Potential of noble fir, Norway spruce, western red cedar and western hemlock grown for timber production in Great Britain

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Abstract

The limited range of commercial timber species in Great Britain has led the forestry sector to consider wider planting of other species. This research addresses wood properties, particularly relevant to structural timber, of noble fir, Norway spruce, western red cedar and western hemlock in Great Britain. Sampling covered three regions to get a representative sample for the country. Bending stiffness, bending strength, density and twist distortion from drying were assessed. The results showed high yields of C16 for all these species, with Norway spruce and western hemlock performing comparatively well to typical British-grown Sitka spruce. Within this dataset, variation of mechanical properties within trees was more important than differences between species. Strength and stiffness increased with age, whereas density followed different trends in the inner and outerwood. The three properties were modelled based on ring number. The use of acoustic techniques to assess the mechanical properties of wood (in particular stiffness), was investigated in clears, sawn timber, logs and trees. The best results were found combining density with acoustic velocity in sawn timber. The use of acoustic techniques in standing trees was more reliable measuring distances of two or three metres, rather than the commonly used one metre; most likely due to a change in the wave propagation. Tree architecture was studied for timber production and quality. Noble fir described the highest merchantable taper profile. Branchiness varied importantly with height in the stem, and models were built for number, diameter and angle of branches. Western red cedar and western hemlock had fewer but thicker branches compared to noble fir and Norway spruce. Future work should produce grading machine settings and address the variation of timber quality and merchantability under different silvicultural regimes. This thesis concludes that the four species investigated can contribute to diversity the timber industry in Great Britain.

Acknowledgements

It is not the typical way of starting this section, but I would like to begin these lines dedicating this thesis to my parents. They always gave me all the opportunities they did not have, and supported me along these years.

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Author's declaration

I, the author, declare that this thesis is my own, except where assistance has been acknowledged or stated otherwise. This work has not been submitted for any other degree or qualification.

David Gil-Moreno, March 2018.

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Abbreviations and acronyms

A list of abbreviations used along this thesis is given below. Specific ones are given in each chapter.

ANOVA: Analysis of variance
CoV: Coefficient of Variation
dbh: diameter at breast height, measured at 1.3 m above ground level
Density$_{384}$: determined on small defect-free prisms according to EN 408
Density$_{timber}$: density of a structural-size piece
G.B.: Great Britain (meaning here England, Wales and Scotland)
GLM: General Linear Model
LOESS: locally weighted smoothing regression method
m.c.: moisture content.
mknot: marginal knot index.
MOE: Bending stiffness
MOE$_C$: Bending stiffness in small clears
MOE$_{dyn}$: dynamic modulus of elasticity, measured acoustically.
MOE$_{sta}$: static modulus of elasticity, measured destructively in bending
MOR: Bending strength
MOR$_C$: Bending strength in small clears
NF: noble fir (*Abies procera* Rehd.)
NS: Norway spruce (*Picea abies* (L.) H. Karst.)
RC: western red cedar (*Thuja plicata* Don ex D.Don)
tknot: total knot ratio index.
TOF: "time-of-flight". Time delay for a stress wave to travel a certain distance.
WH: western hemlock (*Tsuga* heterophylla (Raf.) Sarg.
y/o: years old

Glossary

Basic grade: highest strength class achieved by 100% of the population.

Corewood: inner part of the tree near the pith, typically of low mechanical properties (sometimes called juvenile wood).

Crown ratio (CR): crown length to tree length ratio.

Noble fir (*Abies procera* Rehd.)

Norway spruce (*Picea abies* (L.) H. Karst.)

Optimum grading: hypothetical grading with a perfect grading machine (i.e. using the results from the destructive tests). In this thesis, only the case of a single strength class, with reject, is considered.

Perfect grading machine: hypothetical machine with full, perfect, knowledge of the wood properties of timber to grade.

Radial position: Referred to the position of a structural piece or clear within the radial transect.

Radial transect: Referred to the cutting pattern used to process the logs, centring in the pith.

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.)

Western red cedar (*Thuja plicata* Don ex D.Don)

Chapter 1. Introduction and literature review

1.1 Introduction

Trees change during their lives. They do so in response to, and as a consequence of, growth. This response varies from species to species, depending on factors like genetics, the environment in which they grow, and forest management. Wood quality from planted trees differs from those growing in its natural environment. Therefore, wood properties, growth and tree architecture (taper, straightness, branches, etc.) are interrelated, and growers need to know how they change under different scenarios Those changes can be observed externally (height, diameter, taper, branches distribution, etc.), but they are accompanied by necessary internal changes in wood cells that allow adaptation to both the external influences (biotic and abiotic) and internal needs. As a result, trees produce wood with different characteristics, varying in strength, density, colour, durability, calorific value, etc., that will make it more suitable for certain end uses than others.

Softwoods trees growing in even aged planted forest present important differences between the inner (corewood) and the outerwood, with wood near the pith characterised by large microfibril angle and spiral grain, thin cell walls and short tracheids (Zobel and Sprague, 2012) in comparison to the outerwood. These characteristics influence the suitability of wood for structural purposes.

The three main properties for structural wood quality are: bending stiffness, bending strength and density. The two first are mechanical properties whereas density is a physical property. The three properties change within trees as they adapt to their growing requirements. For example, in hard pines the wood near the pith is of low density and increases outwards, whereas in other species like spruce or hemlock density is high near the pith, decreasing for few years before increasing outwards.

Understanding how they vary it is important as it will help to determine planting densities, rotation ages, treatments and wood quality. Larger volumes will supply a greater amount of wood resources, but not necessarily larger amounts of structural timber. Fast growth is associated with a higher presence of corewood (Kliger et al., 1998; Moya et al., 2013). Longer rotations improve mechanical properties and lessen overall distortion, but shorter rotations produce more regular incomes.

In addition to quantity, the forest wood industry is interested in anticipating the quality of stands. For example, identifying stands that meet the appropriate characteristics in order to produce wood for timber construction, reduces the cost of grading rejects after processing logs and drying sawn timber. Acoustic tools allow estimation of wood quality, principally stiffness. They provide reliable results on sawn timber, but less so when applied to logs and standing trees. Nevertheless the application on trees is of particular interest as it helps in making decisions about the most appropriate end products of trees. However, measurements on trees are not fully understood, which can lead to the wrong allocation of material.

As well as wood properties, stem straightness is another important factor in defining the suitability of timber for structural applications. It determines the length of the sawnwood available per log, and affects mechanical properties as it increases deviations in the grain angle (Macdonald and Hubert, 2002), which may led to either rejecting the logs for sawing or changing the cutting pattern with lower conversion. In Great Britain (G.B.) it was identified for the industry as the most important stem feature for grading the quality of spruce logs (Methley, 1998). More typically for research purposes, straightness is visually assessed on the bottom six meters of the tree.

The full length of trees determines the volume available, and also influences the end use. In G.B., an upper diameter above 14 cm over bark is the minimum size used for sawlogs (Forestry Commission, 2017b), between 12 and 14 cm is for pallet wood, and up to 7 cm for chip/pulpwood and biomass. Changes in sawmill technology, in merchantability standards, and in the requirements from the industry as they adapt to new end-use products, suggests the need of models for prediction of merchantability capable of adapting to varying merchantable limits. In order to estimate the sawlog volume of trees in the four species studied, the construction of taper functions or tree profile models describing the stem architecture of the four species was aimed.

The British forest industry has been mostly built around a few species, particularly Sitka spruce (*Picea sitchensis* (Bong.) Carr) for structural applications. Recent pests and diseases, and climate change have raised concerns of the reliance on those few species to provide timber in G.B. This research undertook, firstly and most importantly, the study of timber growth and wood properties of noble fir (*Abies procera* Rehd.), Norway spruce (*Picea abies* (L.) H. Karst.), western red cedar (*Thuja plicata* Don ex D.Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) grown in G.B. These are species with high productions of timber for construction applications in their native lands. While it is possible to grow these species in G.B. there is little information about the wood quality, merchantability and therefore their commercial viability for structural purposes, or how they would compare to other species more widely planted. It is therefore beneficial to the forest wood industry within G.B. to build up knowledge of the growth and potential characteristics of additional home grown species, so that future interventions can be planned based on reliable information.

1.2 Objectives / Aims of the study

This research performed an assessment of noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. The present study can be considered as the first of its kind on structural-size timber in G.B. for any of these four species. Experimental work was carried out in the forest, log yard and laboratory, and focused on the important timber properties of: bending and dynamic stiffness, bending strength, density, twist distortion, knots, branches and volume.

The study of these four species was a requirement of the funded research project, which specifically included:

- Performance and distortion of structural-size timber and clearwood from the four species.

  This is addressed investigating the wood properties (bending stiffness, bending strength and density) that determine the grading of timber. They are described both in structural-size timber and clearwood. The variation due to the hierarchical data structure is analysed. The study also aims to describe knots and twist distortion in timber, and investigate empirical models in clearwood that describe the variation of wood properties with age.

- Stem form and branching characteristics of the four species.

  On the one hand, the research investigates those variables defining the volume available for sawlogs, the straightness and taper models. On the other hand, tree architecture variables related to timber quality such as branchiness, or potentially correlated like crown and slenderness are also described.

- Investigation of improved acoustic methods for measuring standing tree stiffness.

  The research compares the performance of different acoustic techniques to measure wood properties, and investigates the propagation of a sound wave in a standing tree as a potential cause of the discrepancy in the most common measurements. The effect of knots in the mechanical properties is also studied.

These aims are addressed within this thesis as follows:

- The wood properties
  - In structural-size timber, Chapter 3
    - Bending stiffness, bending strength and density.
    - Twist as drying distortion.
  - In clearwood samples, Chapter 4
    - Variation of bending stiffness, bending strength and density with age.
- The use of non-destructive techniques, Chapter 5
  - acoustic techniques,
    - on small clears, structural sized timber, logs and trees.
    - at tree, plot, site and species level.

        - the wave behaviour in standing trees and the implications.
    - measurement of knots
- Tree architecture and merchantability, Chapter 6
    - Taper
    - Branch characteristics

The present chapter contains an introductory literature review, and Chapters 3 to 6 contain additional reviews of the relevant literature.

Together, these chapters will allow this thesis to make recommendations about the use of these four species. In addition, the research into non-destructive techniques will improve our understanding of the shortcomings of acoustic techniques, and will help to examine the timber quality of other species.

1.3 Background to this study

The United Kingdom was the second largest net importer of forest wood in 2015, behind China (Forestry Commission, 2017c). Construction has been consuming more than 60% of the sawn softwood used in the UK, and more than 80% of the imported softwood (Moore, 2015). In terms of British grown timber, Sitka spruce (*Picea sitchensis* (Bong.) Carr) is the main commercial tree species, occupying 51% of the conifer area and standing conifer volume (Forestry Commission, 2017a). In terms of harvesting, the total volume of softwood harvested in 2009 was 8.1 million cubic metres, 60% of which was Sitka spruce (Moore, 2011). These figures are even more important in Scotland, where Sitka spruce accounts for 62% of the standing conifer volume, followed by Scots pine (*Pinus sylvestris* L.) with just 15%.

Recent outbreaks of pest and diseases in G.B. have raised concerns about the reliance on a Sitka spruce monoculture as well as the limited range of species providing a reserve of timber for a higher variety of end uses. Suitability of the species is also a main concern for timber growers in the scenario of climate change. Species typically have different wood properties in their native lands to those produced in planted forests. Thus, it is necessary to study timber grown under British representative conditions in order to know the real capabilities of the species in G.B.

The Forestry Commission established forests of a wide range of species in the first half of the past century, and already in 1967 stated: "*it was decided to undertake a comprehensive evaluation of the status and potential of the four most important "minor species" in British forestry, Western hemlock, Western red cedar, Grand fir and Noble fir*" (Aldous et al., 1974). Table 1-1 reports the surface planted for the three pertinent species before 1950. At that time, Norway spruce was considered a major species, together with Sitka spruce, Corsican pine (*Pinus nigra* ssp. *laricio* (Poir.) Maire), Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Japanese larch (*Larix* kaempferi (Lamb.) Carriére).

Table 1-1. Area (ha) of minor species in G.B. planted before 1950 (Aldous et al., 1974)

Country	**Noble fir**	**W. red cedar**	**W. hemlock**
	Forestry Commission Plantations		
England	12	61	323
Wales	14	44	140
Scotland	88	42	220
	Privately owned Plantations		
England	40	129	50
Wales	2	-	-
Scotland	68	29	38

The information derived from these was mainly concerned with growth, and produced very limited evidence about the commercially important wood properties of the timber. A report reprinted in 2002 (Lavers, 2002), of which the first edition dates from 1967, included a small amount of data from the testing of small clear pieces grown in the UK, and very few data from structural-size pieces. The values were typically based on a very low number of trees and there was no information on the age or the growing region. In an attempt to clarify the source of the data, it was possible to access the content of 52 folders of the Forest Products Research Laboratory (FPRL), which merged into the Building Research Establishment in 1972, dating back to the 1950s. The files contained the results from timber testing of a wide range of species throughout the UK. Some of them matched with the results published in Lavers (2002), but some others did not find a correspondence. Many publications (Desch and

Dinwoodie, 1996; Dinwoodie, 2000; Gardiner et al., 2011; Moore, 2011) cite this report to indicate the wood properties of different species grown in the UK, but the values should only be used as a rough guide. Nevertheless, based on those data from small clears, there are estimations for structural-size timber (Ramsay and Macdonald, 2013). These are founded on a number of assumptions (about sampling representativeness and differences between small clear and structural size), which were the best guesses based on literature review and previous experience with other British timber. The assumptions were not tested, which is not sufficient for a useful determination of physical and mechanical properties for structural-size timber.

With this purpose, the Forestry Commission aimed to provide a preview into the growth and properties of some conifer species that currently form a minor component of the British forest resource. Presently, Norway spruce is processed in combination with Sitka spruce. The species mix is recognised in the European standard EN 14081, where it is referred to as “British spruce”. In the UK and Ireland this species combination is comprised of approximately 90% of Sitka spruce, with the remaining 10% consisting of Norway spruce. They both have similar wood properties, and although Norway spruce may perform better than Sitka, there was no evidence based on structural-size pieces supporting that. One of the first aims of this thesis is to study whether Norway spruce grown in G.B. has the potential to produce timber outperforming the structural properties of British-grown Sitka spruce.

The main value use of the British spruce resource is sawn timber for use in construction, with packaging and fencing as market with lower quality requirements (Moore, 2011). Norway spruce occupies 61,000 ha in G.B. (Forestry Commission, 2014). Reports from the Forestry Commission include the other three species within the “other species” group, with a total of 40 thousand ha. Inventory data back to 1995 (Wilson, 2011) recorded for Scotland 1,422 ha for noble fir, 32,968 ha for Norway spruce, 37 ha for western red cedar and 1,467 ha for western hemlock. Table 1-2 reports the public surface by countries.

Table 1-2. Public surfaces (ha) by countries in G.B. of the studied conifers (Forestry Commission, 2017d).

Species	Primary species (%)[1]	Surface (ha)			
		Noble fir	Norway spruce	Western red cedar	Western hemlock
England	100%	18	3126	117	347
	100% - ≥80%	7	1649	188	460
	<80%	31	2434	466	879
Wales	100%	248	2231	74	165
	100% - ≥80%	78	1823	56	245
	<80%	153	1743	149	395
Scotland	100%	172	4463	24	125
	100% - ≥80%	105	2608	18	92
	<80%	243	3558	20	242
Total		1054	23634	1111	2950

[1] Primary species refers to the percentage of the species within a subcompartment.

Noble fir, western red cedar and western hemlock are native to west coast of north USA and Canada. Noble fir is typically used in its native land for construction, paper (pulpwood) and plywood. In G.B. it is used as Christmas tree because it has a poor reputation due to the perceived risk of drought crack. Western red cedar is not a true cedar (from genus *Cedrus*), and in North America it can be referred to as western redcedar. This thesis referred to it as western red cedar for consistency with previous British literature. It stands out for its excellent durability and dimensional stability, which makes it a formidable material for outdoor uses, facades and even houseboats. This feature is given by the chemical characteristics of the heartwood, that gives an attractive colour, scent and decay resistance to the wood. In G.B. it is mostly used for decking, cladding, glasshouse framing and beehive manufacture. Western hemlock timber is also used in its native land in construction, roof decking and plywood. It is seen as one of the most useful tree species to be planted for commercial purposes in G.B. (Cameron and Mason, 2013). Norway spruce is native to Scandinavia, and central Europe. The main use in G.B., as part of the British spruce mix, is sawn into timber for use in construction, with packaging and fencing as market for lower quality requirements.

1.4 Wood properties variation and use in construction.

The concept of wood quality depends on the intended end-use. Structural wood quality is based on three key wood properties, namely: bending stiffness, bending strength and density.

- Bending Stiffness, commonly referred to as modulus of elasticity and abbreviated as MOE: It is a measure of the capacity of a material, in this case timber, to resist deflection under certain load.
- Bending Strength, commonly referred to as modulus of rupture and abbreviated as MOR: It is a measure of the maximum load a material can resist before breaking.
- Density: It is the ratio mass (kg) to volume (m^3) at a specified moisture content, and it is used as a proxy for strength in, for example, calculation of connections made with screws and nails. It is low density that is the concern.

