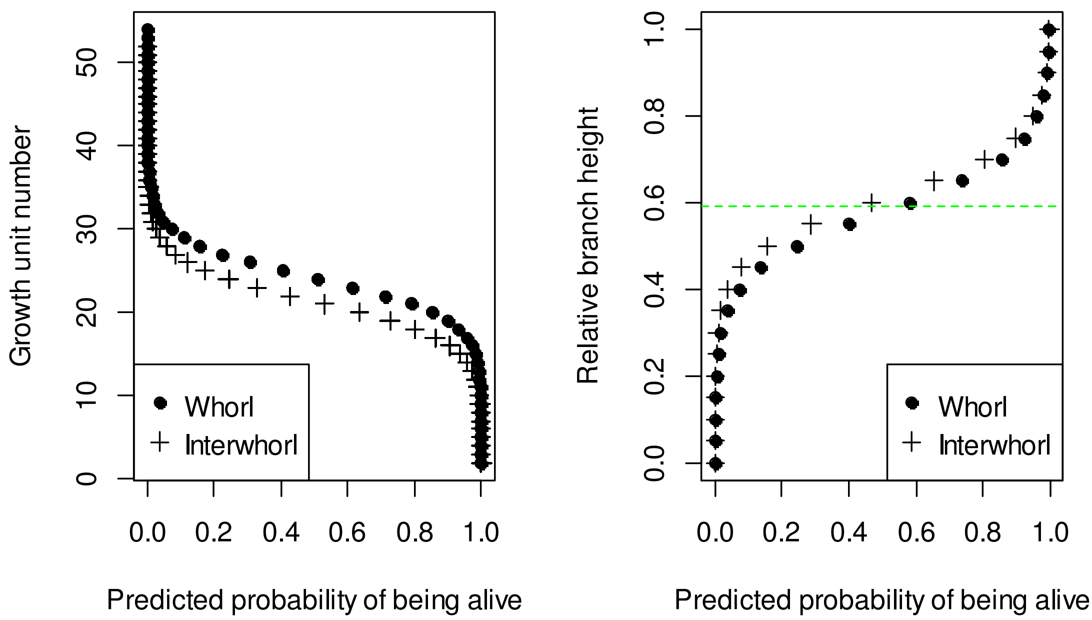

Figure 6-13. Predicted probability of branch status. The left shows as growth unit number increase the probability of being alive decreases. The right shows as relative branch height increases the probability of being alive increases (the green line represents mean crown base).

The likelihood of a branch being alive (branch status) decreases as the growth unit number increases (*i.e.* distance from apex). This is corroborated by plotting the predicted model against both GU number and the relative branch height, which shows that position within stem (relative branch height) affects the status. Noticeably everything above the crown base has greater chance of being alive and everything under the crown does not, while branches at the very limit of the crown base appear to have around a ~50% chance of being alive. The whorl branches appear to have a higher chance of being alive for a given position.

6.4.4 Branch frequency

There was an average of 8.1 branches (SD = 3.05) on every growth unit (which includes all whorl and interwhorl branches). There were 4777 whorl branches and 2409 interwhorl branches with a mean of 4.6 (therefore 5) branches per whorl and 3.2 (therefore 3) branches per interwhorl over an average of 47 growth units per tree. By examining variance components, the variation in number of branches accounted for between sites and plots was negligible, while 11.9% of the variation was explained by difference between trees and 88.1% was within the tree.

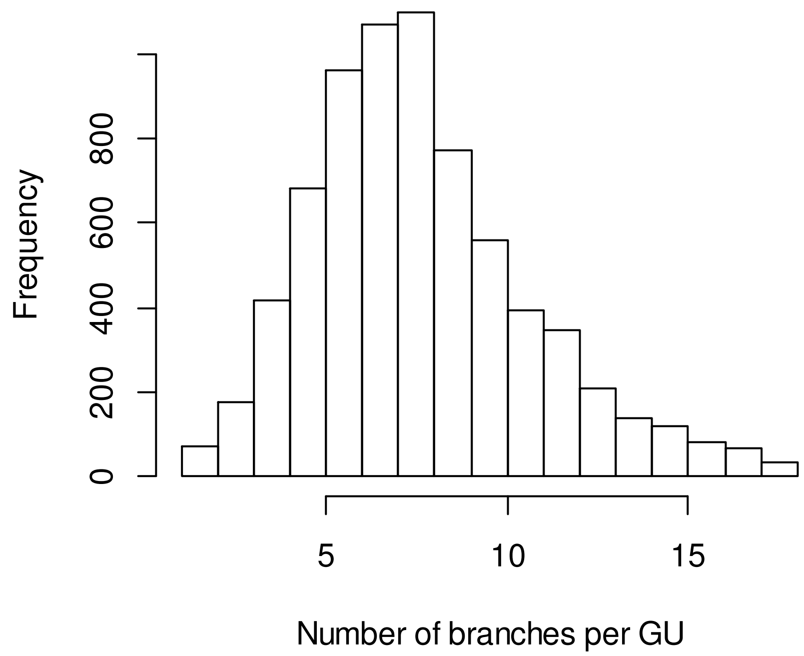

Figure 6-14. Histogram showing number of branches (n=7202) per annual growth unit (n=1129)

There are no obvious trends within Douglas-fir branch number over a GU (growth unit), other than there are usually more whorl branches than interwhorl branches. Figure 6-15 shows position within tree (vertical) has little influence on number of branches per GU, but length of GU may affect the number of branches (r = 0.32).

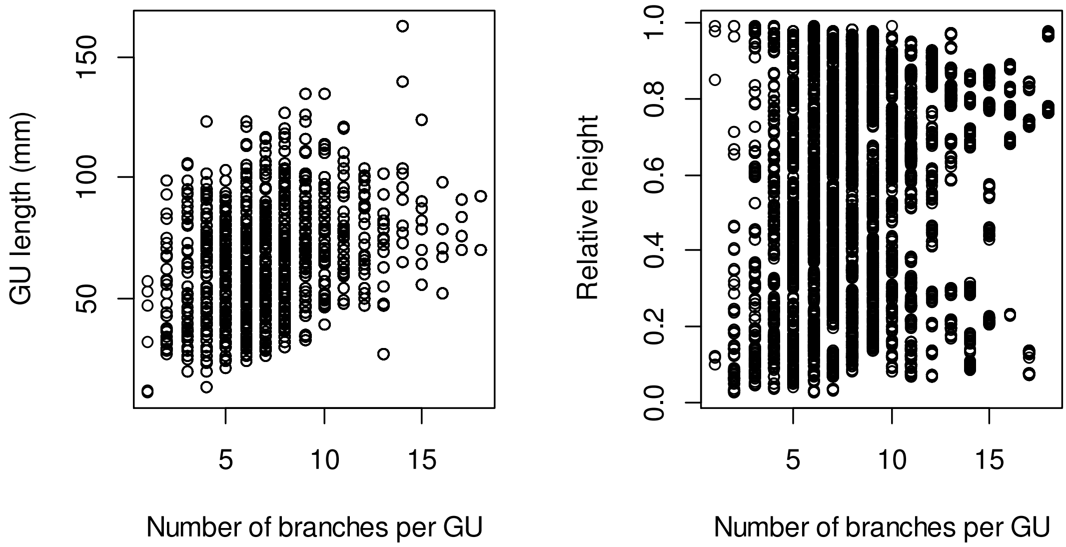

Figure 6-15. Showing number of branches per GU, with length of GU (left) and number of branches per GU at a given height (right). It appears number of branches per GU is higher for a greater GU length.

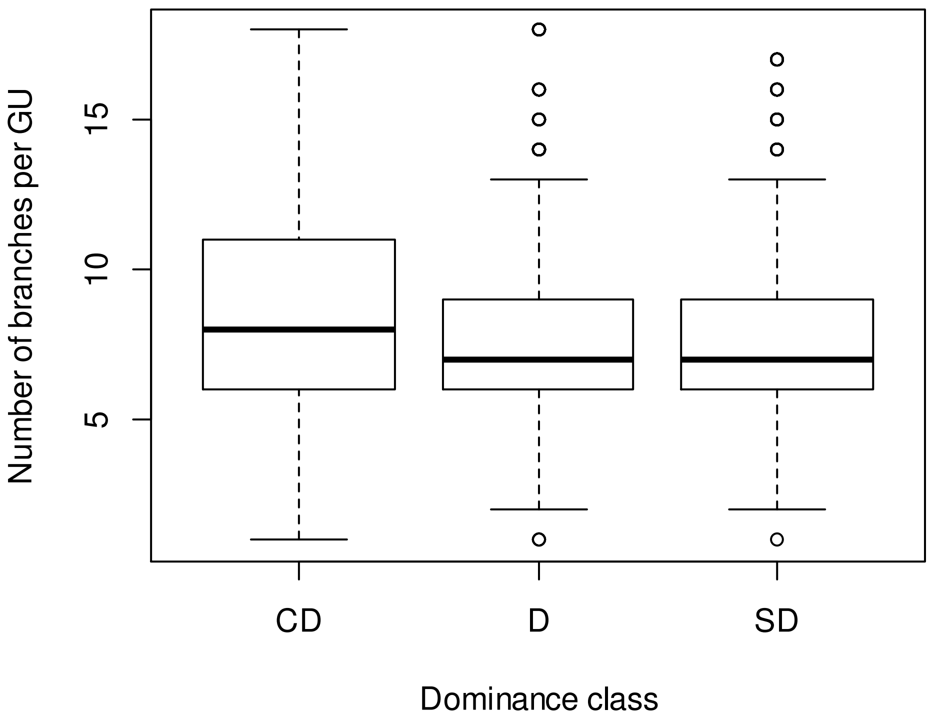

Figure 6-16. Showing dominance class and the number of branches per GU. The co-dominant appears to have more, whereas the dominant and sub-dominant are very similar.

Dominance appeared to have an effect on branch number per GU. While dominant and sub-dominant had a mean of 7.8 and 7.5 branches per GU respectively, the co-dominant had a mean of 8.9 branches per GU. Tree-level variables did not perform well as predictors for number of branches. Like the previous models above (diameter, angle and status) various modelling techniques were examined (*e.g.* Poisson regression which is useful when predicting an outcome variable (branch number) representing counts from a set of continuous predictor variables). Branch frequency (*e.g.* number of branches per GU) is discrete, thus always positive.

The Achim *et al*. (2006) model form did not fit the data for Douglas-fir branch frequency. As there are no easily identifiable trends other than expected (predicted) branch number declines with height in stem, the whorls and interwhorls were subset and fitted. A logarithmic model, based on Auty (2011) who investigated the number of branches per annual growth unit Scots pine (which have no interwhorl branches) and based his model on the generalised linear models presented for Scots pine by Mäkinen and Colin (1999) and for Douglas-fir by Hein *et al.* (2008), changed to the data here and including relative height for each branch is given as:

$$\ln(NBR) = a0 + a1\ln(GUL) + a2BHREL \qquad [6\text{-}4]$$

where ln denotes the natural logarithm and a0...a2 are parameters to be estimated from the data (table below). A pseudo-R^2 of 0.22 was given.

Coefficients	a0	a1	a2
All	-0.42412	0.52117	0.45799
Whorl	-0.34695	0.49493	0.42130
Interwhorl	0.02077	0.45102	0.38841

Table 6-6. Coefficients for the logarithmic model (non least squares) ln(NBR)=a0+a1.ln(GUL)+a2.BHREL for all values, whorl subset and interwhorl subset.

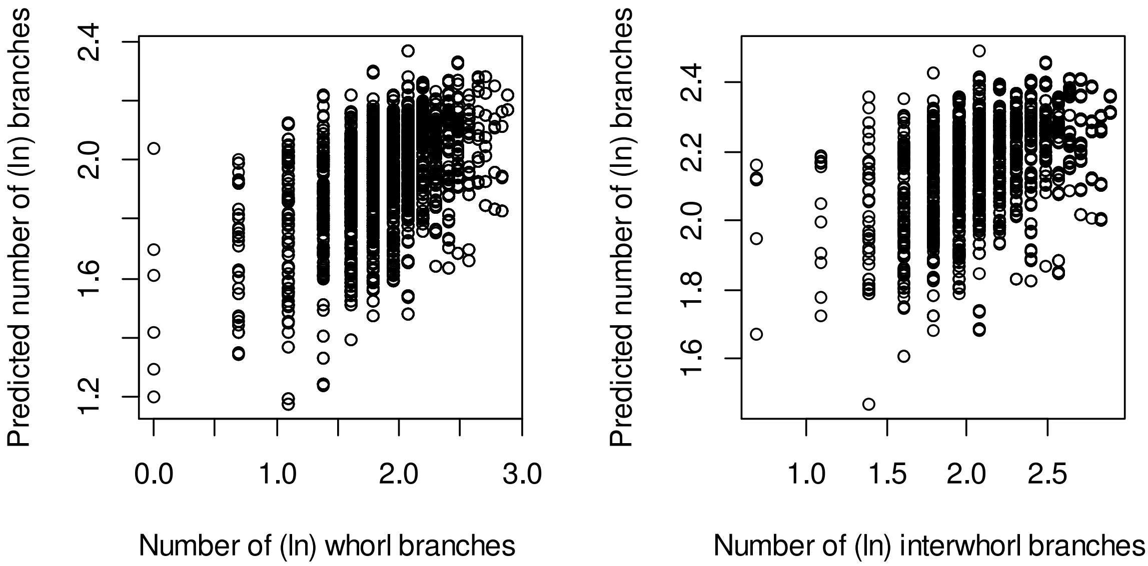

Figure 6-17. Predictied number of logarithmic branches for both whorl (left) and interwhorl (right). Both show a predicted increase of branches (logarithmic) for observed number of branches per GU (logarithmic), with the whorls predited to be slightly higher in number.