In order for engineers to design buildings safely, the three properties are characterised by performance declaration (usually by reference to a strength class), which the actual properties of the timber must equal or exceed. Although mechanical properties can be studied in different directions and planes, typically only bending stiffness (MOE) and bending strength (MOR) are measured, and the rest of mechanical properties (compression, shear, tensile, etc.) are estimated from those (by the equations in EN 384). Density is the most common physical property investigated for structural applications.

The MOE is measured within a range in which the load-deflect relationship is linear (proportional). With increasing load, the material eventually fails at the maximum load (Figure 1-1), which correspond with the MOR load.

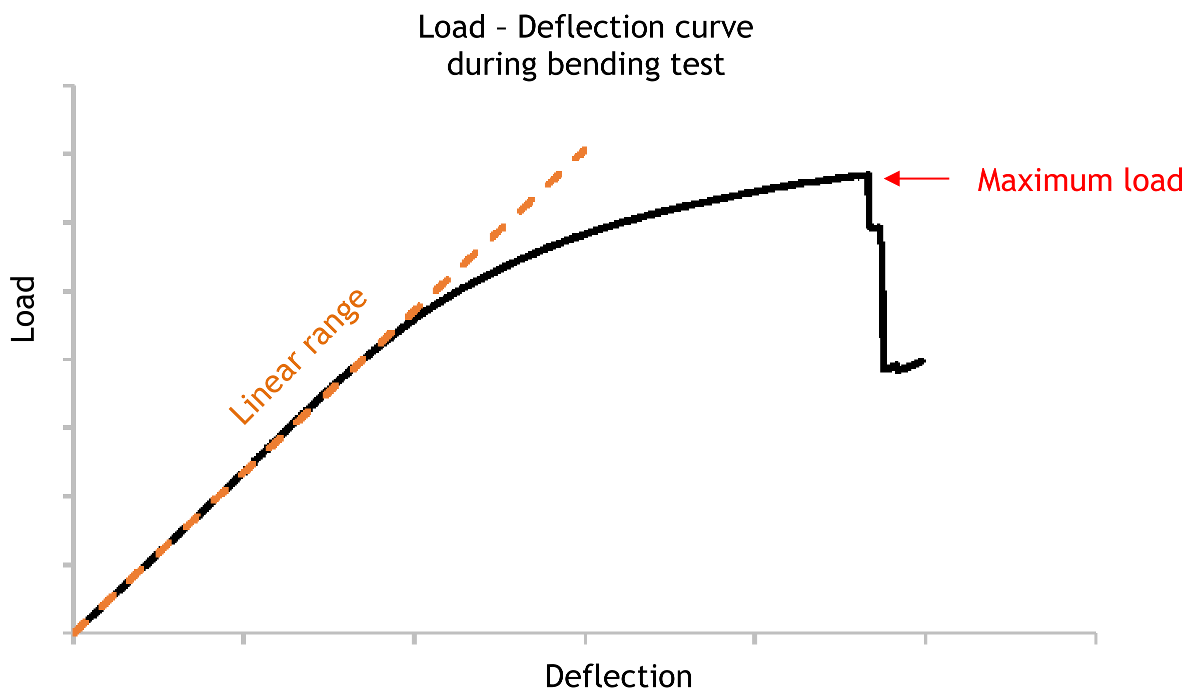


Figure 1-1. Theoretical mechanical behaviour of wood under a load test.

The three properties differ among species, and within them from site to site, within sites, with age, between trees and within trees in response to growth requirements (Burdon et al., 2004; Jyske et al., 2008; Lachenbruch et al., 2011). Regarding the influence of the different sources of variation, Lavers (2002) stated that "*trees are generally of greater significance than the differences in material from different parts of the same tree*". But more recently, a study on Sitka spruce (Moore et al., 2013) found a larger variation in the mechanical properties within trees, but with tree-to-tree variation in density still being greater.

Besides those sources of variation, mechanical properties and density vary with moisture content (m.c.), with stiffness increasing once wood dries below the fibre saturation point, and density decreasing. In order to make wood properties values comparable they must be accompanied by the m.c. at which they were measured. Commonly, the reference m.c. for the wood properties is 12%.

On the contrary, below the fibre saturation point drying distortion may occur. There are several types, but this research only studied twist, because it is the most problematic type of drying distortion for timber construction. It leaves a piece that cannot easily be straightened through nailing or screwing. It also causes problems with glue-laminated timber as the majority of pieces twist in the same direction, and so it is not possible to flip them around to balance one another.

The mentioned variability of wood properties can make certain wood unsuitable for a particular end use. Grading allows the allocation of timber to groups based on bending stiffness, bending strength and density. In Europe, structural timber is typically assigned to groups called strength classes. These classes allow safe design with timber by specifying minimum characteristic values of MOE, MOR and density at 12% moisture content. The three properties need to achieve the requirements of the strength class to which timber is graded. For any particular population of timber and growth area, one of the properties will be restraining the overall grading. Overall, British Spruce typically attains strength class C16 (Moore et al., 2013).

It is possible to grade populations of timber comprising of different species from an identifiable geographical origin, as long as their wood properties are similar and the species grade similarly well. In addition to the mentioned British spruce, the main species combinations in G.B. for home-grown timber are "British pine" (*Pinus sylvestris* and *P. nigra*) and "Larch" (*Larix decidua, L. kaempferi* and *L. x eurolepsis*). In the U.S.A. the species combinations are known as Marketing Categories. The three American native species investigated in this thesis are often graded together in their native lands. The combination "Hem-fir" is used for structural grades. It groups western hemlock and noble fir as well as four other firs: California red fir (*Abies magnifica*), grand fir (*Abies* grandis), Pacific silver fir (*Abies amabilis*), and white fir (*Abies concolor*). Western red cedar is generally graded as an individual species, and less often with other western cedars: incense cedar (*Libocedrus decurrens*), Port Orford cedar (*Chamaecyparis lawsoniana*) and Alaskan cedar (*Chamaecyparis nootkatensis*).

Depending on the intended use, the knowledge on the evolution of wood properties with age (i.e. radial variation), allow to examine possible scenarios regarding timber quality for different rotation lengths in production forests. Wood properties change radially as the trees grow wood outwards. In softwoods MOE and MOR typically increase from the pith outwards. Studies in western hemlock (Kennedy, 1995) and Scots pine (Auty et al., 2016) showed that the MOE values from the pith can be doubled in forty years, with MOR increasing at a more moderate rate in western hemlock (38%), and up to 66% in Scots pine. Density for conifers in the Pacific Northwest of North America typically decreases for the first 5-20 growth rings outward from the pith, followed by a rapid increase until a maximum value is reached asymptotically (Kennedy 1995). This is also the case for Norway spruce (Mäkinen et al., 2007; Saranpää, 2003), Sitka spruce (Gardiner et al., 2011) and black spruce (Alteyrac et al., 2007b) among others. Other species like Scots pine (Auty, 2011) and radiata pine (Tian et al., 1995) describe a rapid increase in density with ring number, followed by a levelling off. These changes relate to the different needs of tree at different stages, which have led to a distinguishing between the corewood and the outerwood. This thesis will use "corewood" to refer to the inner 10-15 growth rings near the pith, most commonly named "juvenile wood", and "outerwood" for the rest as alternative to "mature wood". This recognises discrepancies existing in the actual meaning of "juvenile wood" and "mature wood" due to the mentioned axial and radial differences, but also the onset of reproduction (Burdon et al., 2004).

Chapters 3 and 4 examine the key wood properties both in structural-size timber and clearwood. Chapter 3 also examines the potential yields for grading at different strength classes, the drying distortion in structural samples and assessed the distribution of knots. Chapter 4 contains the modelling of the variation of the three properties with age.

1.5 Non-destructive wood quality assessment

MOR can only be measured by destructive testing. MOE is referred to as static when it is determined in bending under mechanical loading as opposed to dynamic stiffness, or dynamic MOE (MOE_{dyn}), calculated using acoustic tools. Both types of MOE can be obtained without damage to the timber.

The use of such non-destructive techniques (NDT) are nowadays widely used for wood quality assessment. In fact, there are numerous machines based on speed sound propagation which are approved for strength grading of sawn timber.

As with other materials, wood stiffness is closely related to the acoustic behaviour of a wave travelling through it. MOE_{dyn} is derived from measurements from a stress wave. This is a relatively inexpensive and easy method to measure stiffness and predict bending strength. In strength grading, British timber typically performs less well for stiffness than for strength or density. For that reason, the correct determination of stiffness acquires a bigger importance in the allocation and optimisation of the timber resource. All the devices on the market are based on one of two principles:

- Resonance, which measures the resonant frequency (usually fundamental longitudinal) obtained by impact excitation of the specimen, and from which the speed of sound in the wood is calculated.
- "Time-of-flight" (TOF), which calculates the speed of propagation of a sound wave via measuring the time delay between two points.

Whereas the resonance method can be applied to sawn timber and logs, the TOF technique can also be applied to standing trees. Estimations of wood quality have been more successfully achieved by applying the resonance method (Carter et al., 2007; Wang, 2013). A study in the topic (Searles, 2012) found limitations of the currently available techniques applied to standing trees and made suggestions for improvement that this research had the chance to evaluate. A reliable method for the early prediction of wood properties and subsequent segregation would allow informed decisions to be made regarding forest operations, favouring the labours (e.g., pruning on species of high wood value) and selection of trees showing higher performance. This would have the twin benefits of reducing the percentage of material that is rejected for a certain target of quality after the cutting and drying process, and therefore increasing the yield of material that passes the quality required.

Chapter 5 examines the performance of different acoustic techniques to measure the stiffness of trees, logs, structural pieces and clears. The reliability of several methods were examined at a tree, plot, site and species level. The use of acoustic methods to estimate wood strength was also investigated.

1.6 Tree architecture

When timber is the main resource to obtain from the forest, it is essential to know the standing volume of wood, what dimensions trees have and the stem form or taper. The potential productivity of an even-aged forest plantation in British forestry is based upon the estimation of the Yield Class (YC). It is expressed in units of cubic metres per hectare and year (m^3/ha year*), and it is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species* (Forestry Commission, 2016).

Besides the volume, it is important to know the stem diameters along the trunk, particularly when structural timber is the aim. For timber production, logs must achieve a minimum diameter over bark of 14 cm. Taper functions describe the tree profile. They are used to obtain the merchantable volume for different end products relating to diameters and heights. Taper models typically contain the diameter at breast height (dbh) and relative heights as independent variables. These models vary from species to species and from site to site. For the four species in this study there are no established taper functions built in G.B. In addition to the dimensions, for the wood-processing industry is important to know the length of straight logs that can be obtained, as it determines the sawnwood available per log (see §1.1) and the possible end-products.

Slenderness and crown ratio are two other characteristics defining the tree architecture. The crown ratio of trees (length of the live crown relative to tree height, CR) has been used as indicators of stiffness (Moore et al., 2013; Searles, 2012), reporting a negative relationship, that is, the higher CR the lower the stiffness. Other studies found that stem slenderness (relationship between the tree height and dbh) and stiffness relates positive (Lasserre et al., 2009; Searles, 2012; Watt et al., 2006).

Branches are another important part of the tree architecture. They produce knots in the trunk that affect negatively the performance of timber, particularly in bending strength. The interest in branching characteristics in this thesis was to understand their influence on the timber quality of the four species studied, particularly knot size.

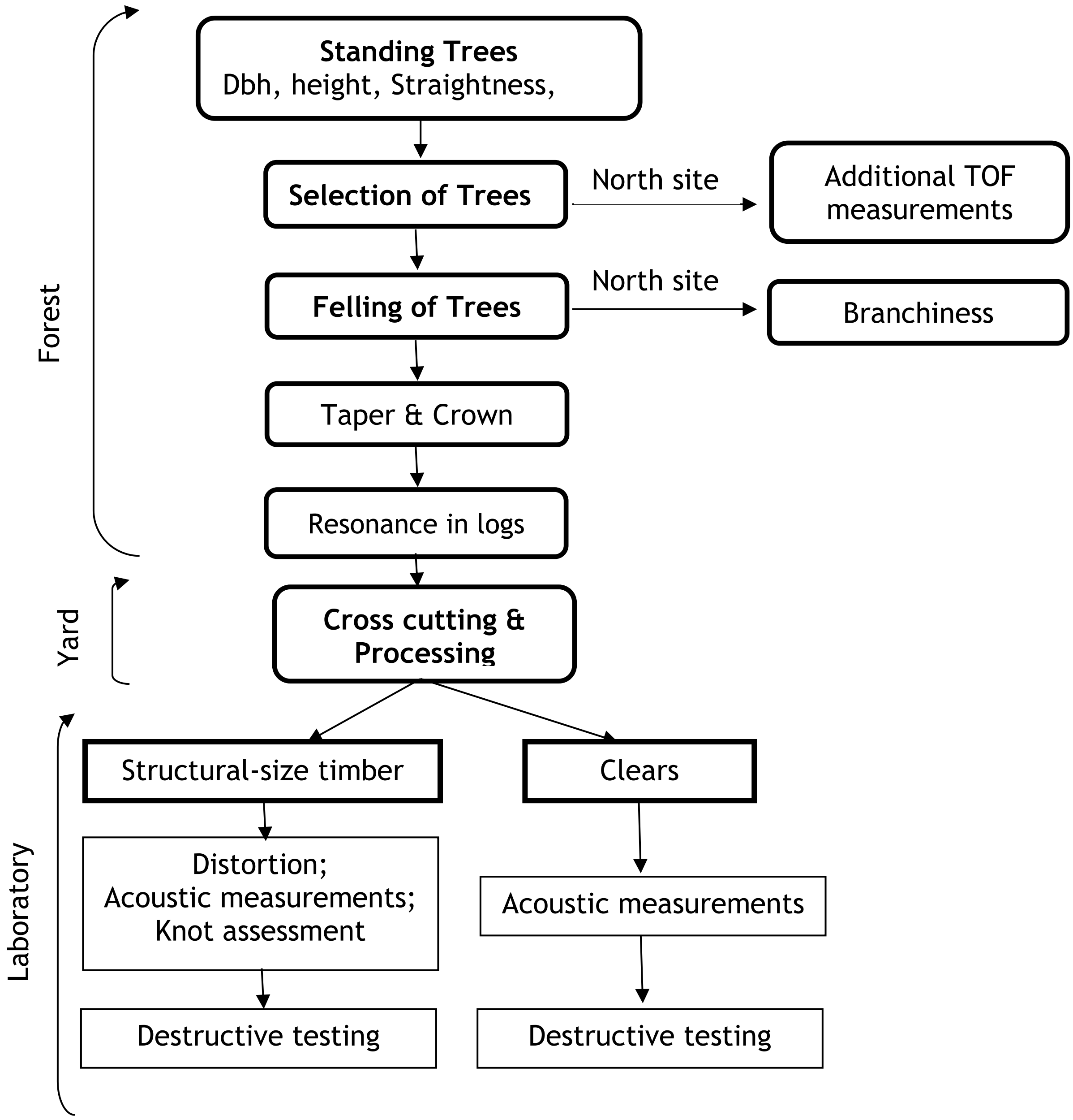
Chapter 6 investigates the architecture of the four species studied. Taper functions describing the stem profile were investigated. Straightness, crown, slenderness and branching characteristics were also described. Results helped to understand better merchantability potential for sawn timber for the four species investigated, and will help forest management decisions for timber production.

Chapter 2. Material and Methods

2.1 Introduction

This chapter describes the common approach followed to collect the data and specimens that formed the base of upcoming analyses. The study was undertaken in three different locations per species, which are here named south, middle and north regions in G.B. The species investigated were noble fir, Norway spruce, western red cedar and western hemlock. Field work in the south and middle latitudes occurred in October 2013, whereas in the north ran between July and October 2014 due to a larger load of fieldwork involving additional measurements within the scope of the project.

The following flow chart describes the sequence of data collection.



2.2 Selection of species and sites

The selection of the species and sites did not form part of the thesis, and it was done beforehand in order to obtain permissions and organise the logistics involved.

The four species studied were chosen from a shortlist of species targeted for planting in G.B. Within the limitations of existing planted forests, the sampling aimed to gather information of different growing regions representative of productive conifer forests in G.B., and managed as pure stands. The sites were located in the growing regions of: South West England, Wales and either South or West Scotland (Figure 2-1). The stands were chosen considering aspects like the condition of the stands, a minimum surface of one ha, age (planted in or before 1980) and the extraction routes. These criteria were revised for western red cedar in Wales (surface of 0.64 ha) and Scotland (0.96 ha), and for noble fir in England (planted in 1983) due to lack of sites fulfilling the initial criteria. It was aimed to find all four species in as close a geographic location as possible, but that was not always possible. Finally, the stands needed to contain trees that could produce 3 m long sawlogs.

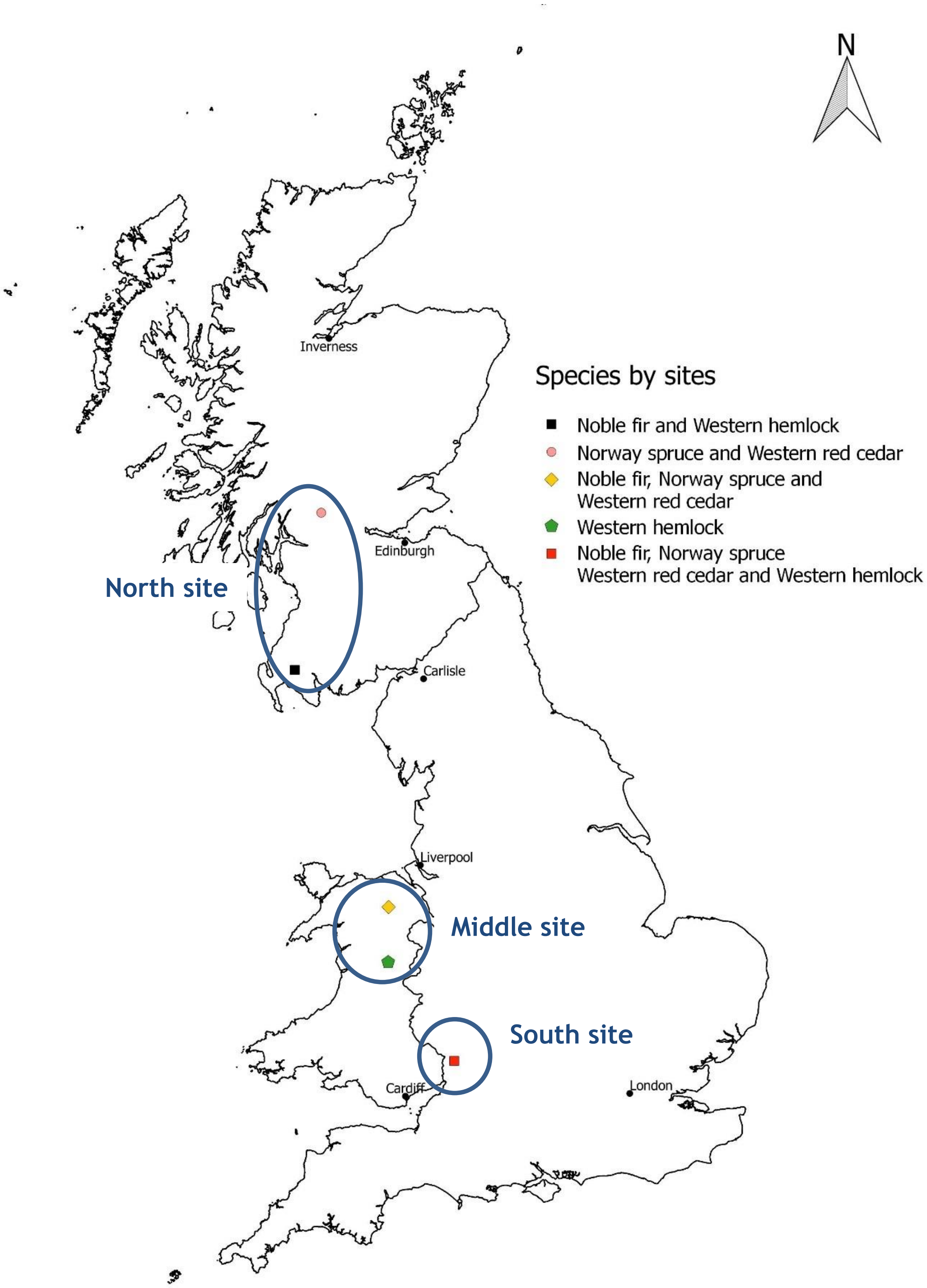


Figure 2-1. Map of the location of sites.

All of the stands were even-aged single species plantations, and most of them had been thinned, although the silviculture applied was unknown. The characteristics of the sites selected are shown in Table 2-1.

Table 2-1. Location of sites selected.

Species	Site	Age	Area (ha)	OS grid	Elevation (m)
Noble fir	South	30	1.0	SO632199	140
	Middle	58	4.70	SH954532	390
	North	38	1.79	NX279666	115
Norway spruce	South	44	13.65	SO616101	100
	Middle	76	7.30	SJ055527	365
	North	44	3.12	NN554007	60
Western red cedar	South	35	2.70	SO646098	205
	Middle	61	0.63	SJ064549	355
	North	78	0.96	NS489982	95
Western hemlock	South	44	5.67[1]	SO643094	205
	Middle	49	4.11	SJ040021	280
	North	78	2.17	NX450644	40

[1] Two different adjacent compartments.

Stocking density for the plantations studied could not be found. For a better understanding of this chapter and future comparisons, the initial planting density was estimated based on current practices at the time of planting (Table 2-2).

Table 2-2. Estimation of initial planting spacing.

		Noble fir	Norway spruce	Western red cedar	Western hemlock
South	Planted	1983	1969	1977	1967
	Spacing	2.0m[1]	1.8m	1.8-2.0m	1.8m
	Density (trees/ha)	2500[1]	3086	3086-2500	3086
Middle	Planted	1955	1937	1952	1964
	Spacing	1.5m	1.5-2.0m	1.5m	1.5-1.8m
	Density (trees/ha)	4444	4444-2500	4444	4444-3086
North	Planted	1976	1970	1936	1936
	Spacing	1.8m	1.8m	1.5m	1.5m
	Density (trees/ha)	3086	3086	4444	4444

[1] Spacing between trees and/or stumps was measured in the blocks.

A summary of the characteristics of the stands investigated is shown in Table 2-3. A more detailed summary is given in Table 6-5.

Table 2-3. Summary of stand and tree characteristics for study sites.

Stand and Tree level characteristics						
Species	**Site**	**Age**	**Density (Stems /ha[1])**	**Trees measured in plots**	**dbh** Mean (Sd)	**Ht (m)** Mean (Sd)
Noble fir	S	30	2040	49	28.0 (6.4)	18.2 (2.0)
	M	58	442	53	35.1 (6.5)	22.8 (2.2)
	N	38	1011	61	30.7 (9.4)	19.1 (3.1)
Norway spruce	S	44	428	64	33.4 (7.6)	23.9 (3.8)
	M	76	414	62	39.4 (5.6)	25.4 (2.1)
	N	44	247	37	44.5 (6.2)	27.3 (2.6)
Western red cedar	S	35	644	58	34.7 (5.9)	19.2 (1.2)
	M	61	796	48	32.6 (10.9)	24.9 (3.3)
	N	78	314	47	64.0 (13.9)	29.0 (3.9)
Western hemlock	S	44	241	48	45.1 (5.1)	26.2 (1.8)
	M	49	995	62	28.8 (7.3)	24.6 (3.0)
	N	78	466	42	48.8 (10.2)	33.1 (2.0)

Site: S, south; M, middle; N, north; [1]Stand density at the time of the data collection based on the plots measured; Ht: Tree height.

Three replicate circular plots were chosen per species and site. Plots avoided the edges of the plantation, and were well spaced from each other in order to be representative of the stand. The initial radius of these plots was set at 8 m (0.02 ha), and increased to 12.6 m or 17.8 m if less than 12 living trees of merchantable size were present. This aimed to obtain a distribution of trees by quartiles with a representative number of individuals in each. The distance from the centre of the plot was measured using a hypsometer and 60° transponder (Haglöf Vertex IV, Sweden) placed at the approximate centre of the stem at breast height. Trees within the distance were marked at the base with a sequential number. The noble fir in the south site was planted in square blocks of approximately 0.012 ha as part of a Forestry Commission provenance trial. All trees in all four plots were measured. The most promising source, and therefore the chosen one for this investigation, was the NF 13011, from Larch Mountain in Oregon (Lines, 1987).

2.3 Forest and sawmill measurements

2.3.1 Standing tree measurements

The dbh was measured with a research diameter tape, to the nearest 0.1 cm, on the trees within the plots with a diameter over 7 cm (Figure 2-2). Trees of less than 7 cm are considered to have no measurable volume. In Europe, dbh is located at 1.3 m height, and measurements are standardised as established in *Forest mensuration: a handbook for practitioners* (Matthews and Mackie, 2006). The total height of those trees was measured using a Vertex IV Hypsometer and a 60° transponder (Haglöf Vertex IV, Sweden). The dbh and height allows estimation of volume and yield class, as well as other quantities.

Stem straightness of the lower six metres was visually assessed by an experienced assessor using the protocol described in Macdonald et al. (2000) so that the viability of the stems to produce sawlogs could be assessed.

In order to estimate the timber quality, as indicated by stiffness, a stress wave timer (TreeSonic, Fakopp, Hungary) measured the time delay in microseconds of a stress wave travelling between two probes inserted into the tree a known distance (Figure 2-3), and velocity calculated afterwards. The probes were separated approximately one metre apart centring on breast height. The north and south side of each standing tree were measured. The acoustic measurements were all taken during the autumn, so no significant variations on the moisture content of trees that could affect the sound wave propagation were expected. Chapter 5 will describe the additional measurements covering longer distances and planes taken on the samples trees selected in Scotland.

Figure 2-2. Dbh measurements.

Figure 2-3. Acoustic measurement on standing trees.

In each plot, the trees were ranked by diameter and grouped in quartiles for sample selection. The three biggest quartiles (named dominant, co-dominant and sub-dominant) contained an equal number with as many samples as possible. The remaining trees made up the smallest category (supressed). The purpose of this selection was to cover the range of diameters in the plot. One individual was chosen at random from each of the top three diameter classes. Three trees per plot were selected, nine per site. If the tree selected was not straight enough to produce a three metre sawlog, or if the felling would introduce a too large localised gap in the remaining canopy, another random choice was done. The selection of four trees was modified because it was not possible to get straight logs from the trees within a quartile. In those cases, a tree of similar characteristics was chosen in the vicinities outside of the plot boundary, and measured normally (dbh, height and time delay), or two trees were selected within the same quartile provided that their diameters were different (in the upper and lower limit of the quartile).

Four blocks of noble fir in the south were measured, but one of them was discarded for tree selection because it did not contain suitable trees to provide sawlogs. An additional tree of western hemlock in Scotland was cut down as part of the felling operations. The tree formed part of one of the plots, and the usual measurements and material collection on felled trees were carried out.

2.3.2 Selected sample tree measurements

Prior felling, breast height, north-facing and south-facing orientations were marked on trees. A total of 109 trees (27 per species and one additional western hemlock) were felled for further assessment of wood properties and stem profile. The trees were felled within ten days after completing the standing measurements. Branches were trimmed off before taking any measurement on the stem.

2.3.2.1 Taper

The stem diameter was measured every metre. This will be described in detail in Chapter 6.

2.3.2.2 Crown

Crown depth was identified on the trees measured for taper (109 trees). Chapter 6 will describe the methodology applied.

2.3.2.3 Wood sample collection

A log of around five metres length with the bottom end at breast height was cross-cut per tree. The lower part, approximately 3.1 m, was designated for structural sampling and the remaining upper part for small clears preparation (Figure 2-4). With three exceptions, the whole five metres logs were acoustically assessed for stiffness measurement as Chapter 5 will describe in more detail.

2.3.2.4 Branch measurements

Characteristics of branches (diameter, height on the tree and angle of insertion) were measured on trees felled in Scotland. A detailed description will be given Chapter 6.

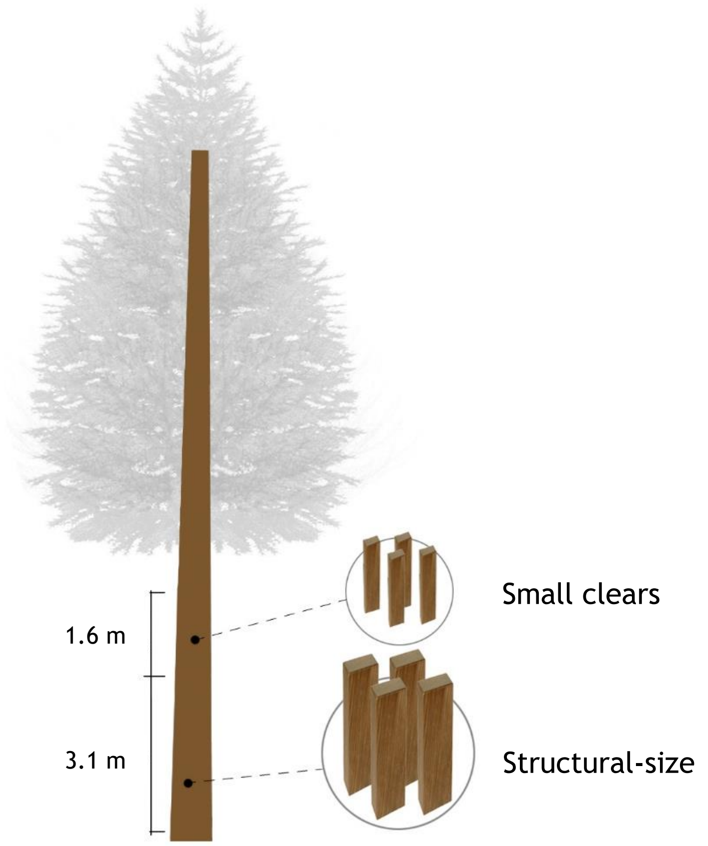


Figure 2-4. Sample material collection. Illustration by Darío Pérez-Moreno.

2.4 Sample preparation

2.4.1 Processing of bending test pieces

The logs from England and Wales were transported to the Northern Research Station (NRS) of Forest Research, where they were cross cut. Two discs of 15 cm thickness were obtained from the bottom and the top for a different study. The bottom 3.1 m was retained for structural-size pieces, and the rest for small clears. A portable sawmill processed the logs. In Scotland, the logs were processed on site in the two northernmost stands, whereas a local sawmill was used in the southern site. The annual rings were identified in the radial transect to track the cambial age of the structural pieces for further comparison. Logs were processed into structural-size pieces with nominal cross sectional dimensions of 100x50 mm following a bark-to-bark pattern with orientation north-south, and with the pith in the centre (Figure 2-5). This cutting pattern was designed to allow rotation length to be accounted for in the analysis.

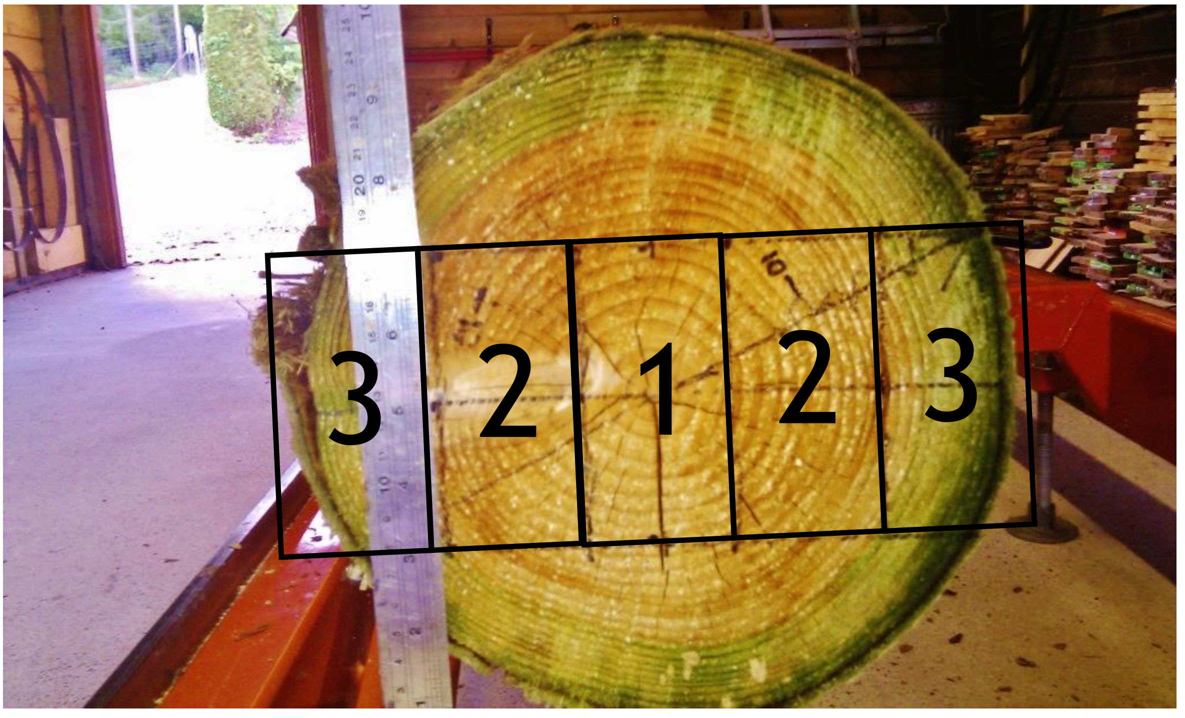


Figure 2-5. Radial cutting pattern of logs, centring the pith. Position 3 added for illustration of the cutting pattern but would not be cut in the log shown.

Specimens were labelled so the tree of origin and the position of the piece could be tracked. A total of 558 structural pieces were obtained, and 90 additional pieces were cut from the offcuts of Norway spruce from the south and middle site.

The structural pieces were kiln dried to 12% m.c. in a GANN HYDROMAT TK-MP 4032 (Gann Mess-u. Regeltechnik GmbH, Germany) located at the NRS. Exceptionally, western red cedar in the north site was dried to 20% m.c. using a milder drying programme that avoided the collapse that the pieces of western red cedar from the south and middle latitudes had previously suffered (Figure 2-6). Collapse is defined in the Wood Handbook (USDA, 2010) as *the flattening of single cells or rows of cells in heartwood during the drying or pressure treatment of wood*. This occurs when water is removed from the saturated cells faster than air replaces the empty space, causing the surface of wood to sink, and more liable to occur using high temperatures (Kape, 2013). Collapse hindered the normal measurements of some variables like the dimensions of pieces among others.