Despite a low R^2 value, the model for branch number per GU indicates that for an observed number, the predicted number will increase, with the interwhorls predicted to have less numbers per GU than whorls.

6.5 Discussion

The aim of this chapter was to examine and model the diameter, angle, status and number of branches for the average UK-grown Douglas-fir. These were predominantly based on the study by Achim *et al.* (2006) who investigated the branching properties of the UK's most common and commercially important conifer, the Sitka spruce.

The diameters of both whorl and interwhorl branches are comparable to other studies (*e.g*. Colin and Houllier, 1992; Achim *et al.*, 2006). Branch diameter was highly variable (90% of the variation) within the tree. The mean diameter was 19 mm and the mean of the largest branch per growth unit was 29 mm. This study shows it is not necessary to measure each branch twice for any potential future studies on Douglas-fir branching habits. The branch diameter was not highly correlated with any tree-level variable and despite a low correlation there was a trend with each branches relative position in the stem (vertically) which Auty

(2011) also found that maximum branch diameter was positively related to its position (*e.g.* growth unit number) in the stem.

The diameter for branches starter smaller near stem apex before increasing in size until crown base before declining in diameter towards the bottom of the tree: this was the basis for the modelling. As seen in Figure 6-6 the model (based on Achim *et al.*, 2006) predicted branch diameter to increase to a peak at crown base before declining in size again. This was far more pronounced for whorls compared to interwhorls. The predicted diameter was comparable to Achim *et al.* (2006), in that their whorl branches peaked before halfway from stem apex (around crown base), and whorls were much larger than interwhorls (predicted). This was similar for thinned and unthinned Sitka spruce stands stands (thinned stands had the same trend, but the overall branches were smaller). Auty (2011) found that predicted maximum branch profiles in the upper part of the crown were similar in both thinned and unthinned stands, thus suggesting thinning (forest control) do not have a large effect on branch diameter in the upper portion of the stem, likely as a result from increase light availability. This is corroborated by Ishii and McDowell (2002) who highlight in the upper portion of the crown there is little to no difference of maximum branch diameter, yet further down the crown, branch diameter will change from an abundant distribution of small-diameter branches in the upper-crown to unimodal distributions comprised of surviving large-diameter branches in the lower portion of crown (Ishii and McDowell, 2002).

Maximum branch diameter will peak around the crown base (Hein *et al.,* 2008; Maguire *et al.,* 1999) showing branch diameter is positively related to branch location (Hein *et al.*, 2008) and depth into crown (DINC), thus emphasizing the use of tree-and-branch-level attributes in predicting size characteristics. This study also found the largest individual Douglas-fir branch per tree occurred at an average of 7% above crown base (93% of crown from stem apex) and that dominant trees had larger branches (which would be expected given the greater light availability), thus future analysis could focus on effect of dominance. This peak in maximum branch size occurring above crown base has been observed in Douglas-fir (*e.g.* Maguire *et al.*, 1994; Hein *et al.,* 2007) and other species such as Norway spruce (Colin and Houllier, 1992) and Sitka spruce (Achim *et al.*, 2006).

The branch angle was also highly variable (83% of variation was within-tree) and had a mean of 73.5°. The mean angle was different for each dominance class but not by a large margin. Using a non-linear model again, the R^2 was low but by plotting the coefficients (Figure 6-10) it can be seen that angle starts sharply with a low angle, (steep branches at the top of the tree) and the angle increases, carrying on (increasing) past crown base. Whorl branches were predicted to have a slightly lower angle than interwhorls. The Achim *et al.* (2006) model for branch angle showed a similar trend in predicted insertion angle, with their data predicting the interwhorl branches would be >10° greater than whorl branches.

Branch angle is thought to be controlled largely by factors such as light availability, gravity and compression wood formation on the underside of branches (Weiskittel *et al.*, 2007a/b) yet silviculturally, Achim *et al.* (2006) suggests no effect of thinning can be seen on branch insertion angle for UK-grown Sitka spruce. GU-level attributes bear significance on branch angle (in this case, the difference between whorl and interwhorl branches) together with branch-level (angle increased very rapidly at the top of the tree and then decreased slowly and linearly towards the base). This was agreed by Hein *et al.* (2008) who also observed this behaviour in Douglas-fir branch angles becoming more right-angled as they approached crown base. Makinen and Colin (1998) and Auty (2011) found that various branch-and-tree-level traits were related to branch angle in Scots pine. Determining branch angle and the factors influencing it are fundamental to branching models and their subsequent significance to maximising quality return in sawn timber. Timber taken from lower in the tree (which is the predominant area structural-grade logs come from) will have a greater angle (more horizontal) which is more beneficial than a lower angle (steeper) as discussed in chapter 2 (smaller overall area in timber occupied by knots which cause a discontinuity of timber grain).

The status (alive or dead) of the branches was variable. There was an average of 4.5 live branches and 3.6 dead per growth unit. The status was not highly correlated with any variable other than vertical position in stem. Using logistic regression (a binomial general linear model which predicts a binary outcome) based on Achim *et al*. (2006) model, it was predicted that the likelihood of a branch being alive is closely associated with position within stem (*e.g*. growth unit number), Everything under the crown base is likely dead and this likelihood increases the further away from stem apex the branch is. The whorl and interwhorl branches were very similar in their likelihood of being alive or dead. Achim *et al*. (2006) showed a similar trend, except the differences between whorl and interwhorl branches were more pronounced, with the interwhorl clearly declining in probability (to be alive) with height (before whorl branches). Auty (2011) agreed with Hein *et al.* (2008), who propose that the probability of a branch being alive diminished towards the base of the crown. Many silvicultural factors affect the branch mortality (Hein *et al.,* 2007; Weiskittel *et al*., 2007a), yet so too do branch-and-GU-level variables such as position in the crown (Hein *et al*., 2007; Ishii and McDowell, 2002) and tree-level attributes such as height-diameter ratio (Hein *et al.,* 2007; Hein *et al.* (2008). This is not good news for timber (unlike diameter and angle, above) as the lower portion of the tree where structural logs predominantly come from are far more likely to have dead branches (knots that will “fall out” on cutting).

The frequency of branches (number per growth unit) averaged five whorls and three interwhorls per growth unit, with the co-dominant having more branches on average. 88% of the variability in number of branches was within-tree. The Achim *et al*. (2006) model did not fit the data well hence a generalised linear model (logarithmic) using length of growth unit and relative height as the main parameters was chosen. The R^2 was low given the data did not fit any pattern well but the model showed for an observed number of branches, the predicted number would be similar. Achim *et al.* (2006) showed that number of interwhorl branches increased in likelihood the closer to stem apex, whereas there was not a high trend in whorl branches. The authors predicted that whorl branch numbers start around four (per growth unit) and peak at five, around two thirds from apex before drop in number slightly.

Weiskittel *et al.* (2007a) indicates that branch growth is affected by a whole host of factors, *e.g.* thinning, re-spacing, and fertilization, but for branch count (frequency) no treatment effects were found. Branch frequency is difficult to predict due to the complex influence of multiple factors (Auty, 2011). It would appear the main factor affecting frequency is annual height increment, *e.g.* GU length (Auty, 2011; Weisktittel *et al.,* 2007) with additional but smaller influence of aspect (Weisktittel *et al.,* 2007) and tree diameter (Auty, 2011), however these studies were conducted on Scots pine and Norway spruce. Maguire *et al.* (1994) implied diminishing number of branches with increasing DINC on young Douglas-fir trees while Ishii and McDowell (2002) report that branch density decreased exponentially for the lower one-half/two-thirds of the crown, generally thought to be due to increased light levels at top of crown or associated with early thinning (Maguire *et al.,* 1994; Maguire, 1983). This is agreed in UK-grown Sitka spruce, as Achim *et al.* (2006) found the effect of thinning was to increase the number of branches, while Maguire *et al.* (1994) suggest dominance influences branch count (*e.g.* due to light availability on larger/taller trees which will increase photosynthetic capabilities). This implies the importance of investigating which tree-and branch-level variables bear the greatest influence on branch frequency of Douglas-fir, which in this case was length of growth unit. as the number of branches was relatively constant vertically up the stem. For timber purposes it would be beneficial to have fewer branches in the lower merchantable portion of the stem.

6.6 Conclusions

The objectives of this chapter were to describe the branching characteristics of Douglas-fir trees grown in Great Britain. Specifically, the factors that most influence timber properties were those that were focused upon here, being branch diameter, angle of insertion, probability of mortality and the frequency.

When grown in the north of the UK, Douglas-fir will generally have the same number of branches anywhere on the stem, but in the lower portion (where most structural- dimensioned timber comes from), branches will have lower insertion angles and smaller diameter branches (usually more beneficial) compared to higher in the stem (*e.g.* around live crown base). Conversely the lower branches will more likely be dead (less beneficial). The models produced could only describe a small proportion of the variation, but are still useful to visualise the data.

Any future work should concentrate on replicating specific silvicultural applications and their effects on branching habits, especially if any changes in forest management (*e.g.* initial spacing) could potentially alter branch characteristics and in turn, timber properties. Including specific silvicultural studies (*e.g.* Hein et al., 2008) with a greater number of individual trees should lead to models that could describe more of the variation. Whereas timber grading settings (covered in the previous chapters) are directly influenced by model predictions (*e.g.* density on the strength of wood), the use of branching models is more complex as they must in some way be related to knot area ratio. Linking branch measurements to knot area ratio would therefore be another area to focus further research.

7 Taper, sapwood, heartwood and dimensional stability profiles in UK-grown Douglas-fir

7.1 Introduction

This chapter aims to describe and predict taper of Douglas-fir, to gain an accurate estimate of volume which can be used to determine merchantable timber volume (or used in biomass or carbon calculations). Alongside volume, heartwood is described and predicted based on height in stem and relationships with tree-level attributes (*e.g*. crown ratio). Heartwood is the darker, inner layer of wood in the tree (which as it contains no living cells, is no longer functional) with extractive materials being deposited in the tracheid walls and cavities at the time the cells die (*e.g.* Graham and Kurth, 1949; Hillis, 1962; Megraw, 1986). The sapwood is the lighter-coloured zone where conduction (water transport, *e.g*. Tyree and Zimmerman, 2002) and storage of starch and lipids happen (Dinwoodie, 2000). The transition zone (a narrow, not always visible band) between heartwood and sapwood is not investigated here. Beauchamp (2011) gives a detailed UK heartwood/sapwood overview (Sitka spruce and Scots pine).

The deposition of extractives (which gives the colour change) in the xylem increase the durability associated with Douglas-fir heartwood, due to some of the chemicals being toxic to bacteria, fungi or insects (*e.g*. Hillis, 1968). In a living conifer, sapwood moisture percent is typically far greater than heartwood (Megraw, 1986). Because these dead cells are encrusted with extractives, the permeability is greatly reduced (Kitin *et al.,* 2009) and the permeability and durability (and moisture content) is important for timber products (*e.g*. Desch and Dinwoodie, 1996). Hence, heartwood is deemed beneficial and as such manipulation of its formation (*e.g*. increasing heartwood area/volume) has been previously investigated (*e.g*. Hillis and Ziegler, 1968; Hillis, 1987; Hillis,1999).

Shinozaki *et al.* (1964) gave the original pipe-theory model for heartwood, whereupon sampling 10 species they determined there is a specific sapwood area required to sustain (*e.g.* supply water to) a certain area of canopy (determined by leaf area index), and any surplus sapwood is thus converted to heartwood. Therefore, the amount of foliage on a tree is usually correlated to the amount of sapwood (Whitehead *et al.,* 1984; Dean and Long 1986; Ryan 1989).