Figure 2-6. Collapse in a tested (broken) piece of western red cedar.

A log of approximately 1.6 m (Figure 2-4) was used for production of clears of 300 x 20 x 20 mm in the longitudinal, tangential and radial directions respectively. They are defect-free pieces, and lack knots, resin pockets, fibre deviation or any other weakness that could appear in the test span and reduce the mechanical performance. A central section was cut per log. For samples collected in England and Wales, this slab followed an orientation previously determined from the disc obtained above the 1.6 m log. In Scotland, the slab followed an orientation north-south because the sawmilling happened in the forest. The annual growth rings were recorded in the slabs prior cutting. The clears were cut from pith-to-bark using a table saw to roughly 22 mm to allow for shrinkage both in the tangential and radial directions. A thicknesser was used after to achieve the final dimensions in the cross section (20 x 20 mm). The presence of knots prevented to obtain pieces containing the pith for some of the trees. A total of 200 specimens of noble fir, 244 of Norway spruce, 214 of western red cedar and 220 of western hemlock were produced. More than one piece per radial position was obtained from some trees. All the samples were used in the analysis unless otherwise stated.

2.5 Laboratory measurements

2.5.1 Structural-size timber

In the laboratory, the timber was conditioned in a controlled environment at 20°C and 65% relative humidity content. These conditions bring a moisture content of the order of 12%, which is the commonly used reference moisture. Prior the destructive testing other characteristics were measured.

2.5.1.1 Drying distortion. Twist.

Twist drying distortion was assessed as stated in BS EN 1310 and Figure 2-7 illustrates. As this question is exclusive to Chapter 3 it will be duly detailed in that chapter.

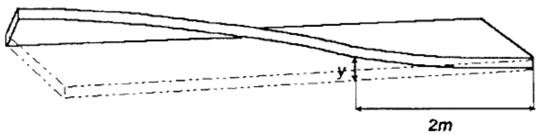


Figure 2-7. Twist as in the standard BS EN 1310 .

2.5.1.2 Acoustic assessment

In the laboratory, the longitudinal resonance frequency was measured in the structural pieces, and the velocity of sound wave propagation calculated. From the dimensions and mass, the density was determined. The relationship of both with MOE allowed an estimation of wood properties. Chapter 5 will describe in detail this and other acoustics measurements practised.

2.5.1.3 Knot assessment

Prior to testing, the critical section was marked in each structural-size piece. The critical section is that which is judged to be the weakest portion of the specimen according to assessment of strength reducing defects including knots, slope of grain, fissures and resin pockets. This section was 500 mm long, and corresponded with the gauge length for the determination of mechanical properties. The section was also used for knottiness assessment of structural pieces (Figure 2-8). The online software Web Knot Calculator v2.2 (Microtec, Italy) reproduced the distribution, size and shape of knots as shown in Figure 2-9 and Figure 2-10. The inputs used were the location of the knot in the board (*X*); the span covered (*Z1-Z2* or *Y1-Y2*) on the side (*S1* to *S4*) and the minimum diameter (*Dmin*). Knots of 5 mm diameter or less were ignored. The side 1 was always the one closer to the pith.

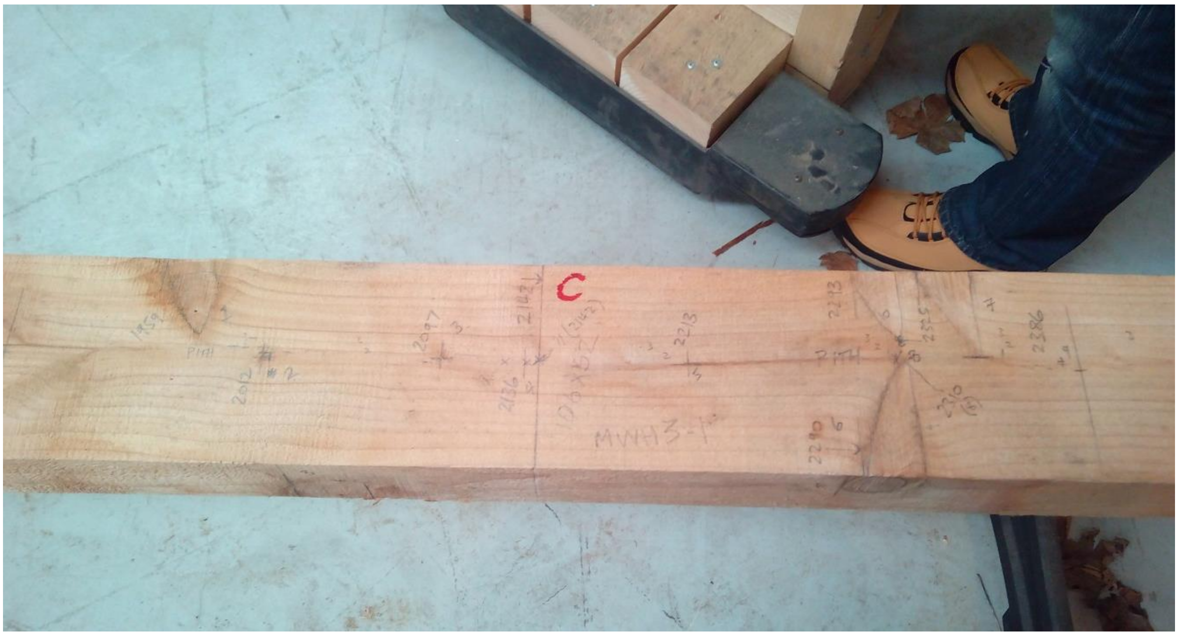
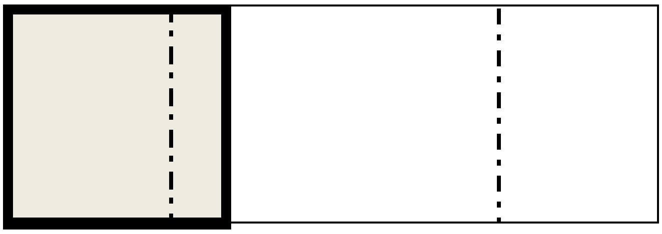


Figure 2-8. Section selected for destructive testing and knot assessment.

The index ratios were based on the size and location of knots on the cross-section of the piece. Indexes used as defined in the software were:

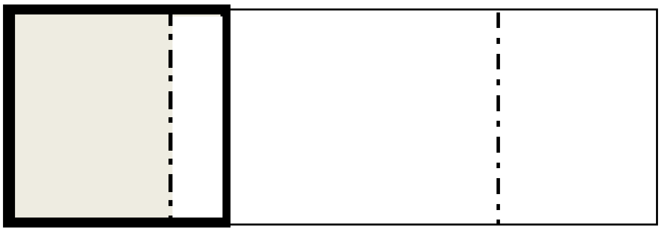
- ***tknot***: It is the ratio of the projected cross-section area of the knot to the cross-section area of the piece.

$$tKnot = \square/(w*t)$$



- ***mknot***: It is the ratio of the major projected cross-section area of the knot or portions of the knot in a margin to the cross-section area of the margin.

$$mKnot = \square/(w*t*\frac{1}{4})$$



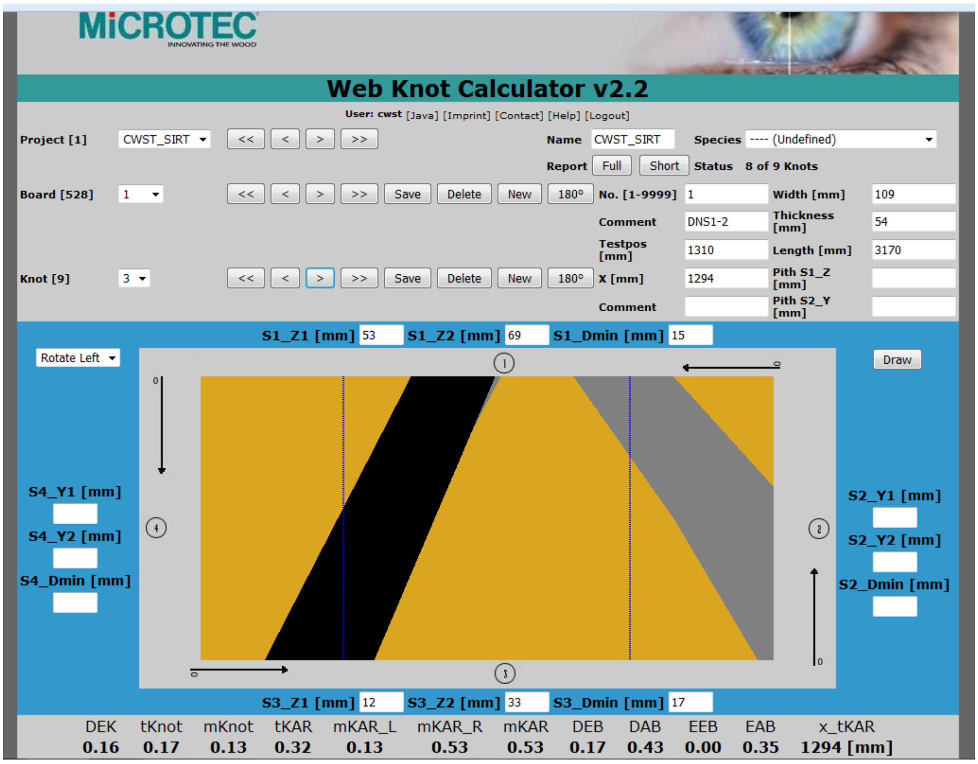


Figure 2-9. Interface of Web Knot Calculator v2.2 for a section with a knot going face to face and one knot going face to side. In black the current section studied and in grey a knot within 150 mm distance.

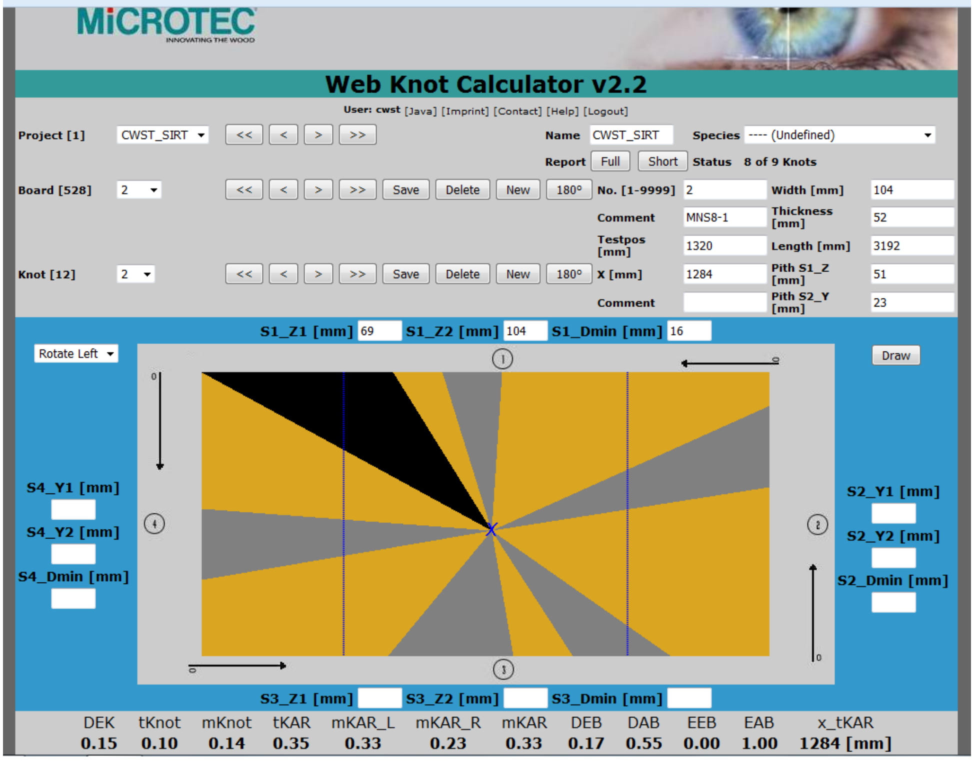


Figure 2-10. Interface of Web Knot Calculator v2.2 for a section containing the pith

The collapse in 30 pieces of western red cedar prevented measurement of the knots on them.

2.5.1.4 Destructive testing of structural-size timber

The specimens were subjected to destructive four point bending tests in accordance with the standard EN 408 using a Zwick Z050 universal testing machine (Zwick Roell, Germany, Figure 2-11). This test measured the static MOE as well as the bending strength (MOR). They both derived from the size of the test section and the load applied, while MOE also involved the measurement of deflection. The test ran at a constant velocity so that the maximum load was reached within a time of 300 ± 120 seconds. The structural pieces, which had been labelled at the top but the side randomly, were loaded with the label facing the operator. This fulfilled the requirements of random orientation of the defects in the cross section under load. The force was applied parallel to the larger cross-section dimension.

Figure 2-11. Zwick machine running a test at Edinburgh Napier University.

The standard EN 408 offers two options to measure MOE in bending: local (MOE_L) and global (MOE_G):

- **MOE_L**, it is based on the middle third of the beam. The deflection is measured at the neutral axis as the average displacement of two transducers placed on the side faces (Figure 2-12). The spans are set according to the depth.

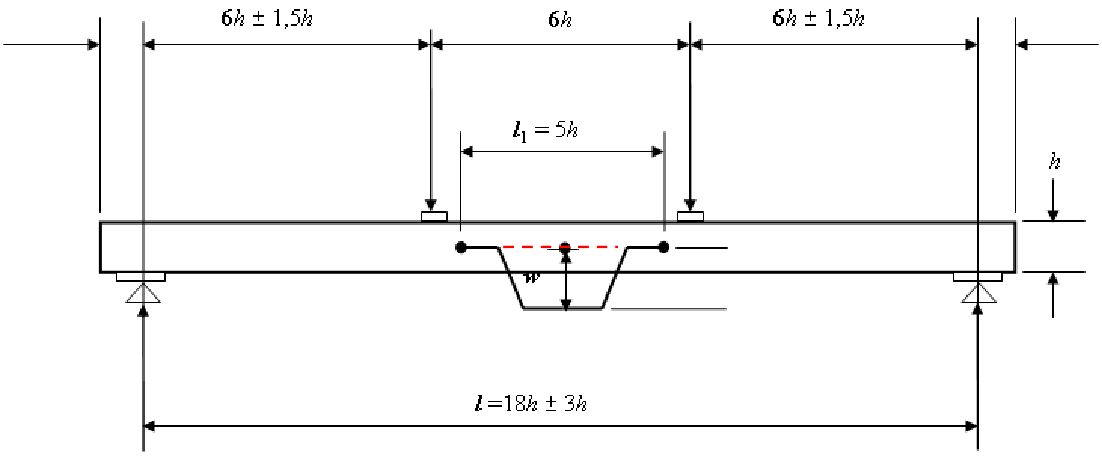


Figure 2-12. Test arrangement for measuring MOE_L in bending (after EN 408). In red, neutral axis added.

In a four point bending test, the bending moment is uniform over the middle third section, and so it is under "pure bending", where the shear deformation does not theoretically exist (Figure 2-13 left).

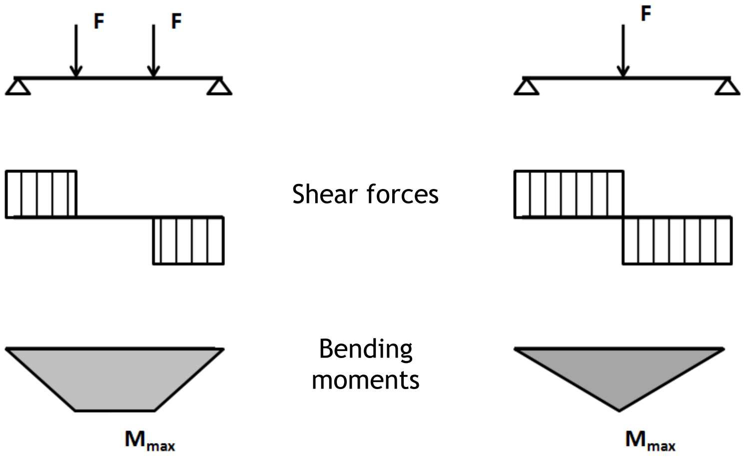


Figure 2-13. Four point bending test for MOE_L (left) and three point bending test for clears (right).

On a four-point bending test, MOE_L is calculated from the equation:

$$MOE_L = 3al_1{}^2\Delta/4bh^3 \qquad [2\text{-}1]$$

where *a* the distance between a loading position and the nearest support (600 mm), l_1 is the gauge length (500 mm), Δ is the slope of the load-deflection curve, and *b* and *h* the thickness and width respectively of the cross section.

- **MOE_G**, it is based on the mid-span deflection in relation to the supports. The deflection is measured at the centre of the span, typically from the centre of the bottom side (tension edge). In this case there is shear deformation of the specimen between the supports and the load points. MOE_G (N/mm^2) is calculated from the equation:

$$MOE_G = \frac{l^3\Delta}{bh^3}[\frac{3a}{4l} - \left(\frac{a}{l}\right)^3] \qquad [2\text{-}2]$$

where *l* is the span in bending (600 mm), and the rest as in MOE_L.