As heartwood may be more dimensionally stable, investigating the swelling rates (sorption) of Douglas-fir trees is undertaken as the difference between heartwood and sapwood would be of interest. As sapwood and heartwood are related to height within a tree (*e.g.* Beauchamp, 2011), which tapers exponentially upwards, taper is also examined (*e.g.* Fonweban *et al.,* 2011). Despite full measurements (stem diameter and cross-sectional area of heartwood/sapwood) taken for every sample, these are not easily obtained, allowing empirical models to be investigated to predict the cross-sectional area from easily measured variables such as DBH or tree height.

7.2 Aims and objectives

Specific aims are to (1) model taper for the average Douglas-fir tree, (2) describe the average heartwood variation based on height, (3) predict sapwood and heartwood area and (4) investigate the swelling rates of Douglas-fir for heartwood and sapwood in different directions.

7.3 Materials and methods

7.3.1 Taper

The taper methodology is described in 3.3.2.1 and consisted of diameter being taken at every metre along the stem (until less than 7 cm diameter).

7.3.2 Heartwood materials and methodology

The heartwood samples were taken along the stem (avoiding whorls) from breast height (1.3 m) until a diameter <7 cm. The same even-age trees were used as the rest of the study, with an average age of 50.1 (42 - 58). Full details are given in chapter 3. Using Image Pro Plus™ (Media Cybernetics, 2007; Bethesda, MD, USA), the total area, sapwood area and heartwood area was measured in all four directions (north, east, south and west). The 3968 samples had a range of 0 – 68% heartwood (grand mean 38%). Full methodology details are given in chapter 3.

7.3.3 Swelling materials and methodology

The swelling rates of Douglas-fir were tested by using samples which were nominally 20 mm x 20 mm x 20 mm. A dominant and sub-dominant tree were sampled, with 3 samples from each tree to show positional trend (*e.g*. from pith to bark similar to the structural battens “inner”, “mid-range” and “outer”). These are summarised as follows:

	Before extraction				After extraction			
	Radial		Tangential		Radial		Tangential	
	Depth*	Density**	Depth*	Density**	Depth*	Density**	Depth*	Density**
”Inner” D	19.695	0.38	19.537	0.38	19.666	0.38	19.352	0.38
”Mid” D	19.721	0.42	19.697	0.42	19.644	0.41	19.582	0.41
”Outer” D	19.677	0.46	19.54	0.46	19.575	0.45	19.433	0.45
”Inner” SD	19.663	0.38	19.675	0.38	19.702	0.37	19.602	0.37
”Mid” SD	19.593	0.51	19.659	0.51	19.496	0.50	19.452	0.50
”Outer” SD	19.642	0.49	19.67	0.49	Fail	Fail	19.431	0.49

Table 7-1. Oven-dry starting values for all samples used, * = as the micrometer was “pushed” upwards by the swelling of the sample, the depth (or height) was recorded as initial starting figure in mm. ** =The density here is given in g/cm^3. ”D” denotes the dominant tree, while “SD” is the sub-dominant. The “outer” sub-dominant radial sample (after extraction) failed (*e.g.* the micrometer malfunctioned).

One measurement per second was taken for 24 hours, hence a large dataset. The data presented here only used every minute (1,440 per sample, per run) instead of every second (86,400 measurements per sample, per run) to minimise logistical software problems. Once samples were in place, the micrometer was reset to zero the instant water was added and subsequently left for 24 hours. Full details are given in 3.7. Results were subset to 22 hours, given the logistical approaches to laboratory set-up (despite being housed in a controlled chamber, any large changes in temperature or human interference, around the 23-hour mark affected the extremely sensitive micrometer).

7.3.4 Statistical package

Using the R package (R Development Core Team, 2014), all functions were carried out in the standard library, nlme library and lattice library.

7.3.5 Statistical methods

Interactions between variables were examined with a correlation coefficient (Pearson's) matrix, which measures the strength of a relationship between two variables (linearly, either positive or negative) and predictability examined with coefficient of determination (R^2), which is the proportion of variance (in the response variable) that is predictable from the independent variable.

7.4 Results

7.4.1 Douglas-fir taper profiles

The taper for the average Douglas-fir tree was also examined and modelled to allow predictions based on empirically determined parameters. Firstly, the data was plotted with height in stem.

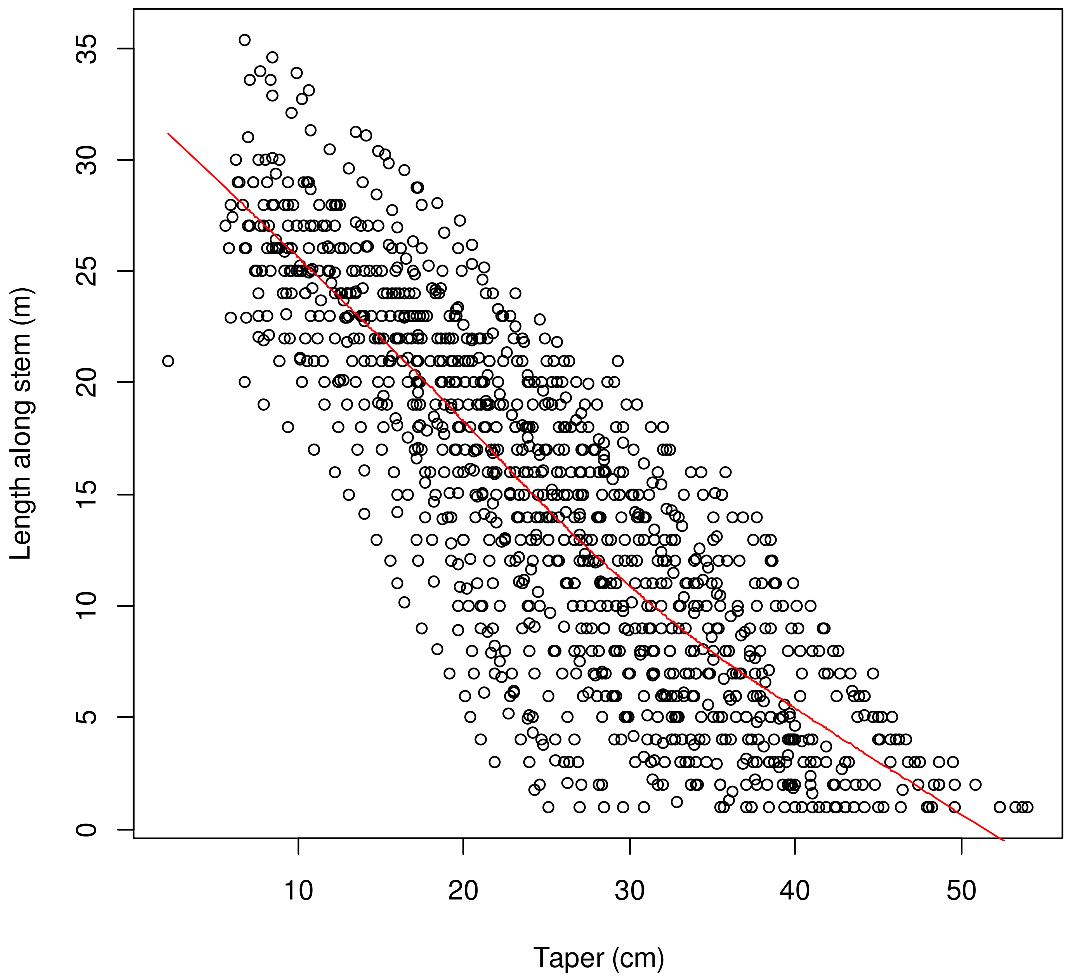

Figure 7-1. Showing how taper decreases the further from bottom of the tree. The red line is a loess line (locally weighted regression) to identify the trend.

As seen, taper changes with height and the above plot shows the further towards stem apex, the smaller the diameter of the tree will be. This relationship is positive (R^2 of 0.69) but cannot be described as completely linear.

After examination of the literature and various model screening, the following model is based on Fonweban *et al.* (2011) who used a variable-exponent taper equation for Sitka spruce (and Scot's pine) grown in the UK. The form was changed slightly and parameterised to the Douglas-fir data:

$$y = DBH.p^{[a0+a1(z-1)+a2(\exp(a3z))]} \quad [7\text{-}1]$$

where p is (ht-x)/(ht-1.3) and z = x/ht (relative height along stem), ht is tree height, x is distance along stem and DBH is diameter at breast height, and a0…a3 are to determined empirically from the data. Using this model, 96% of the variation can be described.

Coefficients:	Estimate	Std. Error	t value	Pr(>|t|)	Signif.	RSE	Adj. R^2
Taper model based on Fonweban et al. (2011)							
a0	0.77387	0.01541	50.222	< 2e-16	***	2.014	0.96
a1	0.17503	0.07918	2.210	0.0273	*		
a2	1.77014	0.21593	8.199	6.48e-16	***		
a3	-6.85802	1.02532	-6.689	3.53e-11	***		
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1							

Table 7-2. Coefficients for the taper model based on Fonweban *et al*. (2011). a0…a3 are to be determined empirically.

The relationship (linear) between observed and predicted diameter is strong and the three variables necessary to determine accurately the taper (diameter at a given point) are distance from stem apex (or ground) to the given point, DBH and tree height.

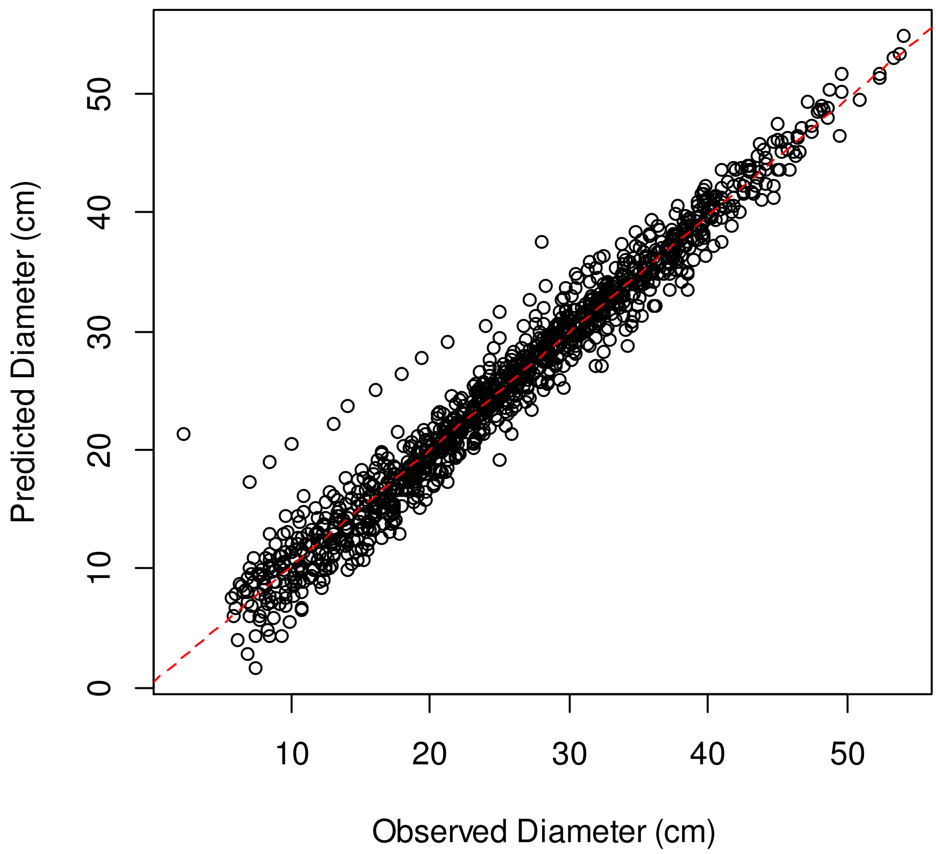

Table 7-3. Showing the taper model and its predicted values for observed vales. The red line is the fit (R^2 0.96).

7.4.2 Heartwood results

The heartwood percent (cross-sectional area) of all samples ranged from 0 - 67% (with a mean of 39%). At breast height (1.3 m) the minimum heartwood percent was 42% and maximum was 65% (mean of 54%).