Both local MOE_L and MOE_G were measured simultaneously (Figure 2-14) until the force applied was 3 kN. Then, the transducer measuring the MOE_G was removed to avoid damage by excessive deflection, and only the MOE_L transducers measuring the displacement of the test section remained until the failure load was achieved. A linear model was afterwards fitted in order to examine the relationship between MOE_L and MOE_G, and predict a pure bending modulus of elasticity (MOE_{PB}), that is without shear deformation, from MOE_G.

The test continued until achieving the maximum load, and the bending strength calculated as follows:

$$MOR = 3Pa/bh^2 \quad [2\text{-}3]$$

where *MOR* is the bending strength (N/mm^2), *P* is the is the maximum load achieved, and the rest as for MOE_L and MOE_G.

Finally, a 50-mm long density sample spanning the full cross-section and free of defects was cut from each structural piece near the failure point. This sample was used to calculate density from mass (weighed in a digital balance to the nearest 0.01 g) and volume (recording length, width and thickness to the nearest 0.01 mm with a digital calliper), and to measure the moisture content using the oven drying method as indicated in the standard EN 13183.

2.5.1.5 Characteristics values and adjustment factors

The values describing the mechanical properties and density in a grade are called “characteristic values”. They represent statistical values of a timber population, determining the capability of a sample to be used as construction material and consequently to be assigned to a strength class. In order to calculate those, the measurements need to be adjusted to the reference conditions given by the standards. Density and bending stiffness were adjusted to a standard 12% moisture content. For density, according to the standard EN 384, a change of 0.5% occurs for every 1% difference in m.c. Actual m.c. values above 12% m.c. decrease density in adjustment, and values below 12% m.c. increase density. For bending stiffness, a change of 1% occurs for every 1% difference in m.c., with values above 12% m.c. increasing stiffness and values below 12% m.c. decreasing it.

Likewise, bending strength measured on the 100 mm nominal depth was adjusted to a standard reference timber size 150 mm depth as indicated in EN 384.

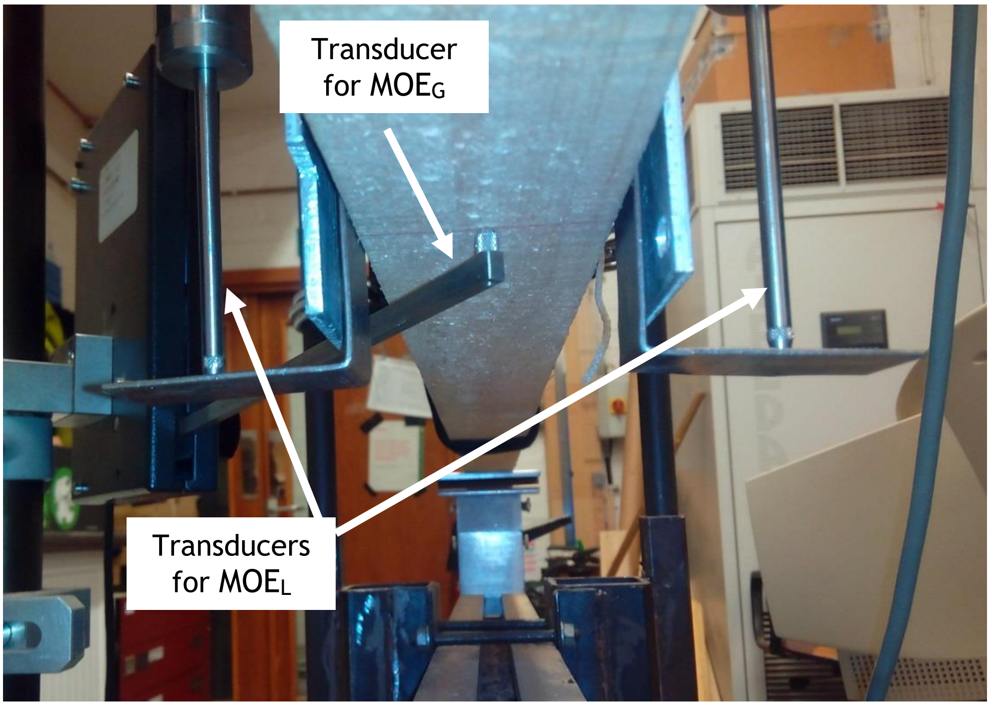


Figure 2-14. Detail of the transducers measuring the local and global displacement.

In addition to the moisture content and depth adjustment, the process of assigning grades to a population involves adjustments for statistical confidence and other considerations. This will be addressed in Chapter 3.

2.5.2 Small clear specimens

As with the structural pieces, the small clears were brought to constant weight by storing in a conditioning unit at 20°C and 65% relative humidity (12% equilibrium moisture content). The samples were weighed in a digital balance (nearest 0.01 g) and dimensions recorded. Length was measured (nearest 1 mm) with a ruler and width and thickness (nearest 0.01 mm) with a digital calliper at three points along the length. Density was calculated after from mass and volume.

2.5.2.1 Acoustic assessment

Prior to destructive testing, an acoustic assessment of wood quality was carried out. In this case, the velocity was measured with ultrasonic time-of-flight, as opposed to the resonant method used in the structural pieces. This aimed to predict the wood properties without testing to failure (see §5.4.1).

2.5.2.2 Destructive testing of small clears

The bending MOE and MOR was determined destructively in accordance with procedures described in BS 373 on three-point bending. Under this test the bending moment is maximum at mid-span (Figure 2-13, right). A universal testing machine (H5KT, Tinius Olsen Ldt, Redhill, UK) was used (Figure 2-15). Distance between supports was 280 mm and the test speed set up at 6.604 mm/min. The orientation of the annual rings was parallel to the direction of loading (Figure 2-16), but the face subjected to compression placed at random.

Figure 2-15. Small clear specimen under a test load.

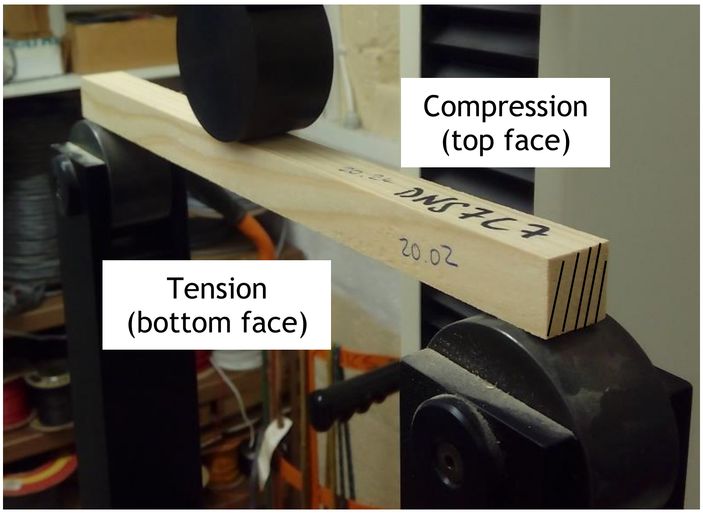


Figure 2-16. Detail of the ring orientation.

Those specimens for which was not possible to produce a perfect clear, and contained some small knots, were orientated with the knot in the top face, the one subjected to compression and less likely to fail. In such a way the influence of the knot was minimised and the specimen treated as a defect-free piece, unless it was observed an influence of the defect in the failure. Determination of MOE_C (N/mm^2) in a three point bending test was calculated as follows:

$$MOE_C = \Delta l^3/4bh^2 \qquad [2\text{-}4]$$

where Δ is the slope of the load-deflection curve, *l* is the test span (280 mm), and *b* and *h* the thickness and width respectively of the cross section. Tests continued over the limit of proportionality to failure, achieving the maximum load (P, in newtons) which determines the MOR (N/mm^2) in a three-point bending test as given by

$$MOR_C = 3Pl/2bh^2 \quad [2\text{-}5]$$

where l, b and h are the span and dimensions as before. The mass was weighted again after the testing to account for possible material lost while testing, and dried in an oven at a temperature of 103°C. The difference in weight, due to the loss of water content, was taken as the moisture content of the piece, although it was not used for the adjustment of MOE and density to 12% m.c. because the pieces had an average moisture content of 13.7% in noble fir and Norway spruce, and 13.2% and 13.7% in western red cedar and western hemlock.

2.6 Statistical analysis

The statistical analysis for this thesis was carried out with the R open-source statistical programming environment (R Development Core Team, 2016), including the selection and evaluation of models. Each chapter of the thesis had a specific description of the statistical analysis applied, but there were common analysis that this section advances:

- Descriptive statistics gave some basic features of the data such as mean, standard deviation and median. Percentiles were calculated to show the dispersion of values using the non-parametric or ranking method with a linear interpolation.
- Quantify the variation of wood properties attributable to each stratum in the experiment. A random effects model was used to estimate the variance components of the hierarchical data structure of different properties. The model was tested with the lme library in R (Pinheiro et al., 2016), and accounted for the nested effects between species and sites, plots and trees and had the form:

$$y_{ijklm} = \mu + Sp_i + S_{j(i)} + P_{k(ij)} + T_{l(ijk)} + \varepsilon_{m(ijkl)} \quad [2\text{-}6]$$

where y_{ijklm} was the individual observation (measurement) of the variable investigated (MOE, MOR, density, both in structural pieces and clears, twist and branch characteristics), μ is the overall mean, Sp_i is the random effect of the ith species $S_{j(i)}$ is the random effect of the jth site within the ith species, $P_{k(ij)}$ is the random effect of the kth plot within the jth site, $T_{l(ijk)}$ is the random effect of the lth tree within the kth plot and $\varepsilon_{m(ijkl)}$ is the residual error. The random effects were assumed to be independent and followed a normal distribution such that $(\sim N(0, \sigma^2))$, where σ^2 was the variance of the correspondent random effect.

- The strength of the correlation between variables was measured with Pearson's or Spearman's correlation depending whether the interest was the linearity or the rank association. The correlation between variables used the following criteria: very weak (0 -0.19), weak (0.2 - 0.39), moderate (0.4 - 0.59), strong (0.6 - .79) and very strong (0.8- 1).
- One-way ANOVA evaluated whether there were any statistically significant differences between the means of the variables. The effect of species in the relationships between properties was determined with an ANOVA on a GLM. This is described in the appropriate chapters.
- Akaike's information criterion was used to compare models fitted on the same data set. The model with the lower AIC was preferred. The significance of terms was evaluated with likelihood ratio tests.
- The model efficiency was measured as the linear relationship between observed and predicted values. Model performance was also assessed using the following error statistics:

mean error, $E = \frac{\Sigma(y_i - \hat{y}_i)}{n}$

root mean squared error, $RMSE = \sqrt{\frac{\Sigma(y_i - \hat{y}_i)^2}{n}}$

mean absolute error, $|E| = \frac{\Sigma|y_i - \hat{y}_i|}{n}$

mean percentage error, $E(\%) = \frac{100}{n}\Sigma\frac{|y_i - \hat{y}_i|}{\hat{y}_i}$

where y_i is the observed value, $\hat{y}_i$ is the predicted value, and n is the number of observations.

Chapter 3. Properties of structural-size timber

3.1 Introduction

It is widely known that wood properties vary from species to species, but they also vary considerably within species due to differences in genetics (McLean et al., 2016; Moore et al., 2009d), environment (Moore et al., 2009c), management (Walker, 1993) and also the age of trees (Kliger et al., 1998; Moore et al., 2012). The four species studied are used in North America and Europe for construction applications. However, because properties vary within a species, assessment of wood properties must be made on a representative sample of timber from the growth area, they cannot be assumed to be the same as they are elsewhere.

In particular, bending stiffness (MOE), bending strength (MOR) and wood density are the key properties of commercial importance. To the author's knowledge, there is little or no evidence on the wood properties of structural-size timber of the four species grown in G.B. This chapter examined and compared those wood properties with the performance in G.B. of established commercial species, particularly Sitka spruce, for a similar rotation length.

For species that are suitably similar it is possible to grade them together. This is potentially a way to combine lesser conifers with an established species, or grade lesser conifers together. In G.B. there is a long-standing commercial use of Norway spruce being processed together with Sitka spruce in a species combination known as "British Spruce". The proportion of Norway spruce in the mix is approximately 10% overall. In this study Norway spruce was examined in its own right. Other example combining the species studied is the well-established in North America species combination "Hem-fir", mix of western hemlock and different species of firs, among others noble fir, and graded for structural timber.

As well as MOE, MOR and density, drying distortion is an important quality measure for structural timber. This chapter includes a preliminary assessment of twist, that is the most problematic type of drying distortion for timber construction. Knots were also assessed, as they are another factor in customer acceptance, separately from the mechanical properties.

Results add knowledge about the aptitudes of the four species investigated grown in G.B. to be used as structural material.

3.1.1 Objectives

The aims of this chapter for noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. are:

1. The performance of wood properties of sawn timber.

   Determine the key grade properties: bending stiffness, bending strength and density. Assessment of knots is also undertaken.

2. The variation and relationships of wood properties.

   Quantify the variation in these three wood properties due to species, sites, plots and trees and the relationships between them as well as knot indexes.

3. Characteristic values and grading.

   Determine the values characterising the wood properties of the populations studied, as well as the potential yields and the grading with common machine indicating properties. Results are compared with other species grown in G.B.

4. Drying distortion. Twist.

   Assess the nature of drying distortion twist for the four species within this study, and compare with other species grown in G.B.

3.2 Literature review

There are three key wood properties that characterise material for timber engineering: bending stiffness (or modulus of elasticity, MOE), bending strength (or modulus of rupture, MOR) and density (see §1.4 for definitions).

Table 3-1 shows some values of the three properties of structural-size timber published in literature from material of the four species studied grown in their native lands. The values must be taken only as a rough guide as they gather material from different ages and/or sizes or with testing and adjustments different to those in the current European standards.

Table 3-1: Mean values of wood properties of structural timber published in literature.

	Noble fir	Norway spruce	Western red cedar	Western hemlock
Pieces	n/a	1551	n/a	529
MOE (kN/mm^2)	11.2	13.4	6.2-7.7[1]	12.0
MOR (N/mm^2)	74.4	49.1	51.7[2]	51.2
Density (kg/m^3)	433-492	460	370-385[3]	492
	(0.37-0.42)		310-340[4]	(0.42)

Sources: noble fir: http://www.wood-database.com/noble-fir/; Norway spruce: (Fischer et al., 2016); western red cedar: [1] http://www.realcedar.com/architects/engineering-data; [2] http://www.wood-database.com/western-red-cedar; [3] (Gonzalez, 2004); [4] (Cown and Bigwood, 1978); western hemlock: (Middleton and Munro, 2001).
Moisture content at 12% except in 1 (unknown); density in noble fir and western hemlock converted from specific gravity (in brackets).

Wood properties for structural timber are measured on individual pieces in symmetrical four point bending in accordance with EN 408. Chapter 2 explained that in MOE_L the shear deflection does not theoretically exist, whereas MOE_G includes a shear effect, and it is less sensitive to localised low stiffness defects, and so likely more representative of the wood stiffness (Ridley-Ellis et al., 2009). MOE_L and MOE_G are related, but there are differences associated to the physics of the deformations and experimental errors. Laboratories rarely measured both simultaneously. MOE_L was the standard method until 2003 when MOE_G was added in the new version of EN 408. A conversion equation in EN 384 (MOE_{384}) allows to adjust MOE_G to an equivalent shear-free MOE.

$$MOE_{384} = MOE_G \times 1.3 - 2690\ (N/mm^2) \qquad [3\text{-}1]$$

The equation [3-1] presents physical inconsistencies, like obtaining negative results for low MOE_G, and more importantly it has been shown to underestimate the real capabilities of British timber (Gil-Moreno et al., 2016). In order to overcome this, the 2016 revision of EN 384 included the possibility of using another relevant equation derived from test data which this chapter will refer to as MOE_{PB}. Hence, there are three types of MOE: local, global and shear-free or “pure bending”, which will be referred to later in the thesis as MOE_L, MOE_G and MOE_{PB} or MOE_{384} depending on the conversion equation applied.

MOR is calculated from the equation [2-3]. For density, there are two densities of interest. When the piece of timber is destructively tested, the density is determined from a small defect-free prism obtained near the failure point ($Density_{384}$). Density can also be determined from the mass and volume of the structural-size piece ($Density_{timber}$), although EN 384 applies a conservative adjustment by dividing by 1.05 in case of softwoods.

Chapter 1 introduced that trees adapt to their individual circumstances as they age, which in part, is cause and consequence of the radial variation of wood properties. Therefore, comparison of wood properties is ideally done on plantations of similar age and similar management. Comparing the MOE, MOR and density of Scots pine of three sites, Moore et al. (2008) found that the majority of the variation (47-58%) was due to differences between the individual pieces within a log (one piece cut from the inner part and one from the outer part). The vast experience on Sitka spruce in G.B. has allowed quantifying the variation of wood properties within the species using all the pieces obtained from a standard cutting pattern in a sawmill. A study on 12 sites of Sitka spruce (Moore et al., 2013), concluded that most of the variation in mechanical properties occurred within a tree (37-56%), followed by differences between individual trees (25-36%), and between sites (18-26%). For density there is not a clear predominant variation, with studies where most of the variation (50.8%) occurred within trees (Moore et al., 2009d), and others where most of the variation (51.1%) was between trees (Moore et al., 2013).