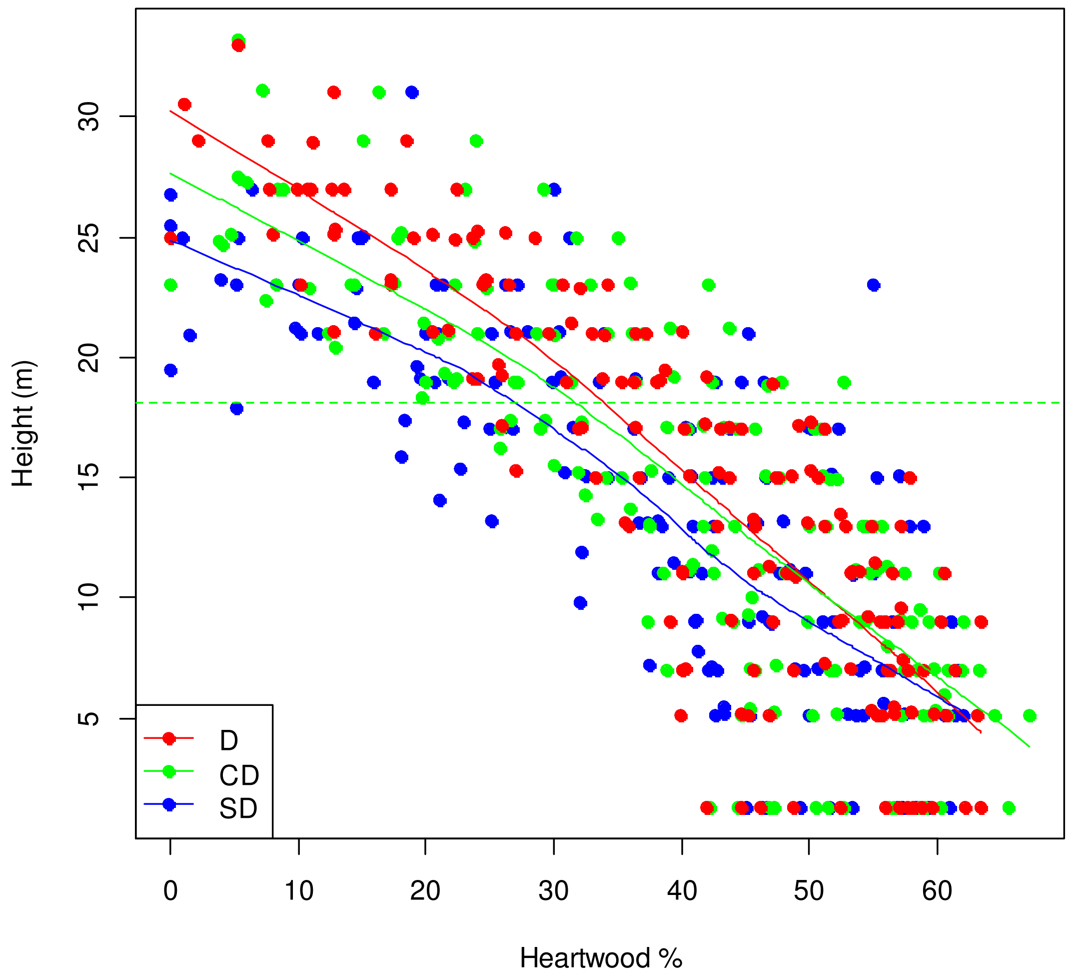

Figure 7-2. Showing the heartwood percent at a given height for all samples. D = dominant, CD = co-dominant and SD = sub-dominant. The adjusted R^2 is 0.66.

Figure 7-2 shows that heartwood percentage increases the further down the stem (distance from stem apex). At breast height (1.3 m) the lowest heartwood found was 42%. It seems predominantly but not entirely linear, thus could be construed as slightly non-linear. Using all samples gives an R^2 of 0.66 (heartwood percentage determined from height). Dominant trees have a higher insertion (30%), more than co-dominant (28%) and sub-dominant (25%), showing that larger trees have a greater heartwood area in the upper stem. The mean heartwood percentages for all discs in a dominance class are similar for dominant and co-dominant (39.19% and 39.06% respectively) and slightly lower for sub-dominant (37.27%).

While the interest lies in the average-tree across the UK, it should be noted there is a difference in heartwood percentage between the sites. LA was 43%, with LT 6% lower, MA 8% lower, PI 3% lower and RU 4% lower than LA.

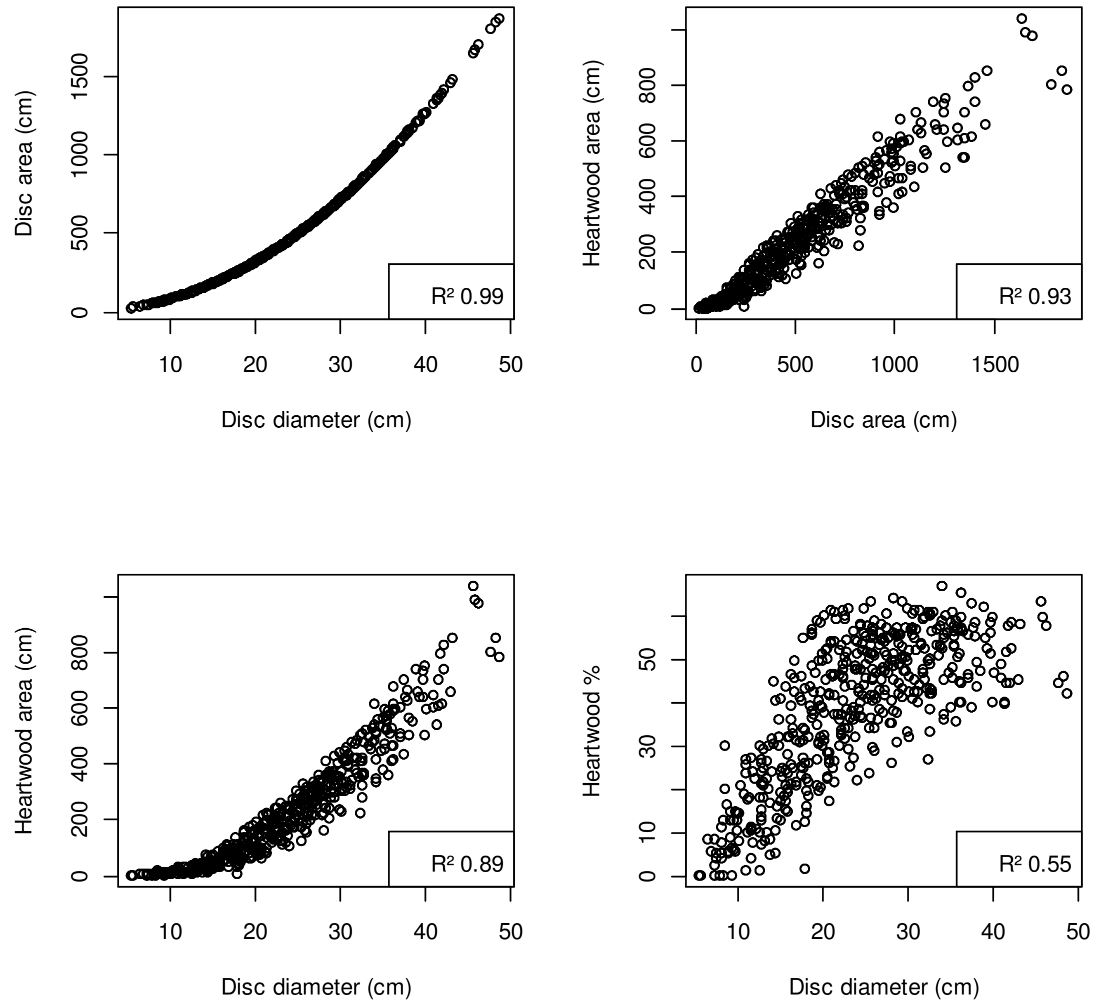

Figure 7-3. Showing various relationships with heartwood content. Heartwood area has a strong relationship with disc area and disc diameter. Heartwood percentage is positive but not as strong.

There was some variation in disc area, as area was approximated based on them being circular (with the algorithm πr^2) when they are not in fact perfectly circular. The heartwood area can be accurately determined if the disc area is known (R^2 of 0.93), likewise the disc diameter can also account for a large amount of the variation in heartwood area (R^2 of 0.89). While it is heartwood percent that is of greatest interest (*e.g.* for timbers durability), heartwood percentages cannot be accounted for as much as heartwood area, hence the simplest method to determine heartwood content would be to measure disc diameter and convert to area.

Heartwood percentage was not correlated with any tree-level variable (*e.g.* height, BDH, crown ratio, HD ratio), as expected due to the variation with a tree (vertically up the stem and horizontally over the radius). Heartwood percentage was able to be determined much better with disc-level variables. The disc diameter (R^2 of 0.55), disc area (R^2 of 0.42) and height of disc (R^2 of 0.66) were all correlated with heartwood percent. Using simple linear regression, if both the disc height and diameter is known, 75% of the variance can be explained. Upon examination of the partition of the sum of squares for the regression, the disc height explained 66% while disc diameter explained 2%, the relationship between disc height and diameter was 7% and residuals (unexplained) was 25%.

However, despite this (a model with predictor two variables giving an R^2 of 0.75), the chosen model is a simple linear model, using only one variable (disc area) to determine heartwood area using standard linear regression. Given that calculating disc area is a relatively easy (as disc area is πr^2), ascertaining heartwood area can be done without cutting the tree down (simply measure diameter of stem at a given height) and this will predict the heartwood area, accounting for 93% of the variation.

Figure 7-3 (top left) shows the linear relationship, which has an R^2 of 0.93 (RSE = 52 on 3966 degrees of freedom) and the equation $y=mx+c$ (where y is heartwood area, m is 0.55, x is disc area and c is -44.00).

7.4.3 Swelling results

In both the radial and tangential directions, an “inner”, “mid” and “outer” sample from both a dominant and sub-dominant tree was swollen as described in the materials and methods. Table 7-1 shows details of all 24 samples, including the density data which seems largely unchanged after extraction (acetone bath >24 hours), which indicates the extraction method may have been unsuccessful.

All 24 models were the same general form, that of Michaelis-Menten kinetics (a well-known model of kinetics generally used in biochemistry). This essentially uses a maximum rate at maximum substrate conditions (Michaelis and Menten, 1913) and the Michaelis constant which is the reaction rate of half the maximum (*e.g*. time taken to achieve half of the maximum). This was the basis for model form used in this study:

$$y=(a1*x)/(a2 + x) \qquad [\,7\text{-}2\,]$$

where y is the swelling rate, x is time (in minutes) and a1 and a2 are empirically determined parameters to be estimated from the data. This model was fit to each sample run (as seen in Table 7-1) and amalgamated in Table 7-4 and Figure 7-4.

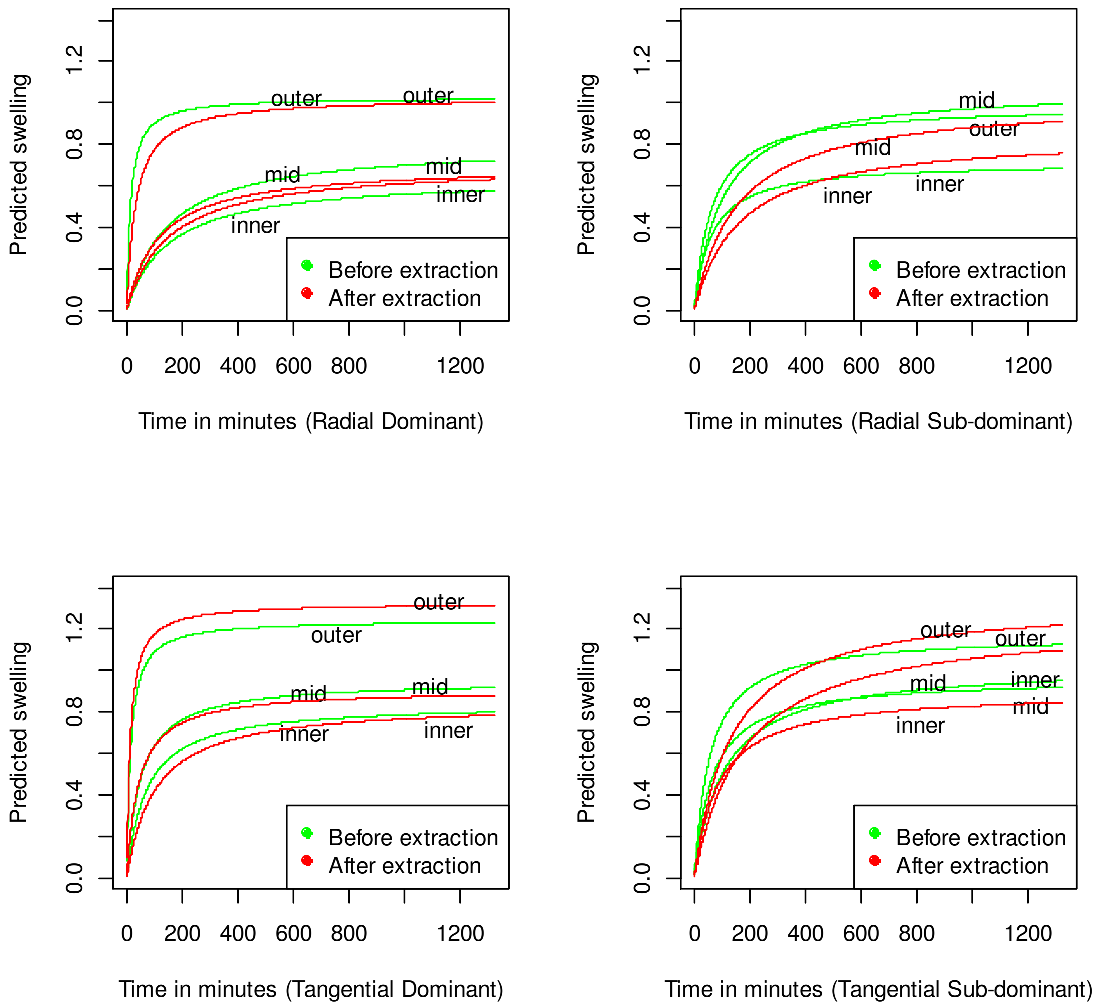

Figure 7-4. Showing all 24 models (one failed as explained previously) and their predicted swelling rates based on time (in minutes). The tangential samples swelled more than the radial samples. While each direction (radial or tangential) reached a similar maximum value, the dominant "outers" had a far higher initial rate compared to the sub-dominants "outers".

As seen above, swelling was greater for the tangential compared to radial direction. For both directions, before and after swelling and both dominance classes, the "mid" and "inner" were relatively close except for the radial sub-dominant "outer" which was predicted to be lower than the "mid". The differences between before and after extraction were probably negligible. The "outer" samples in the dominant (both directions) have a steep incline, where they swell greater than the sub-dominants (in both directions). Table 7-4 shows the parameters for each model.

Position	Dominance	Direction	Extraction	Parameter a1	Parameter a2
Inner	D	Radial	before	0.799109	144.118
Mid	D	Radial	before	0.642044	150.8104
Outer	D	Radial	before	1.027358	13.99283
Inner	D	Radial	after	0.701022	149.5329
Mid	D	Radial	after	0.699935	116.5032
Outer	D	Radial	after	1.025832	32.67424
Inner	SD	Radial	before	0.712108	60.4883
Mid	SD	Radial	before	1.069839	100.37
Outer	SD	Radial	before	0.989239	63.5526
Inner	SD	Radial	after	0.849147	163.693
Mid	SD	Radial	after	1.018431	156.3876
Outer	SD	Radial	after	Fail	Fail
Inner	D	Tangential	before	0.841614	70.89524
Mid	D	Tangential	before	0.950641	49.52537
Outer	D	Tangential	before	1.243894	14.29177
Inner	D	Tangential	after	0.844296	101.4189
Mid	D	Tangential	after	0.908987	43.17748
Outer	D	Tangential	after	1.325952	12.79413
Inner	SD	Tangential	before	0.961386	63.5311
Mid	SD	Tangential	before	1.023825	104.3078
Outer	SD	Tangential	before	1.17222	55.64718
Inner	SD	Tangential	after	0.899353	85.75843
Mid	SD	Tangential	after	1.245535	177.0747
Outer	SD	Tangential	after	1.338089	128.8433

Table 7-4. Showing parameters a1 and a2 for all 24 models (one failed as explained previously). D = dominant and SD = sub-dominant trees.

7.5 Discussion

The aim of this chapter was to describe and model the variation in taper, swelling and heartwood of the average Douglas-fir tree growing in the UK. The heartwood is deemed desirable by most-end users and sapwood conductive area supports water transport which is essential for a trees life. The taper of a tree is predominantly a biomechanical trait where load is distributed accordingly along the stem (simply put, the lower part of the tree holds more weight compared to the top). The swelling of Douglas-fir wood is important to timber processors and end users who wish to examine dimensional stability (*i.e*. does it swell greatly in any directions if in contact with water?).

Disc diameter and heartwood percentage was correlated positively but the disc diameter (easily recordable) only described 55% of the variation in heartwood percentage, similar to Beauchamp (2011) who also found relationship between areas strong but found the relationship between sapwood depth and disc diameter was weak. Douglas-fir heartwood percentage was correlated well (R^2 of 0.69) with height in stem, but a discs area is highly correlated (R^2 0.93) with heartwood area for a given disc. Translating this information for the structural timber user (*e.g*. decay resistance in heartwood) shows that on average there will be more than 50% of the cross-sectional area that is heartwood at the bottom of the tree (breast height). The sub-dominant trees had slightly less heartwood area than dominants and co-dominants.

From sampling three distinct stem areas (bottom, 1/3 of height and top of merchantable log), Wellwood (1955) found that cross-sectional percentage of Douglas-fir sapwood was greatest at base and lowest in the middle portion. Smith *et al.* (1966) determined that sapwood thickness (of Douglas-fir with an average age of 85) is extremely variable, within and between trees. The average sapwood thickness increased with certain variables including DBH and crown class (from suppressed to dominant) and also included diameter outside bark (d.o.b.) of samples. In determining sapwood thickness they found using 13 different variables in multiple linear-regression analysis would account for 78% of the variation whereas using only d.o.b. would account for 54%. Using disc diameter, 89% of the variation in Douglas-fir heartwood area was accounted for, and 55% of the variation in heartwood percent.

For swelling, using the Michaelis-Menten kinetics model it was seen that the tangential compared to radial direction swelled more (maximum swelling amount). There was generally a notable difference between “inner” and “outer” (not “mid”) for all samples, but the dominant “outer” sample swelled at a far greater rate for both tangential and radial samples. Oven-dry Douglas-fir wood here generally started to absorb water almost instantaneously, for both extractives present and not. It appears the extraction method (acetone bath) did not work for this experiment and swelling kinetics for un-extracted wood is discussed. Above the fibre saturation wood is dimensionally stable (theoretically) and below that wood shrinks as water is lost from the cell walls (*e.g*. Dinwoodie, 2000, Moore, 2011) which conversely mean dry wood would swell as it gains moisture (*e.g*. Rijsdijk and Laming, 1994). Changes in dimension are potentially problematic to the structural timber industry as in-service conditions may change the moisture content (MC) of the wood and cause movement (*e.g*. swelling, warping).

It has been shown that wood does not shrink in the longitudinal direction anywhere near as much as in the radial and tangential directions (*e.g*. FPRL, 1967; Harding, 1988; Walker, 2006), and of those two it is tangential that shrinks more thank radial. Yang (2009) found that the mean shrinkage of Douglas-fir in longitudinal, direction was negligible, but tangential was greater than the radial direction. When changing from green to oven-dried they shrunk 6.05% and 4.15%, respectively, or from green to 12% MC 2.97% and 1.78% respectively. Similarly to this study, the author also found that tangential and the radial shrinkage shows a trend of increase from pith to bark. The difference between both radial and tangential (lateral) and longitudinal (axial) directions are assumed to be because of the difference in orientation of the cells (more specifically, the MFA in the S_2 layer) but the differences between radial and tangential directions are not yet well understood.

Trees are tapered in such a way as to provide optimal distribution of (wind) load to avoid stem failure (*e.g.* Mattheck, 1991). Ascertaining taper profiles of trees can aid calculations of timber volume (Max and Burkhart, 1976) and can convey useful information pertaining to demand of certain products (mixtures) in the vertical profile (*e.g*. logs, bars, posts, stakes) which need to be predicted (Sharma and Zhang, 2004; Trincado and Burkhart, 2006), or included in forest inventory systems (Trincado and Burkhart, 2006).

Some of the screened models for taper were complex single equations (*e.g*. Kozak, 1988) and the model chosen was a variable-form taper function adapted by Fonweban *et al*. (2011) for German and Italian grown Douglas-fir (INRA/ENGREF, 1999), for Norway spruce (Houllier *et al*., 1995) and Atlas cedar (*Cedrus atlantica* Manetti) by Courbet and Houllier (2002). Using only the height of the measurement could describe 69% of the variation. However, using the model based on Fonweban *et al.* (2011), distance along stem (individual branch height), DBH and total tree height were needed (two of these three are easy and not time consuming to record) to describe 96% of variation, which is useful for predictions of taper for product assignment.

7.6 Conclusion

Specific aims were to (1) model taper for the average Douglas-fir tree, (2) describe the average heartwood variation based on height, (3) predict sapwood and heartwood area and (4) investigate the swelling rates of Douglas-fir for heartwood and sapwood in different directions.

It was found that 96% of the variation in taper can be explained by three variables (DBH, height and the given height where prediction is to occur). Heartwood of Douglas-fir will be on average more than half the cross-sectional area at the bottom of tree, and 93% of the variation in heartwood area can be explained by the disc area, such is the linear relationship between them. Swelling of dried timber occurs more in the tangential direction than the radial direction. The sapwood ("outer") of dominant trees swells at a greater rate than any of the other samples.

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8 Review

8.1 Summary and the aim and objectives of this study

. The main aims were to describe and model:

- 1 – The timber properties of UK-grown Douglas-fir
  - Age-related trends in strength, stiffness and density of clearwood samples
  - Strength, stiffness and density of structural-sized samples
  - Distortion of structural-sized samples
- 2- Branching characteristics of Douglas-fir
  - Branch size
  - Branch frequency
  - Mortality probability
  - Angle of insertion
- 3 - Heartwood formation and dimensional stability of heartwood
  - Heartwood/sapwood (proportion) variation up the stem
  - Taper profiles of Douglas-fir
  - Swelling rates of heartwood/sapwood

8.2 Limitation to materials and methods

Five sites were chosen to represent the average Douglas-fir tree; three sites in Scotland and two in Wales, to represent a "north region" and "mid-region" (as the data from Bawcombe, 2013 would act as a "south region"). Based on relevance to general UK forestry practises, the age range was 42-58 years at time of felling. Testing for an entire representative range of Douglas-fir within the UK could not feasibly happen within the time and budgetary limits of this study. However, the aims and objectives could be met with three trees per plot, three plots per site over five sites, totalling 45 trees. Given the amount of clearwood samples (n=272), structural samples (n=188), branching measurements (n=7207) and the high number of taper, heartwood and swelling measurements achieved from this number of trees, the number was therefore deemed appropriate to determine a "mean-tree" summary for most characteristics/properties and provide information about variability. However, this meant replication of silvicultural regimes or genetic differences could not be examined (discussed below). The number of full-sized structural battens was not large enough to be adopted for grade settings (*e.g.* MiCROTEC ™), but they can form part of a larger population of samples for this purpose. The clearwood samples were only taken from pith to bark on the north side unlike the structural battens which took the whole cant (*e.g.* bark-pith-bark). Azimuth was not taken for branching due to investigation of the literature, which can show slight increase in size on southern-facing branches (in the northern hemisphere).

8.3 Key findings

The main findings of this study are split into several categories, but all relate to Douglas-fir as a timber for the end-user. Douglas-fir's timber properties, branching habits, swelling and heartwood and finally taper will be summarised.

Firstly: timber properties and their variation. The main limiting property for structural, UK-grown Douglas-fir sampled in this study is stiffness. Douglas-fir was found to be stiff, stronger and denser than UK-grown Sitka spruce (*e.g.* Lavers, 1983, Moore, 2011). The mean stiffness, strength and density was 9,100 N/mm^2, 34 N/mm^2 and 460 kg/m^3 respectively for structural (full-sized) samples and 8,500 N/mm^2, 79 N/mm^2 and 490 kg/m^3 respectively for clearwood (small, defect-free) samples (5th percentiles found in text). Douglas-fir distorted more by twist than cup, bow or spring. Searles (2012) found 36% of Sitka samples were rejected based on twist while for Douglas-fir it was less than 10%, and the figures presented here for twist were considerably lower than Moore *et al.* (2009a) found. The theoretical pass-grade of the structural Douglas-fir timber in this study is 99% C18.

When building models for MOE and MOR of structural and clearwood samples, it was found that generally using one main variable would be able to predict the response variable almost as well as a model containing two (or more) explanatory variables. The structural samples had a marked difference between juvenile ("inner") and mature ("outer") wood for MOE, MOR and density. The small, clearwood (defect-free) samples corroborated this difference in properties dependant on position; with the main explanatory variable being cambial age (ring number from the pith are easily counted). As density is affected by age like MOE and MOR, it was not used for the age-related models, but if age was not the sole concern, using density as a primary model variable would increase the predictive modelling power (to predict MOE and MOR) by around 20%. However, one can also ascertain the sawnwood MOE by using simple, cost-effect acoustical methods (non-destructive testing) to describe most of the variation.