The three properties relate well enough to make the relationship useful for prediction of wood properties, particularly MOE and MOR. For Norway spruce for example (Høibø et al., 2013) it has been reported values of r = 0.82 for the relationship of MOE and MOR, r = 0.79 for MOE and density and r = 0.71 for MOR and density.

Even though measurements are taken on individual pieces, for timber grading what matters is the collective properties in a grade, and not the properties of the individual pieces. The values describing the three properties in a grade are called "characteristic values", which for MOE is the mean ($E_{0,mean}$) and for MOR and density the lower 5th percentiles ($f_{m,k}$ and ρ_k respectively). In Europe there are grades, called strength classes, with defined minimum characteristic values. The process of assigning strength classes to a sorted population involves adjustments for statistical confidence and other considerations. Table 3-2 shows some of the strength classes defined in the standard EN 338, from which the most commonly used in softwoods are C16, C24 and to a lesser extent C18.

Table 3-2: Characteristics values for the strength classes C14 to C24 (EN 338). MOR and density refer to the 5th percentile of the population. MOE refers to mean.

Wood property	Characteristic property values for each strength class					
	C14	C16	C18	C20	C22	C24
Strength (N/mm^2)	14	16	18	20	22	24
Stiffness (kN/mm^2)	7	8	9	9.5	10	11
Density (kg/m^3)	290	310	320	330	340	350

The percentage of a population achieving a strength class is referred to as yield. In order for a population to be graded to a certain strength class, the three properties must achieve the required characteristic values.

Typically one of the three propeties limits the grading to a certain strength class. Density has traditionally been seen as the limiting property for grading timber in G.B., but actually it is the least limiting property on Sitka spruce (Moore, 2011), Douglas fir (Drewett, 2015) and Scots pine (Moore et al., 2008). Overall, British spruce typically attains strength class C16 limited by stiffness (Moore et al., 2013).

In order for timber to be machine graded, an indicating property (IP) closely related to one or more grade determining properties (MOE, MOR or density) is measured by the grading machine. When populations of different species have similar values and variances of the wood properties, and correlations with the grading parameters, the species can be graded together as species combination (e.g. "British spruce" and "Hem-fir").

In addition to the measurement of wood properties, grading requires a visual override inspection to cover strength reducing factors that are not automatically assessed by the grading machine, or the visual grading rules, and other important aspects of customer acceptance such as knot appearance and twist distortion.

Knots reduce the bending strength of wood due to the deviation of the fibre direction around them, and in grading some machines use them in combination with MOE_{dyn} and/or density for prediction of timber quality.

Twist is a type of drying distortion that has been seen as of utmost importance for end-user satisfaction for structural applications (Perstorper et al., 1995a). It is caused by several factors, for example the difference in longitudinal shrinkage within one board (Ormarsson and Cown, 2007). Johansson et al. (2001) studied the influence on twist of ring curvature and spiral grain, and reported that about 50% of the variation in twist could be explained by the average growth ring curvature, and 70% together with spiral grain angle. It also found a very low correlation between density and twist (R^2 = 0.12). As a result, pieces from the centre of the log, with higher longitudinal shrinkage, spiral grain angle and ring curvature, tend to twist more than outerwood (Holland and Reynolds, 2005; Moore et al., 2012).

Depending on the grade of twist, it will not be possible to correct the distortion through nailing or screwing, causing many times a piece of timber to be rejected for construction (Johansson et al., 2001; Kilger, 2001) even though it may have achieved the requirements of a certain strength class. The current version of the standard EN 14081 sets a single limit of 2 mm/25 mm width measured over a 2 m length. These values refer to dry graded structural timber with average moisture content (m.c.) of 20% or less, but sawmills or customers may apply more restrictive limits with the in-service m.c. of 12% in mind.

In summary, this chapter examines the capabilities to produce structural timber of the four species studied, with data representative of the British conditions.

3.3 Material and methods

3.3.1 Material

Collection, processing and testing of structural pieces is fully described in Chapter 2 Material and methods. A summary is provided below.

- Three even-aged single species planted stands from different regions.
- Nine trees per species and site, except ten western hemlock in the north.
- One log per tree, with the bottom part at breast height.
- Pieces of 50x100 mm nominal size following radial transects (Figure 2-5).

A total of 558 pieces of structural timber were obtained, split as indicated in Table 3-3.

Table 3-3. Pieces of structural-size timber obtained by species and site.

Species	South	Middle	North	Total
Noble fir	34	46	47	127
Norway spruce	42	50	51	143
Western red cedar	32	39	67	138
Western hemlock	49	33	68	150

In addition, 90 pieces were cut from the offcut of Norway spruce from the south and middles site. These pieces were also tested to destruction and used to investigate the correlation between wood properties, but were not used for the comparison of wood properties between stands because the annual rings were not recorded.

3.3.2 Methods

The logs were processed into structural-size timber following a bark-to-bark pattern, and kiln dried to 12% m.c., except western red cedar from the north site which was dried to 20% (see §2.4). Afterwards, the pieces were conditioned in a controlled environment (20 °C and 65 % relative humidity) at Edinburgh Napier University to reach constant mass.

3.3.2.1 Mechanical and physical properties determination

Prior to testing, the density of the whole piece of timber ($Density_{timber}$) was calculated from the mass and average dimensions, and the critical section to test (600 mm between the two loads) was marked in each piece (see §2.5.1 for details). Following, the pieces were subjected to destructive four point bending tests according to EN 408. The MOE_L, MOE_G, and bending strength were measured simultaneously. Afterwards, a 50 mm length sample was cut near the failure point of each specimen to determine $Density_{384}$, and the m.c. calculated by the oven dry method as specified in EN 13183-1. In accordance with EN 384, the MOE_L, MOE_G and $Density_{384}$ were adjusted to 12% m.c., and bending strength adjusted to 150 mm depth (see §2.5.1 for details on the adjustments).

3.3.2.2 Knot assessment

The knots within the critical section were measured (see §2.5.1.3 for details). Collapse prevented measurement of knots in 30 samples of western red cedar. The software Web Knot Calculator v2.2 (Microtec, 2009) provided among other indexes:

- *tknot*: ratio of the projected cross-section area of the knot to the cross-section area of the piece.
- *mknot: r*atio of the major projected cross-section area of the knot or portions of the knot in a margin to the cross-section area of the margin.

The output of the software also allowed to obtain the number of knots per piece.

3.3.2.3 Twist

Twist was measured in the laboratory on the radial structural pieces over a 2 m distance as stated in EN 1310, and as Figure 3-1 shows.

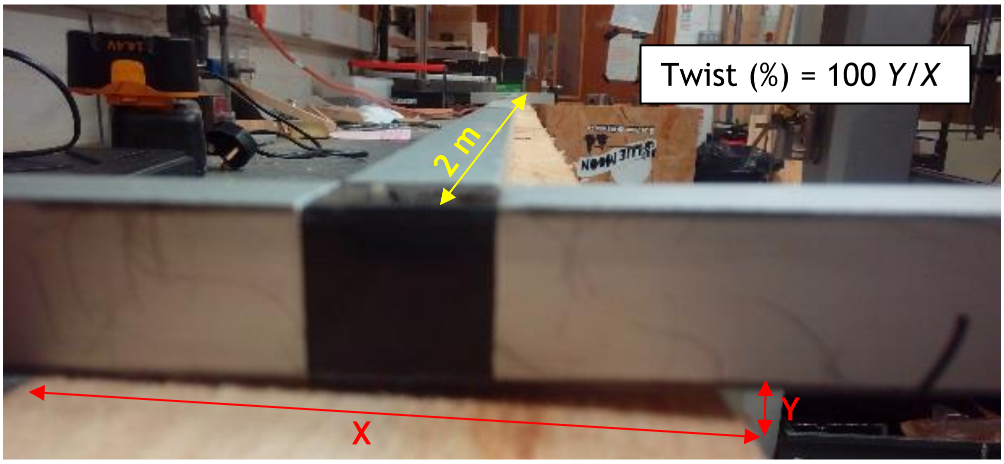


Figure 3-1. Measurement of twist in the lab.

The angle of twist over width was calculated by trigonometry, and the results standardised to 100 mm width so that a comparison with the limits given for 25 mm width in visual grading can be made. Twist could not be assessed on 21 of the specimens of western red cedar because the collapse prevented accurate measurement.

3.3.3 Statistical analysis

The statistical analysis was carried out with the R open-source statistical programming environment (R Development Core Team, 2016).

1. Performance of wood properties of sawn timber.

Descriptive statistics for the 12 sites samples (four species in three sites) and the distribution of wood properties by radial position was investigated. Percentiles were calculated with the non-parametric (ranking) method using a linear interpolation and assuming that the lowest number is the lower bound and the upper bound is undefined.

The number and size of knots was compared between species with a mixed effect model, and the distribution by radial position studied.

2. Variation and relationships of wood properties.

For each property, a random effects model was used to estimate the variance components of the hierarchical data structure as explained in equation [2-6]:

$$y_{ijklm} = \mu + Sp_i + S_{j(i)} + P_{k(ij)} + T_{l(ijk)} + \varepsilon_{m(ijkl)} \qquad \textbf{[2-6]}$$

where y_{ijklm} is the observation of the variable investigated (MOE, MOR, density and twist) on an individual piece, μ is the overall mean and the random effects (*Sp, S, P* and *T*) are assumed to be independent and to follow a normal distribution (see §2.6 for more details).

Pearson's correlation measured the strength of relationships between variables. Whether the relationship between MOE_G and MOE_L was affected by species was examined with a linear model of the form:

$$MOE_L = \alpha_0 + \alpha_1 MOE_G + \alpha_2 Species + \alpha_3 MOE_G{:}Species + \varepsilon \qquad [3\text{-}2]$$

where α_0 is the regression coefficient of intercept, α_1 is the regression coefficient of slope, α_2 represents the additive effect of the species studied, α_3 is the interaction term between MOE_G and species and ε is residual error not explained by the model. ANOVA was conducted on this model in order to test if species was significant, and if a different relationship exists per species.

3. Characteristic values and grading.

Characteristics values, basic grade (i.e. the highest strength class that was obtained with 100% grading yield) and yields for different strength classes were calculated. Only the pieces obtained from the radial transect (558 pieces) in each log were used in order to compare material with the same cutting pattern. The pieces affected by collapse were included because it was considered that the mechanical properties had not been affected.

The results reported here did not include the adjustment to the fifth percentile values given in the standard EN 384 (k_v) for in-line grading machines because the study aimed to keep to the actual properties measured. The standard EN 14358 states that strength parameters should be assumed as logarithmically normally distributed and density as normally distributed. The data did not always show the same distribution in the four species studied so the non-parametric calculation was used instead for both strength and density. This is, anyway, the method to be used when calculating properties for machine strength grading. The characteristic values for the four species were determined for a one-tailed test at a confidence level of $\alpha = 0.75$. This aimed for a 75% probability that the characteristic value (either the 5th percentile or the mean) will be greater than the estimate of the characteristic value.

Finally, a comparison with Sitka spruce grown in G.B. for a rotation length of 45 years was made restricting the material here studied to the same age.

4. To assess the twist on structural timbers.

Differences in twist between mean values were investigated with a single one way ANOVA analysis. An honestly significant difference test (HSD) with $\alpha = 0.05$ investigated afterwards differences between the species. Distribution of twist between species and radial positions were compared and twist examined for the requirements established in the standards.

3.4 Results

3.4.1 Performance of wood properties of sawn timber

The following histograms show the distribution of the data for MOE_G and MOE_L (Figure 3-2), and for MOR and $Density_{384}$ (Figure 3-3).

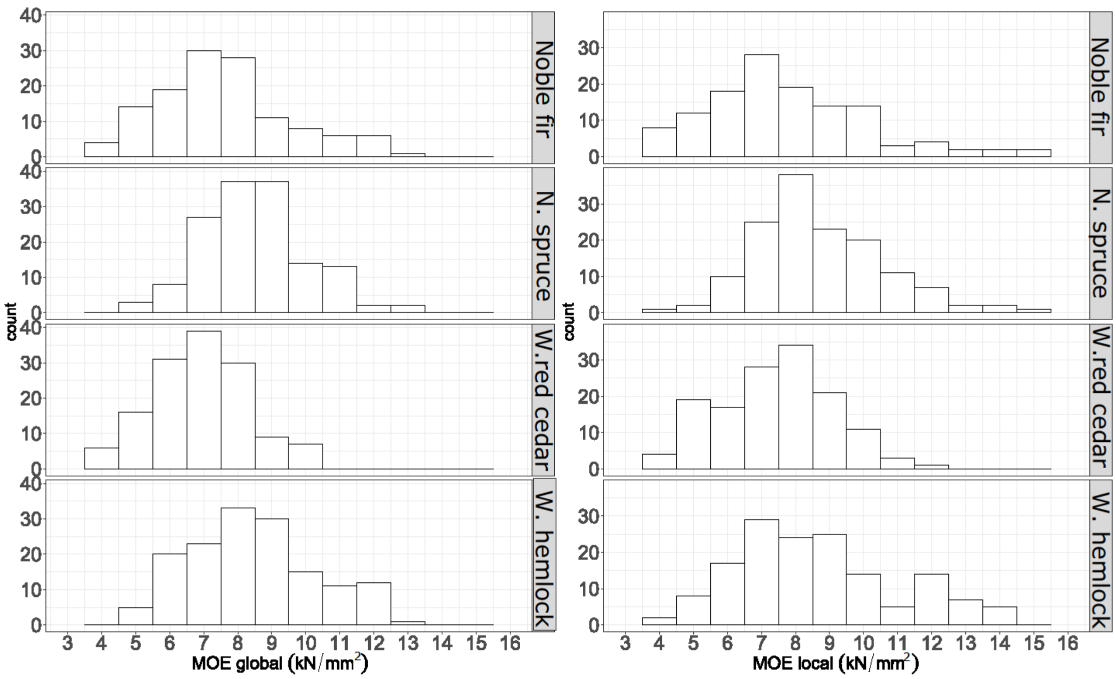


Figure 3-2. Histogram of MOE_G and MOE_L by species.

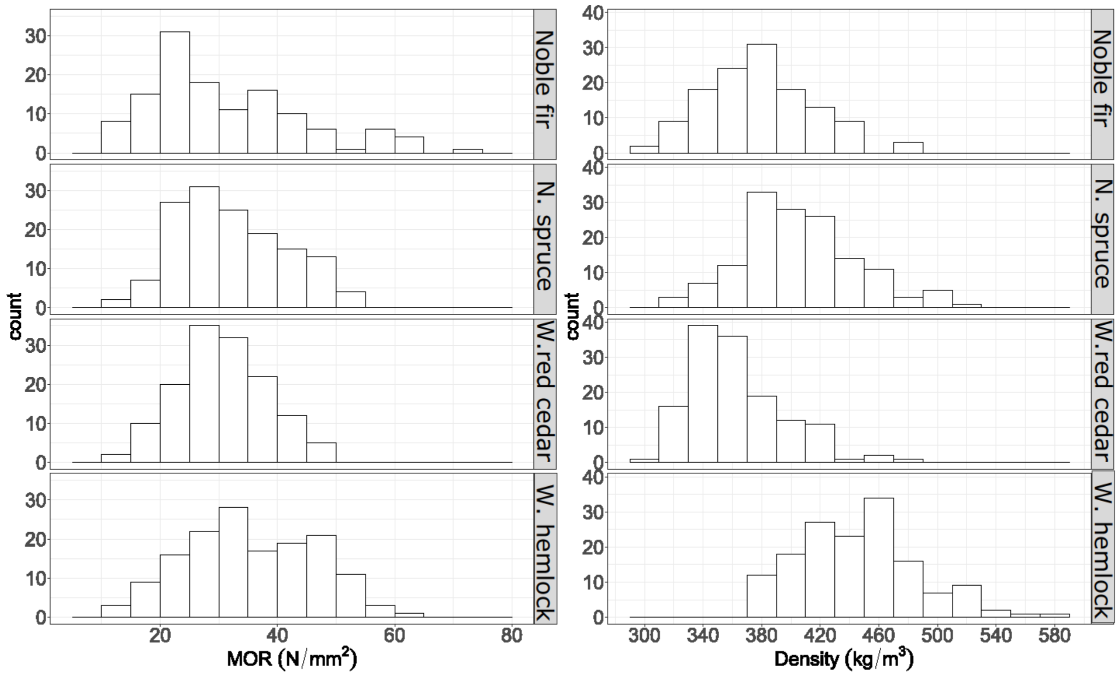


Figure 3-3. Histogram of MOR and Density$_{384}$ by species.

While for noble fir and western red cedar most of the values of MOE_G were between 6 and 8 kN/mm^2, for Norway spruce and western hemlock were between 7 and 9 kN/mm^2. The four species had MOE_L mostly represented between 7 and 9 kN/mm^2 with western red cedar showing fewer pieces above 9 kN/mm^2. The range of values of MOR in noble fir was wider than in the rest, with hardly any noticeable difference in the other three species. Density spanned higher values in western hemlock, followed by Norway spruce and with western red cedar in a lower range.

Figure 3-4 illustrates how MOE_G changed with radial position. Radial position 2, obtained on either side of the pith, was the most represented with 216 pieces. The histograms for Norway spruce overlaid the graphs with and without the extra pieces cut out of the radial transect to illustrate the influence of the outermost wood. The extra pieces fell within the high range of values.