Secondly: branching habits. After investigation of literature and noting that there is a 7% decrease from structural to clearwood MOE yet a 57% decrease from clearwood MOR to structural MOR, it was deemed branching caused a severe decline of strength (knots represent a discontinuity to the timber grain). The main influence of branching on strength is the size of branch (and therefore, knot). However, the angle, status (alive or dead) and number of branches will all influence timber properties. For structural timber purposes, it was shown that Douglas-fir will generally have the same number of branches anywhere on the stem, but for the lower portion (where most structural-grade timber comes form) a more beneficial branch angle and diameter branches compared to higher in the stem (*e.g.* around live crown base) will occur, but these are more likely be dead and therefore unsound, causing weakness in timber.

Thirdly: heartwood, swelling and taper. It was found taper, which is useful for predictions of assortments of timber products can be largely explained by the height of tree, diameter of tree and the distance to where the prediction is needed. The heartwood area of Douglas-fir which is beneficial (better decay resistance and lower moisture content), can be described well by individual variables such as the diameter of the disc (which would explain 89% of the variation). At the bottom of the tree where structural timber is largely harvested from, there will on average be more than 50% heartwood. The swelling of Douglas-fir occurs more in the tangential direction than the radial direction, with "outer" (predominantly sapwood) samples swelling the most.

8.4 Implications for Douglas-fir and future recommendations

This study and the results bring about certain recommendations for future work. Specific, replicated silvicultural regimes should be tested to study the effect of control (*e.g.* spacing, thinning) on Douglas-fir timber properties to determine their effects, especially if any changes in forest management (*e.g.* initial spacing) could potentially alter tree characteristics and in turn, timber properties (which would likely be the case for all timber species). Coupled with this, replications of pruning experiments could perhaps shed statistically significant light on the effect knots have on strength in Douglas-fir. This is also the case for genetics which have been proven can influence wood properties. Various other recommendations exist, for example it could be more efficient for any future work on Douglas-fir to only take one diameter measurement per branch (maximising efficient use of time *in-situ*); however having two allows errors to be more easily noticed. Azimuth could be recorded for branching and timber properties if the study at hand calls for it. Swelling or shrinkage in the longitudinal direction has been noted to be of small magnitude (*e.g.* FPRL, 1967; Harding, 1988; Walker, 2006; Yang, 2009) and in the case of this study, was below the limit of detection for the apparatus. More accurate apparatus is required to measure this. For the structural (sawnwood) samples, a quantity still needs to be added to allow grading settings to be made for UK-grown Douglas-fir. With more time, there exists the possibility to demarcate each growth ring (cambial) on full-sized samples in the field prior to conversion, or alternatively transport the full log to a facility where demarcation can occur. With the clearwood samples, the full central cant should be taken to correlate with structural samples (bark-to-bark). This is imperative, given the radial variation.

The differences between clearwood properties and the structural mechanical properties is examined below, incorporating the radial differences (as predominantly described by age for this chapter) between juvenile wood (younger/earlier age) and mature wood (older/later age).

Clearwood	MOE		MOR	
	mean	SD	mean	SD
"inner"	6823 (N/mm^2)	1532	65 (N/mm^2)	14
"mid-range"	9591 (N/mm^2)	1639	87 (N/mm^2)	14
"outer"	10565 (N/mm^2)	1602	95 (N/mm^2)	12

Table 8-1. Showing defect-free samples and their radial groupings for MOE and MOR

Table 8-1 corroborates the radial variation in MOE and MOR with age. It appears that MOE is very similar in structural timber compared to defect-free (Table 8-2) but the difference in MOR is large. This is likely as a result of defects, predominantly knots (their size, angle and status) as discussed in chapter 6.

Structural	MOE		MOR	
	mean	SD	mean	SD
"inner"	6980 (N/mm^2)	1480	26 (N/mm^2)	6
"mid-range"	8160 (N/mm^2)	1560	30 (N/mm^2)	10
"outer"	10700 (N/mm^2)	2100	40 (N/mm^2)	12

Table 8-2. Showing full-sized structural samples and their radial groupings for MOE and MOR

The (age) groupings were chosen to best reflect structural groupings of "inner", "mid-range" and "outer" samples for clearwood properties. It is evident that cambial age appears to have a direct influence on the stiffness of Douglas-fir wood, regardless of the biological reason (*e.g.* wider rings in younger aged wood amounting to lower latewood proportion). Unsurprisingly given their correlation, the pattern is similar with the strength (MOR) of Douglas-fir clearwood.

While MFA was not studied, it should be discussed. Microfibrils (cellulose) are part of the reinforcing structures within a conifer cell wall and the angle refers to the helical winding deviation from the cell axis. As introduced in chapter 2, this will refer to the S_2 layer given its significance. The alternating MFA angles between the S_1-S_2-S_3 layers is what gives plant cell walls the necessary axial stiffness and collapse resistance required for upright growth (*e.g.* Donaldson, 2008) in conifers. Barnett and Bonham (2004) and Donaldson (2008) review MFA in detail.

There are various methods of measuring MFA (including iodine precipitation where crystallised iodine fills between the microfibrils to reveal orientation, polarised light microscopy, scanning electron microscopy, automated scanning X-ray diffractometry and near-infrared spectroscopy). These are all time-consuming at various levels and the former are done on such small scales (single tracheid or single cell wall) that detailed, replicated analysis which would include within-tree and between-tree samples was not logistically feasible for this study.

Some studies show density is the most significant in predicting the stiffness of coniferous wood (*e.g*. Cown *et al.*, 2004) while others show it to be MFA (*e.g*. Cave and Walker, 1994; Evans and Ilic, 2001). Usually however, a combination of both MFA and density predict stiffness more highly. MFA is generally less significant in predicting MOR compared to density. This has already been corroborated in UK-grown Douglas-fir. Bawcombe (2013) found that (at whole tree level) flexural MOE was more strongly associated with variations in MFA than density, but MOR (both flexural and compressive) were more strongly associated with density variations. Bawcombe (2013) also found a larger MFA immediately adjacent to the pith, with rates of change decreasing significantly in later years of growth (mature wood had higher density and lower MFA for all trees). Auty (2010) also shows trend in UK-grown Scots pine (MOE was strongly correlated with MFA, while density had a strong influence on MOE and MOR in particular). McLean (2008) found a radial tend in UK-grown Sitka spruce where MFA decreased from pith to bark (*i.e*. a "better" angle in the mature wood) which is evidenced in other studies for other species and areas (*e.g*. Megraw, 1986; Barnett and Bonham, 2004, Auty, 2010). It is therefore very likely that MFA would vary from pith to bark in this study.

A plausible biological explanation for a high MFA in the juvenile wood (or certainly the first few rings) is to allow flexibility of the young seedling, before changing to a lower MFA (less flexible, more rigid) for mature wood, which concern would be to physically cope with weight of the large(r) crown (*e.g*. Timmel, 1986; Lindstom *et al.*, 1998, Dinwoodie, 2000). As shown throughout, the criteria for high quality structural timber are high strength and stiffness. These are in turn affected by inherent wood properties including slope of grain, density, knottiness, and MFA (Alteyrac *et al.*, 2006a; Jozsa and Middleton, 1994; Megraw, 1985; Panshin and de Zeeuw, 1980; Walker and Butterfield, 1996; Zhang, 1997) which are affected by changes in management or environment.

Spacing (distance between each plant at a given phase) or stocking density (the amount of stems for a given area) are deemed to be one of the most important (silvicultural) factors for determining conifer timber quality (*e.g.* Brazier and Mobbs, 1993; Macdonald and Hubert, 2002; Moore *et al.*, 2009[a]; Smith and Reukema, 1986). A tree (or stand) is directly affected by the stocking density throughout its entire life, as the space available for a tree to utilize will affect its stem and crown characteristics. At wider initial spacings the diameter growth is faster as space is more available during the juvenile phase due to reduced within-stand competition (*e.g.* Long *et al.*, 2004; Harrington *et al.*, 2009, Auty, 2011) before canopy closure. As introduced in chapter 2, there are three main ways of controlling spacing (at establishment; respacing of normally stocked stands before canopy closure and thinning of older stands).

From a biological viewpoint, thinning will have a similar effect on the tree as spacing. That is, the amount of space available (hence light and water uptake) will be affected. Thinning regime strongly affects stand productivity (Bartelink, 1998), hence should be viewed as essential silvicultural practice despite certain policies of ‘no-thin’ becoming more common for financial reasons (*e.g.* Grayson, 1981). Yet these shorter-term economic alternatives (*e.g.* delaying thinning) can cause stand instability (Rollinson, 1985; Cameron, 2002). There are arguments for and against thinning ranging from its importance in favouring the best stems to decreasing latewood percentage or increasing stem sway, as well as reducing stand density and increasing girth (*e.g.* Erickson and Harrison, 1974; Barger and Ffolliott 1976; Brazier 1977; Cown and McConchie 1981; Timell 1986; Telewski, 1995; Reader and Kurmes, 1996; Cameron, 2001; Wang *et al.,* 2001; Cameron *et al.,* 2005; Carter *et al.,* 2005; Briggs *et al.*, 2007; Cameron and Thomas, 2008). Delayed thinning can render a Douglas-fir crop unduly susceptible to windthrow (Forestry Handbook 6, 1989).

Shorter rotations will generally yield less volume. However, while some short rotations (<50 years) can yield high rates of wood production, the quality of that wood can be low (Senft *et al.*, 1985; Maguire *et al.*, 1991) as well as ecologically low in quality (*e.g.* Busing and Garman, 2002). Alongside silvicultural regime, the value of increasing rotation length is a way to improve mechanical properties and structural yields (Bendtsen and Senft, 1986,) mainly through their effect on tree growth and wood formation and the proportion of juvenile wood, as the proportion of juvenile wood to mature wood tends to increase with faster growth and shorter rotations (*e.g.* Clark III *et al.*, 1996; Larson *et al.*, 2001; Burdon *et al.*, 2004; Eriksson *et al.*, 2006 Lasserre *et al.*, 2009; Auty, 2011). Longer rotations would be expected to positively influence structural timber yields in grading (Duchesne, 2006). Clark III *et al.* (1996) argue that there are economic benefits of longer rotations, yet Moore *et al.* (2012) agree that while longer rotations will result in timber with improved mechanical properties, they suggest it is unlikely to be economic. While silviculture affects tree growth and subsequent timber properties, so too does the physical environment as Douglas-fir has certain requirements to flourish.

Variation in timber (*i.e.* juvenile zone) arises largely from these anthropological influences, *e.g.* spacing and rotation length (Clark III *et al.,* 1996). Given the likelihood of UK-timber quality decline as old growth forests and slower-grown, naturally regenerated stands have been largely replaced by faster-grown (or quicker rotated) and wider-spaced stands, the wood properties influenced by such will undoubtedly also be influenced (Zobel and Van Buijtenen, 1989; Petty *et al.,* 1990; Kennedy, 1995; Kretschmann, 2008) therefore the impetus for maximising high-quality timber is paramount. It is sugested that Douglas-fir be planted close together (less than 2 m) and be thinned frequently and on time (not delayed). Any climate shift towards higher accumulated average temperatures will likely affect Douglas-fir timber for the better, as drier, warmer summers will likely increase latewood percentage which (as discussed earlier) lends itself to higher strength and stiffness.

8.5 Conclusion

Douglas-fir is a highly-valued timber species in the UK that is likely to be more suitable in a range of sites with a forecast increased climate scenario. Stronger, stiffer and denser than the most commercially important timber species currently grown (Sitka spruce) in the UK, Douglas-fir has the potential to supply the end-user with a durable and at a minimum, comparably-graded timber material. While anecdotally thought of to require a more nutrient rich medium than Sitka spruce, the soils located at each of the five sites tested here ranged from podzols to sandy brown earths. The results here have allowed a better understanding of Douglas-fir quality and growth in the UK and predictions of its variation. While Douglas-fir is not a potential “like for like” (in grading terms) replacement for imported C24 pine and spruce, it does grade well with acoustic grading machines meaning it has potential for small volume grading by sawmills using portable grading machines (*e.g.* Brookhuis MTG). Douglas-fir has the ability to continue producing quality timber for the UK in the future.

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10 Appendices

10.1 Soil

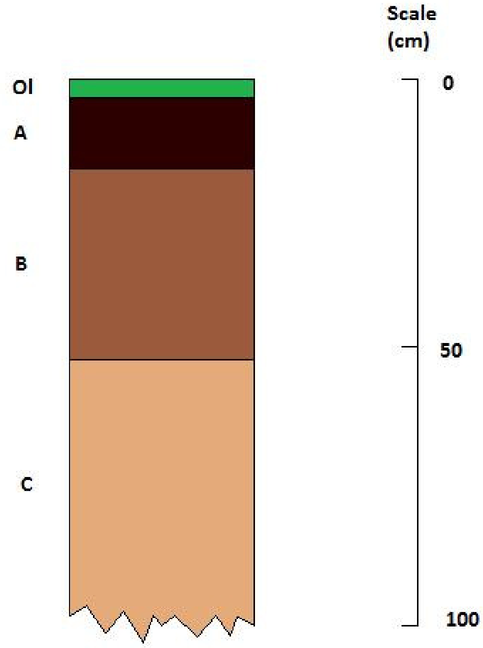
This soil horizon is a representative example of the dug pits as explained in text.

A horizon consists of humified organic matter incorporated into the mineral soil to give a dark brown colour

B horizon is distinguished from underlying **C** horizon by a richer brown colour due to weathering and the residual accumulation of iron oxides

A and **B** horizons have crumb or small blocky structure of friable consistence

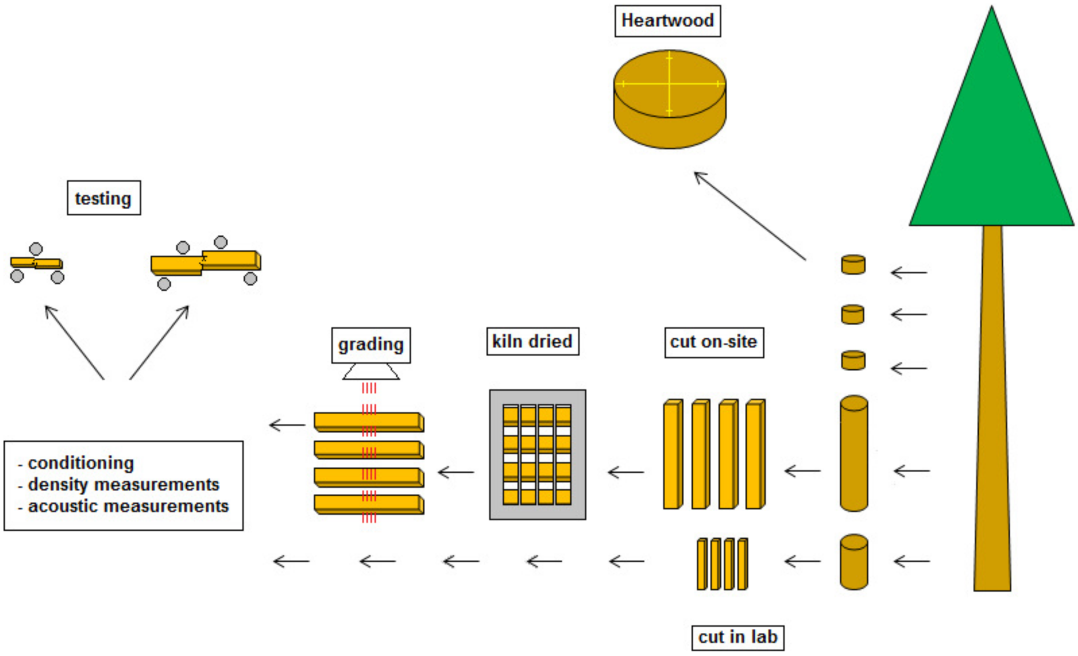
C horizon may either be unconsolidated and friable or very stony merging into bedrock or indurated material



Showing a representative 1 m soil horizon (brown earth), indicating various layers.

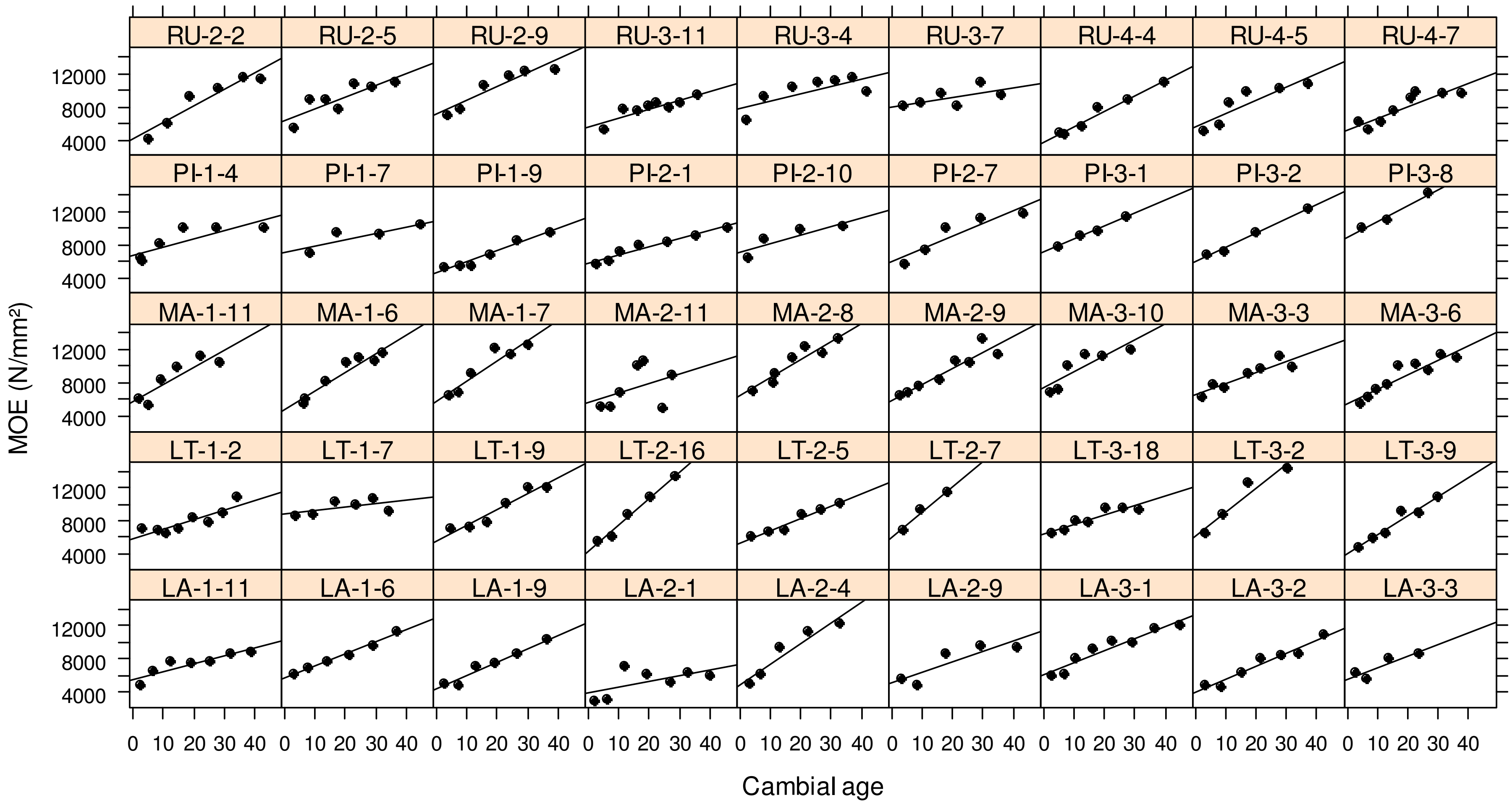
10.2 Working method

The following figure is a representation of workflow only, incorporating section 3.3 and 3.4 (Structural batten and clearwood preparation).

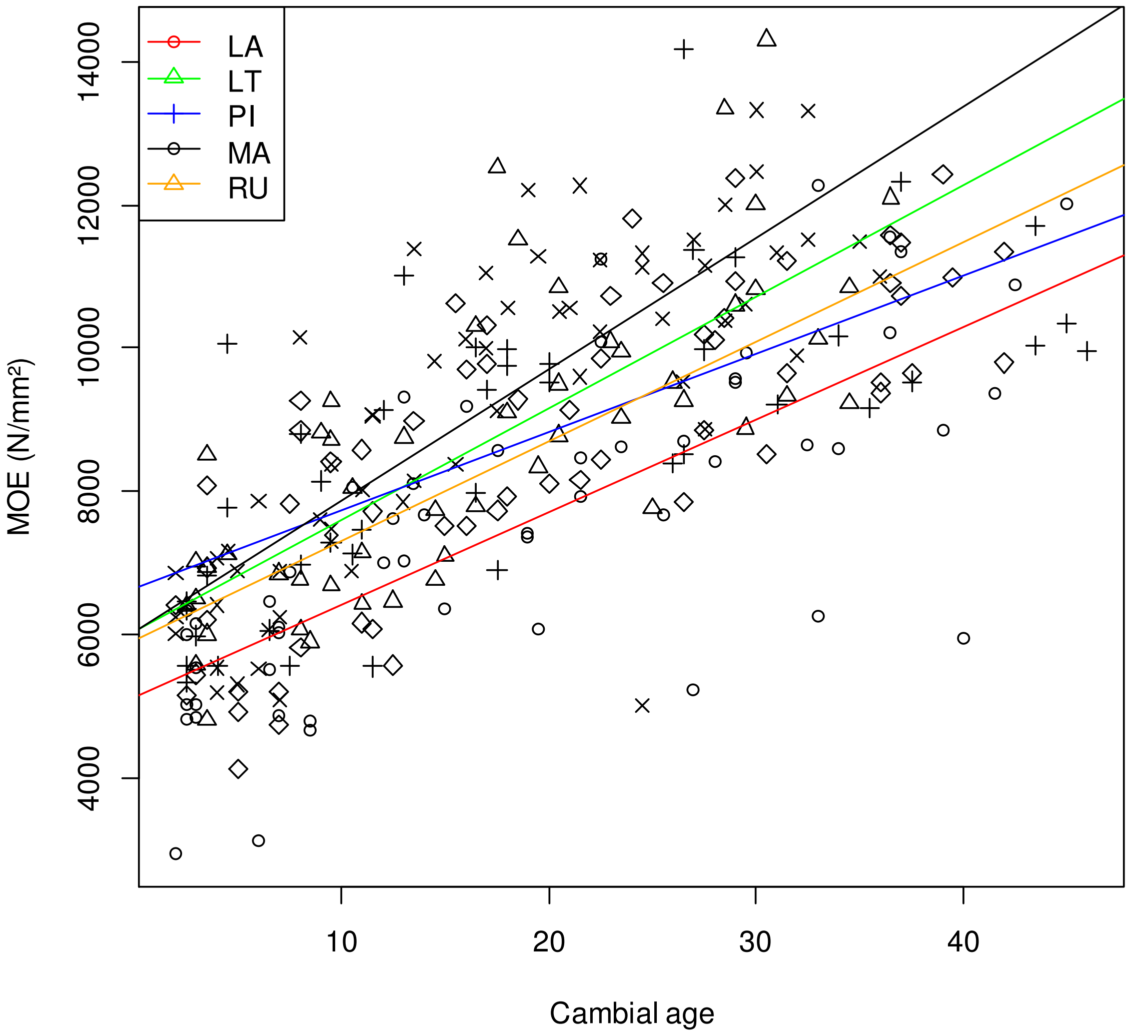


10.3 Clearwood chapter

The clearwood chapter is concentrated on age-related trends in Douglas-fir for the average tree and as a consequence differences in sites were not applicable to the main text. However, it is of interest given that the sites were all different in some way. The MOE and MOR are given below for every tree individually, and also every tree within a site(s).