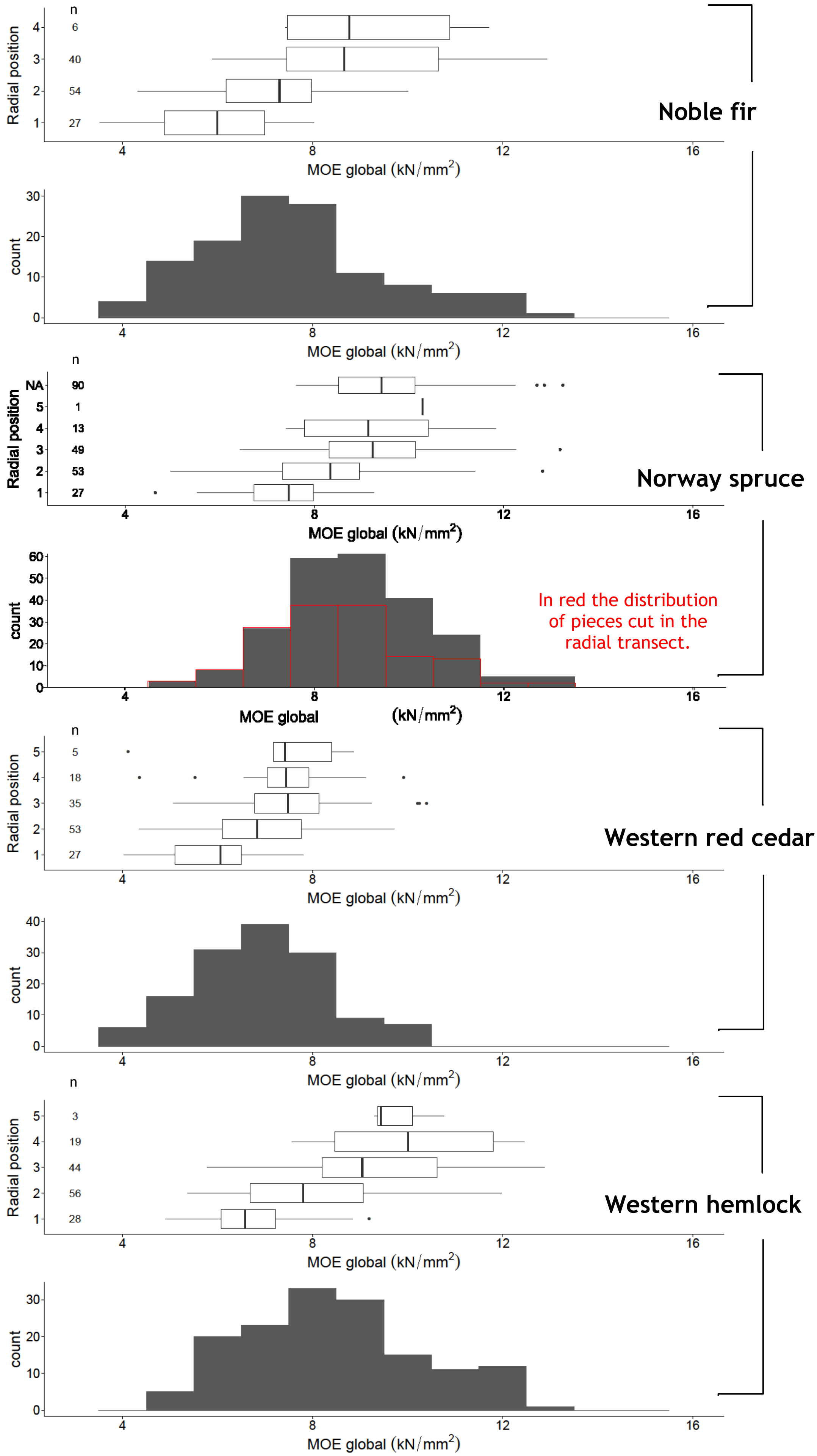


Figure 3-4. Histograms of MOE_G and quartiles by radial position.

For the data here investigated MOE_G increased with the radial position, that is, with age. A similar pattern was shown by MOE_L, MOR and $Density_{384}$ (appendixes), although the latter showed a decline towards the radial position 2 and a rise thereafter. Chapter 4 will address in detail the evolution of wood properties with age through the use of clearwood.

A summary of the wood properties measured for structural grading is offered in Table 3-4. Only the pieces from the radial transect were included so that results were comparable. The 5th percentile and the median showed the dispersion of values. The mean MOE of noble fir and western red cedar was in general lower well than Norway spruce and western hemlock.

In general, older stands achieved higher values in the wood properties. This happened between and within species. An exception was the forest of western red cedar in the north site, which performed less well than the younger ones in the south and middle sites. Likewise, there was important differences in the mechanical properties of western red cedar between sites, but whether this was only due to the influence of the site could not be concluded. The stand of noble fir in the middle site achieved values that compete with the performance of the stands of Norway spruce and western hemlock. The following section (§3.4.2) will quantify these differences.

Table 3-4. Summary of wood properties by species and sites (S; south; M: middle; N: north).

	Noble fir				Norway spruce				Western red cedar				Western hemlock			
	Overall	**S**	**M**	**N**	**Overall**	**S**	**M**	**N**	**Overall**	**S**	**M**	**N**	**Overall**	**S**	**M**	**N**
Age of stands		30	58	38		44	76	44		35	61	78		44	49	78
Number of pieces	127	34	46	47	143	42	50	50	138	32	39	66	150	49	33	68
MOE local (kN/mm^2)																
Mean	7.7	6.5	9.3	7.1	8.8	9.0	9.4	8.0	7.5	8.0	8.2	6.8	8.6	7.7	8.2	9.5
Sd	2.4	1.4	2.5	2.1	2.0	1.6	2.3	1.8	1.7	1.2	1.7	1.7	2.4	1.8	1.7	2.7
CV (%)	31	21	27	29	23	18	24	23	23	13	21	25	28	23	21	28
5^{th} per	4.3	4.4	6.3	3.9	5.9	6.7	6.9	5.3	4.6	6.3	5.6	4.4	5.3	5.2	6.3	5.5
MOE global (kN/mm^2)																
Mean	7.6	6.5	9.0	7.0	8.5	8.7	9.0	7.8	7.0	7.2	7.5	6.5	8.5	7.8	8.2	9.1
Sd	2.0	1.3	1.9	1.6	1.5	1.2	1.7	1.4	1.4	1.0	1.4	1.4	1.9	1.5	1.4	2.1
CV (%)	26	20	21	23	18	14	19	17	20	14	18	22	22	20	17	23
5^{th} per	4.7	4.8	6.6	4.4	6.3	6.9	6.7	5.3	4.7	6.0	5.6	4.3	5.8	5.4	6.3	6.1
MOR (N/mm^2)																
Mean	31	27	39	27	32	33	33	31	31	31	34	28	36	35	32	37
Sd	13	9	15	10	9	9	10	10	8	6	8	8	11	10	10	12
CV (%)	42	35	38	37	29	26	30	31	26	11	22	29	31	29	30	31
5^{th} per	15	15	19	14	19	22	20	17	17	21	21	16	19	18	19	20
$Density_{384}$ (kg/m^3)																
Mean	379	346	406	376	406	403	428	386	363	366	365	361	447	440	438	457
Sd	37	21	31	31	40	31	42	34	33	31	34	34	41	39	25	46
CV (%)	10	6	8	8	10	8	10	9	9	5	9	9	9	9	6	10
5^{th} per	324	313	367	333	346	358	373	332	320	331	324	315	386	378	407	391

Regarding knots, Figure 3-5 (left) shows the distribution of knots per species. ANOVA of a mixed effect model with species as fixed effect, and site and tree within site as random effects investigated the differences between species, and showed that the mean number of knots across the four species was different (*P*<0.001).

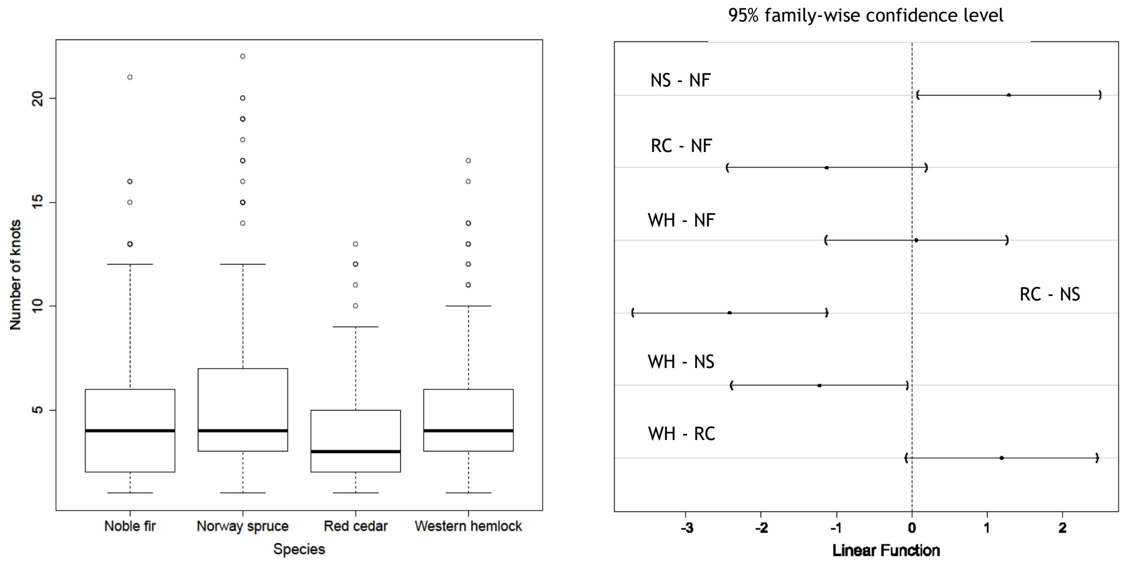


Figure 3-5. Number of knots per piece by species (left) and Tukey's HSD for the difference in the mean number of knots at the 95% family-wise confidence level (right).

The posthoc Tukey (HSD) test in Figure 3-5 (right) showed that the pairs containing Norway spruce were different to the other three species (*P*<0.05). In practical terms this means that Norway spruce had more knots per piece. On intervals containing the zero there was no statistical evidence that the pair had a different mean.

A significant difference in the number of knots was observed between radial positions (*P*<0.001), where the average number of knots per specimen decreased with increasing radial position, especially between positions 1 and 2 (Figure 3-6). The statistical difference in the number of knots observed previously in Norway spruce was mostly due to the higher number of knots around the pith. Considering all the pieces together, a significant difference in the number of knots was observed between all pairs of radial positions (*P*<0.001), except between 3-4, 3-5 and 4-5.

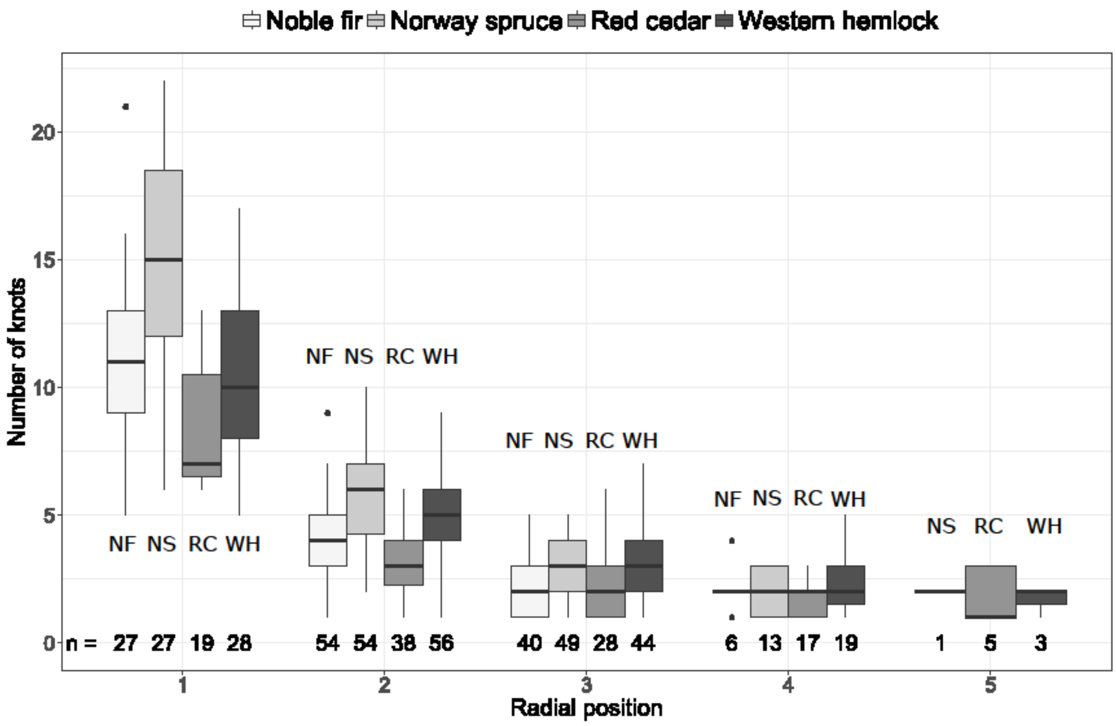


Figure 3-6. Number of knots by radial position and species (n: number of pieces).

When examining the size of knots using the total knot area (*tknot* index), a significant difference was observed between radial positions (P<0.001), where the trend was to decrease outwards (Figure 3-7, left).

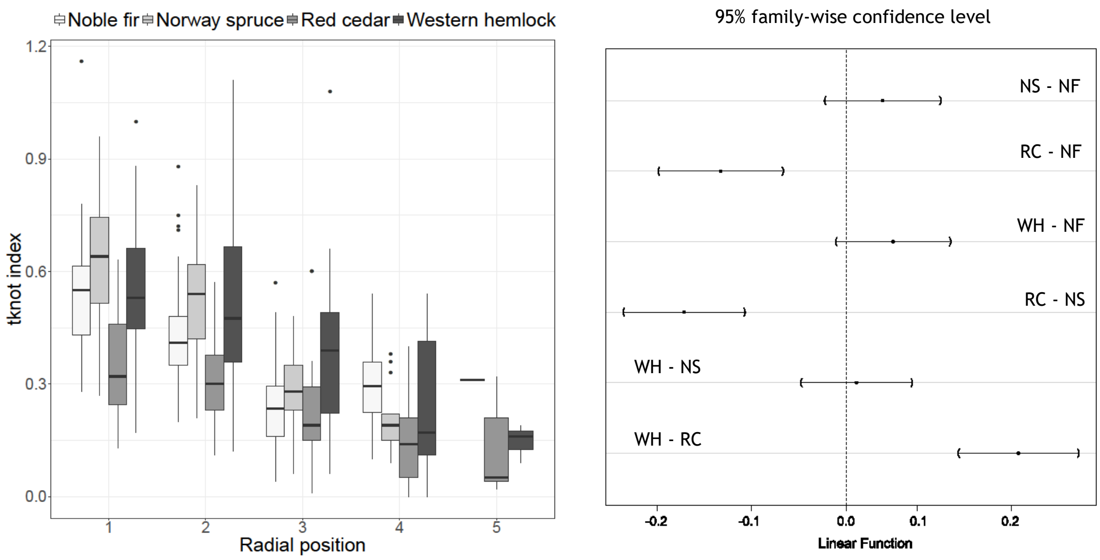


Figure 3-7. *tknot* index by radial position and Tukey's HSD confidence interval for *tknot* at the 95% family-wise confidence level.

A significant difference in the *tknot* was observed between species (P<0.001) at the 95% family-wise confidence level, where western red cedar was lower compared to the other three species (P<0.001), with no statistically significant differences between the other pairs (Figure 3-7, right).

3.4.2 Variation and relationship of wood properties.

This section quantifies the influence of the different stratum of the experiment in the results examining the variance components (Table 3-5). Even though there are observed differences between species, most of the variation in the mechanical properties was due to differences within trees, particularly in the case of MOR, and actually species had a very small influence. Conversely, species was the most important source of variation in $Density_{384}$.

Table 3-5. Percentage of variance components for the different stratum in the data collection. Only radial pieces investigated.

	Species	Site	Plot	Tree	Within tree
MOE_L					
Overall	<0.01%	14.3%	11.3%	11.2%	63.2%
Noble fir		29.5%	6.0%	2.4%	62.0%
Norway spruce		2.3%	20.2%	17.5%	60.0%
Western red cedar		14.3%	12.0%	11.3%	62.4%
Western hemlock		7.6%	11.5%	13.5%	67.5%
MOE_G					
Overall	7.4%	15.1%	10.4%	11.5%	55.7%
Noble fir		37.9%	5.0%	3.7%	53.4%
Norway spruce		4.0%	24.5%	16.2%	55.3%
Western red cedar		7.7%	14.8%	12.9%	64.6%
Western hemlock		3.7%	9.4%	16.7%	70.1%
MOR					
Overall	<0.01%	8.7%	4.9%	12.3%	74.1%
Noble fir		24.1%	0.0%	8.5%	67.4%
Norway spruce		<0.01%	6.0%	15.0%	79.0%
Western red cedar		11.4%	2.0%	20.9%	65.8%
Western hemlock		<0.01%	10.7%	9.5%	79.8%
$Density_{384}$					
Overall	43.9%	10.0%	2.5%	15.3%	28.3%
Noble fir		49.9%	6.2%	5.5%	38.3%
Norway spruce		21.4%	<0.01%	36.5%	42.1%
Western red cedar		<0.01%	<0.01%	22.1%	77.9%
Western hemlock		<0.01%	9.1%	37.4%	53.5%
Twist					
Overall	1.7%	19.9%	<0.01%	4.2%	74.1%
Noble fir		13.9%	2.5%	<0.01%	83.6%
Norway spruce		5.3%	<0.01%	<0.01%	94.7%
Western red cedar[2]	n/a	n/a	n/a	n/a	n/a
Western hemlock		4.4%	<0.01%	10.2%	85.3%

[1] Variance of twist in western red cedar was not analysed due to the different drying setting used.