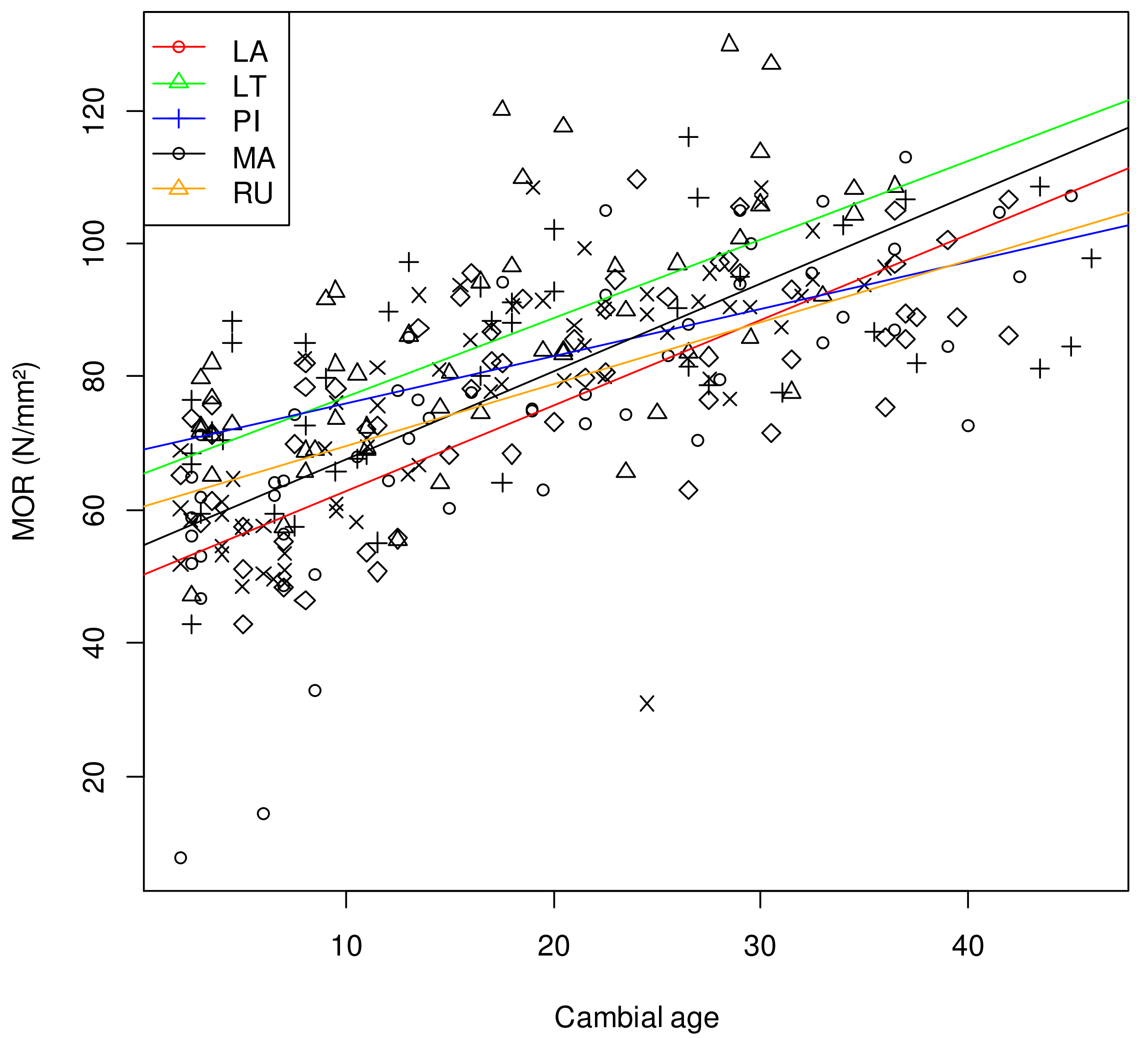


Cambial age for each tree from the five sites (LA, LT, MA, PI, RU). Most are predominantly linear in appearance (despite the asymptotic nature) but several could be construed as non-linear. All individual trees show a general increase in cambial age.



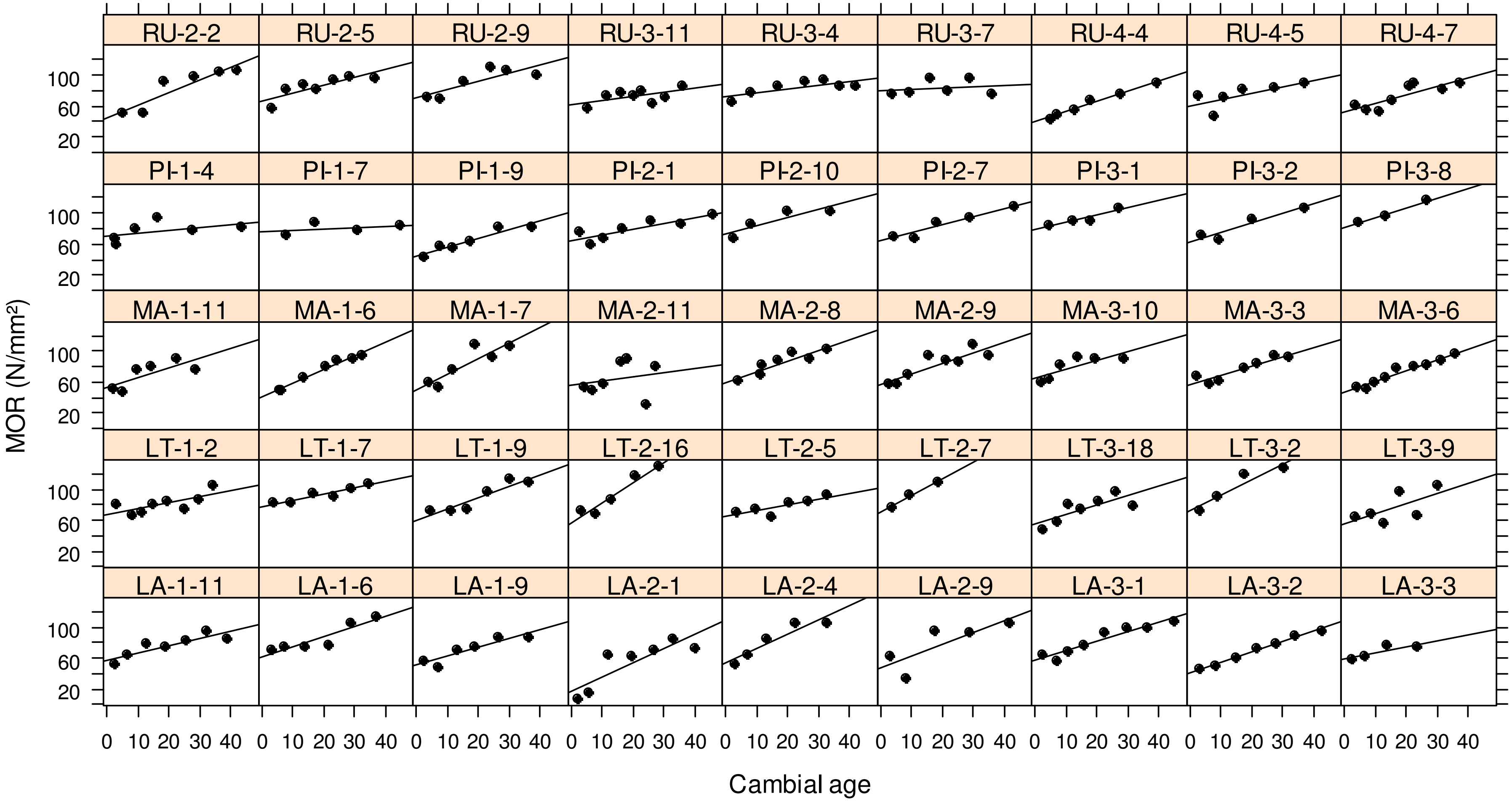
Showing the change in MOE with increased cambial age, using individual line of best fits for each site.

For MOE, it appears that the five different sites (PI, LA, LT, MA, RU) all have different intercepts (6640, 5120, 6060, 6020 and 5900 respectively) and different coefficients (R^2) of 0.48, 0.54, 0.56, 0.64 and 0.61 respectively, $p<0.001$ for each of the five sites.



Showing the intercepts of MOR for each site. A cambial age of 0 does not exist but for a cambial age of 1, the intercept is not zero as evidenced. The slope of the line changes for each site, with PI being the most consistent across the age range (highest intercept, lowest at the top end of scale). MOR does increase as the cambial age increases for all sites.

For MOR, the 5 different sites (PI, LA, LT, MA, RU) all have statistically different intercepts (68, 50, 65, 54 and 60 respectively) and different R^2 values, of 0.34, 0.57, 0.41, 0.55 and 0.45 respectively.



Cambial age for each tree from the five sites (LA, LT, MA, PI, RU). Most are predominantly linear in appearance but several could be construed as non-linear. MOR for all individual trees shows a general increase in cambial age

10.4 Site variables for branching chapter

The variables are used in chapter 6 for branching habits are not based on site, but all sample trees (i.e. a “mean-tree”). However, site differences are of some interest and the tree-level and branch-level attributes are given below.

	LT		LA		PI		Overall		Shapiro-Wilk test
Age	45		57		58		53.5	[5.9]	w = 0.625, p < 0.001
							{45.0	58.0}	
DBH	41	[7.9]	37.6	[6.4]	34.9	[6.0]	37.6	[7.3]	w = 0.9468, p < 0.001
	{25.3	50.4}	{27.1	46.9}	{26.5	47.6}	{25.3	50.4}	
CL2	15.6	[2.8]	12.1	[1.5]	11.9	[2.4]	13.1	[2.9]	w = 0.9147, p < 0.001
	{10.6	22.2}	{10.8	15.3}	{8.0	16.8}	{8	22.2}	
CR2	51	[6.2]	34.6	[5.0]	40.4	[5.3]	42.2	[8.5]	w = 0.9494, p < 0.001
	{43.1	66.4}	{27.9	44.7}	{30.2	48.3}	{27.9	66.4}	
LT	30.7	[2.8]	35.2	[2.9]	29.2	[2.7]	31.3	[3.8]	w = 0.9608, p < 0.001
	{24.6	35}	{30.6	68.8}	{25.65	34.76}	{24.6	38.8}	
HCB	14.9	[2.0]	23	[3.2]	17.3	[1.5]	18.1	[3.9]	w = 0.9285, p < 0.001
	{11.2	18.4}	{18.97	29.99}	{14	19.6}	{11.2	28.0}	
HD	76.7	[10.1]	95.4	[13.2]	84.7	[8.2]	85.0	[12.6]	w = 0.934, p < 0.001
	{66.3	97.2}	{79.5	118.6}	{73	96.7}	{66.3	118.6}	
HT	30.8	[2.7]	34.4	[3.4]	28.2	[2.9]	30.8	[3.9]	w = 0.9376, p < 0.001
	{25.1	35}	{29.2	38.5}	{25.5	34.3}	{25.1	38.5}	

A summary of tree-level attributes by site. Values shown are the mean, standard deviation [ ] and range of values { }. For abbreviations see table xx above. Only the largest branch per whorl was used for the Shapiro-Wilk test due to population size (despite none of the data being normally distributed). While the average-tree is examined it is useful to know the differences between sites for later discussion.

	LT		LA		PI		Overall		Shapiro-Wilk test
BHREL	0.6	[0.26]	0.56	[0.28]	0.58	[0.27]	0.58	[0.27]	w = 0.9449, p < 0.001
	{0.03	0.99}	{0.05	0.99}	{0.02	0.99}	{0.03	0.99}	
BHT	18.3	8.1	19.8	[10.3]	17	[8.03]	18.2	[8.79]	w = 0.9725, p < 0.001
	{0.63	34.8}	{2.00	38.3}	{0.67	34.5}	{ 0.63	38.3}	
D.whorl	12.4	[8.20]	15.6	[10.2]	12.2	[8.15]	13.2	[8.89]	w = 0.948, p < 0.001
	{0.20	31.8}	{0.29	60.6}	{0.18	50.0}	{ 0.18	60.6}	
HREL	0.58	[0.26]	0.54	[0.29]	0.57	[0.27]	0.56	[0.27]	w = 0.9421, p < 0.001
	{0.00	0.98}	{0.04	0.98}	{0.01	0.98}	{0.00	0.98}	
ins.angle	70.4	[13.5]	76.6	[14.6]	74	[12.2]	73.5	[13.5]	w = 0.9684, p < 0.001
	{15	115}	{15	140}	{10	115}	{10	140}	
max.bd	32.2	[12.9]	27.6	[9.44]	28.4	[9.37]	29.4	[10.8]	w = 0.9868, p < 0.001
	{6	78}	{7.0	57.5}	{5	70}	{5	78}	
mean.bd	21.2	[8.16]	18.7	[5.97]	18.3	[5.98]	19.3	[6.88]	w = 0.9845, p < 0.001
	{5.28	45.0}	{5.87	35.6}	{5	46.3}	{5	46.3}	
num.bd	8.56	[3.18]	7.8	[3.06]	7.93	[2.90]	8.11	[3.05]	w = 0.9581, p < 0.001
	{1	18}	{2	17}	{1	17}	{1	18}	
num.db	2.44	[3.38]	4.86	[4.60]	3.62	[3.64]	3.58	[3.96]	w = 0.8503, p < 0.001
	{0	14}	{0	17}	{0	15}	{1	17}	
num.lb	6.15	[4.84]	2.94	[3.79]	4.31	[4.19]	4.53	[4.49]	w = 0.8534, p < 0.001
	{0	18}	{0	16}	{0	14}	{0	18}	
rel.bd	0.67	[0.26]	0.69	[0.24]	0.66	[0.27]	0.67	[0.26]	**
	{0.11	1.00}	{0.12	1.00}	{0.11	1}	{0.11	1}	

Again, a summary on branch-level attributes by site. Values shown are the mean, standard deviation [ ] and range of values { }. For abbreviations see table 3.1. Only the largest branch per whorl was used for the Shapiro-Wilk test (hence n/a for **) due to population size