Within species, in general the biggest variation occurred within trees both in mechanical properties and density. In noble fir, site was the largest source of variation in density, and had a higher effect on the mechanical properties than in the other species. Variation in twist was mostly attributed to differences within trees.

The strength of the relationship between different wood properties was measured with Pearson's correlation (Table 3-6). Only the pieces cut in the radial section were included because knots were only measured on those.

Table 3-6. Pearson's correlation (r) between variables for radial pieces.

	Noble fir	Norway spruce	W. red cedar	W. hemlock
MOE_G - MOE_L	0.95	0.93	0.95	0.94
MOE_L - MOR	0.81	0.78	0.77	0.77
MOE_G - MOR	0.79	0.77	0.75	0.79
$Density_{384}$ - MOE_L	0.73	0.69	0.40	0.53
$Density_{384}$ - MOE_G	0.78	0.76	0.44	0.56
$Density_{384}$ - MOR	0.62	0.60	0.39	0.43
$Density_{timber}$ - $Density_{384}$	0.90	0.88	0.88	0.90
$Density_{timber}$ - MOE_L	0.62	0.64	0.33	0.45
$Density_{timber}$ - MOE_G	0.70	0.71	0.38	0.48
$Density_{timber}$ - MOR	0.54	0.52	0.32	0.36
Twist - MOE_L	-0.42	-0.24	0.19	-0.10
Twist - MOE_G	-0.44	-0.28	0.15	-0.16
Twist - MOR	-0.22	-0.21	0.13	-0.13
Twist - $Density_{384}$	-0.27	-0.25	0.09	0.01
tknot - MOE_L	-0.53	-0.52	-0.39	-0.63
tknot - MOE_G	-0.55	-0.52	-0.39	-0.61
tknot - MOR	-0.47	-0.52	-0.52	-0.63
mknot - MOE_L	-0.44	-0.53	-0.45	-0.61
mknot - MOE_G	-0.34	-0.43	-0.39	-0.59
mknot - MOR	-0.46	-0.56	-0.52	-0.62

All P values<0.001

Correlation between mechanical properties was in general strong. The strongest pair was between the two moduli of elasticity, MOE_L and MOE_G. Density correlated well with the mechanical properties, particularly stiffness in Norway spruce and noble fir, and less well for western red cedar and western hemlock. The strength of these correlations will be useful to calculate prediction models of structural wood properties (see §3.4.2.1).

An analysis of variance (ANOVA) comparing the wood properties by species showed that wood properties were different by species (P<0.001 for MOE_L, MOE_G, MOR, $Density_{384}$ and distortion). In addition, ANOVA of a GLM showed that relationships between the studied wood properties were influenced by the effect of species in all cases (P< 0.001).

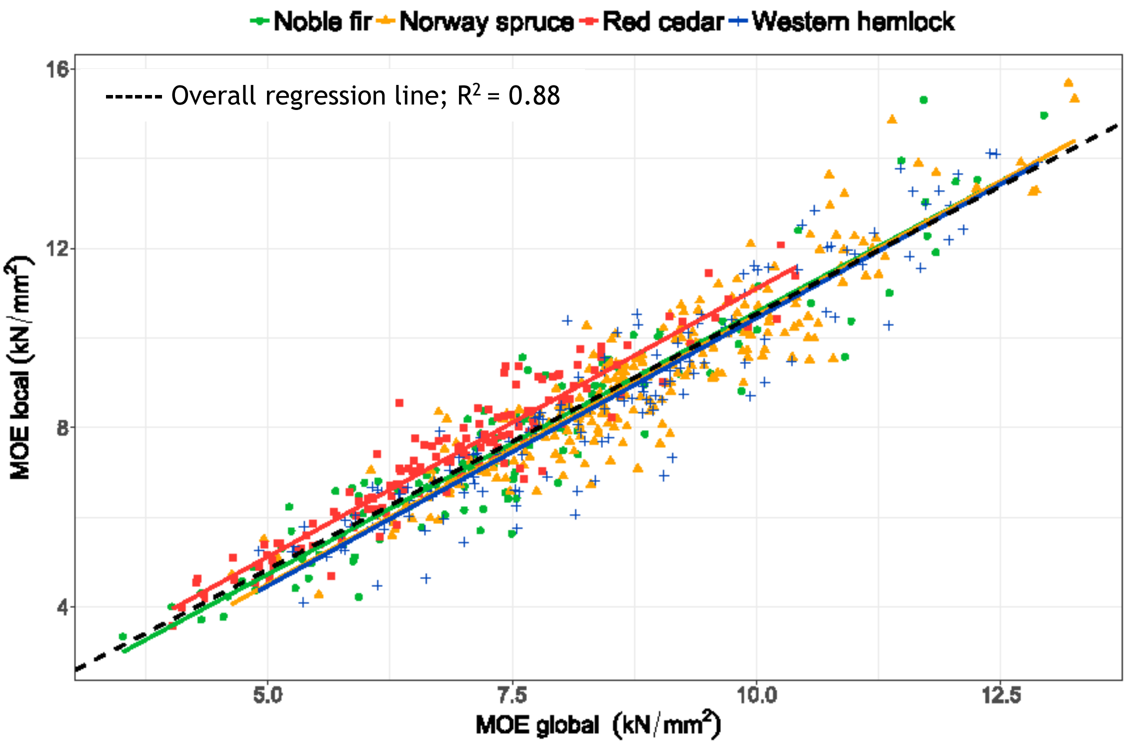


Figure 3-8. Relationship between MOE_G and MOE_L with the linear regression line for the four species together.

The effect of species on the relationship between MOE_G and MOE_L was investigated using ANOVA of equation [3-2]. The extra pieces obtained for Norway spruce were also incorporated in the model to account for a bigger variation. Species affected the intercept term ($F_{3\ 643}$ =*20.4, P< 0.001*) but not the slope ($F_{3\ 640}$ = *0.17, P= 0.92*) as Figure 3-8 shows. Western red cedar, for which stiffness was lower (Table 3-4), had a slightly higher intercept term than the other three species by about 0.55 kN/mm^2 (P<0.001). There was no significant difference between noble fir and Norway spruce. A small difference existed between noble fir and western hemlock where hemlock had a lower intercept by about 0.2 kN/mm^2 (P<0.05). Therefore, the rate of change between MOE_G and MOE_L was the same for the four species, indicating the variation in stiffness within the test span length, and relative shear deflection, is similar within the pieces of all species. The reason for a higher intercept in western red cedar is difficult to say, but one option is the shear modulus having a bigger influence, or measurement errors due to a non-square cross critical section consequence of the collapse, or possibly greater elastic compression of the test specimen depth when under load. The results in Table 3-7 reports the different regression coefficients for the relationship MOE_G - MOE_L.

Table 3-7: Regression coefficients (kN/mm^2) for each species. SE = Standard Error

	Species	Estimate	SE	*P*-value
Intercepts	Noble fir	-1.262	0.147	<0.001
	Norway spruce	-1.397	0.230	0.107
	Western red cedar	-0.807	0.237	<0.001
	Western hemlock	-1.450	0.236	<0.036
	Slope	1.189	0.017	<0.001
Equation: MOE_{PB} = Slope x MOE_G + Intercept + error				

A linear relationship between MOE_L and MOE_G across the four species was investigated, resulting in the following equation:

$$MOE_{PB} = 1.139 \times MOE_G - 0.856 \quad [3\text{-}3]$$

The equation [3-3] provides an alternative to the equation 7 given in the standard EN 384:2016 for calculation of the pure bending modulus (MOE_{PB}). It could be used for timber grading, although it may be specific to the testing arrangement used. The standard also allows the direct use of MOE_L for timber grading.

A general regression line between MOE_G and MOR for all the pieces tested gave a relationship of R^2 = 0.53 (RMSE = 7.2 N/mm^2). ANOVA of a linear model between the two properties showed that the relationship was different between species, affecting the intercept ($F_{3\ 643}$ = 24.6, P= <0.001), but not the slope ($F_{3\ 640}$ = 2.2, P= 0.09), which is illustrated in Figure 3-9. This raised the possibility of grading MOR for the four species together using a stiffness based IP, which will be examined in section 3.4.3.

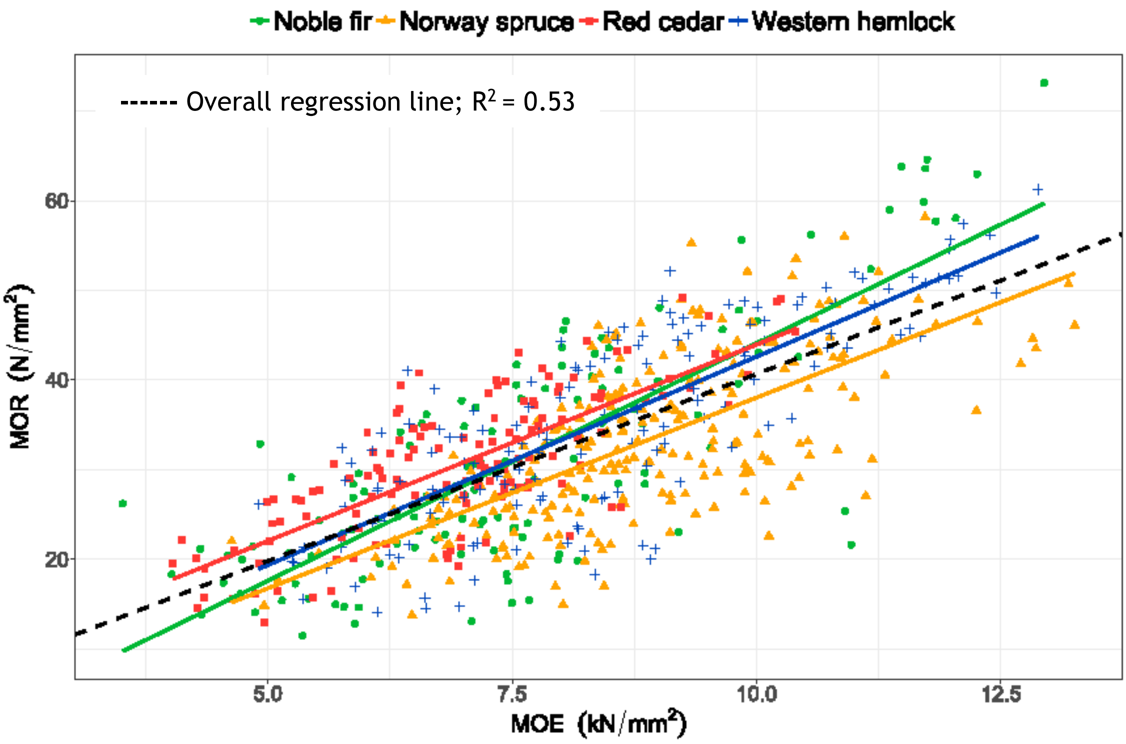


Figure 3-9. Relationship between MOE and MOR in structural timber with the linear regression line for the four species together

ANOVA of a linear model indicated that the relationship of Density384 with MOE and MOR was different between species, affecting both the intercept and slope ($F_{3\ 873}$ = 26.6, *P*= <0.001 and $F_{3\ 640}$ = 10.4, *P*= <0.001 for MOE; and $F_{3\ 643}$ = 7.3, *P*= <0.001 and $F_{3\ 640}$ = 7.9, *P*= <0.001 for MOR). Therefore, species may not be graded together using density as IP.

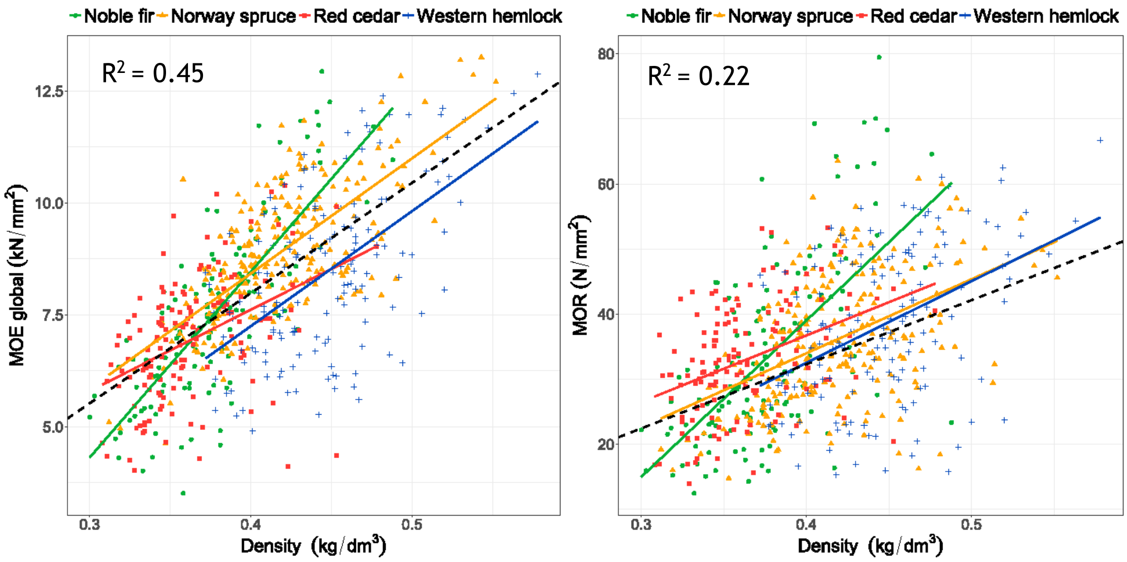


Figure 3-10. Relationship between Density384 with MOE (left) and MOR (right) with linear regression per species and overall.

The overall relationship of $Density_{384}$ with MOE_G was moderate (R^2 = 0.45, RMSE=1.4 kN/mm^2), and poor with MOR (R^2 = 0.22, RMSE=9.2 N/mm^2, Figure 3-10). The grade of association of other wood properties will be examined in Chapter 5, as part of the non-destructive assessment of wood properties.

3.4.2.1 Models for wood properties prediction.

Below is included a list of equations for prediction of wood properties in structural pieces according to the data studied.

Table 3-8. Models for prediction timber properties at piece level

Equation number	MODELS	R^2	RMSE
For the four species			
[3-3]	$MOE_{PB} = 1.139 \times MOE_G - 0.856$	0.88	
Noble fir			
[3-4]	$MOE_G = 41.5 \times Density_{384} - 8.1$	0.61	1.23
[3-5]	$MOE_G = 38.4 \times Density_{timber} - 7.8$	0.49	1.41
[3-6]	$MOE_G = 32.4 \times Density_{timber} - 4.2 \times tknot - 3.9$	0.63	1.21
Norway spruce			
[3-7]	$MOE_G = 25.7 \times Density_{384} - 1.9$	0.51	1.06
[3-8]	$MOE_G = 26.7 \times Density_{timber} - 2.7$	0.47	1.10
[3-9]	$MOE_G = 26.7 \times Density_{timber} - 2.8 \times tknot - 1.7$	0.65	0.90
Western red cedar			
[3-10]	$MOE_G = 18.2 \times Density_{384} - 0.4$	0.19	1.23
[3-11]	$MOE_G = 17.7 \times Density_{timber} - 0.3$	0.14	1.27
[3-12]	$MOE_G = 24.7 \times Density_{timber} - 3.3 \times tknot - 1.8$	0.52	1.31
Western hemlock			
[3-13]	$MOE_G = 25.7 \times Density_{384} - 3.0$	0.32	1.54
[3-14]	$MOE_G = 25.9 \times Density_{timber} - 3.5$	0.23	1.64
[3-15]	$MOE_G = 27.3 \times Density_{timber} - 5.2 \times tknot - 1.7$	0.62	1.25

3.4.3 Characteristic values and grading

3.4.3.1 Characteristic values and optimum grading

Characteristic values of the key wood properties for construction were calculated for specimens simulating a rotation length of 45 years by using only pieces cut from the 45 rings closest to the pith. Table 3-9 shows the values by species and sites, but the small number of pieces for some of the groups must be taken into account before extracting any conclusion. A two-tailed test for a confidence level of α = 0.95 was calculated for the mean.

Table 3-9. Summary of wood properties by sites for a rotation length of 45[1] years.

	Noble fir			Norway spruce			Western red cedar			Western hemlock		
Prop\Site	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**
Pieces	34	45	47	42	35	51	32	37	46	49	33	56
MOE_L (kN/mm^2)												
$E_{0,mean}$	6.5	9.3	7.1	9.0	8.8	8.0	8.0	8.2	6.3	7.7	8.2	9.0
CI (±)	0.5	0.9	0.6	0.5	0.7	0.5	0.4	0.6	0.4	0.5	0.6	0.7
MOE_G (kN/mm^2)												
$E_{0,mean}$	6.5	9.0	7.0	8.7	8.5	7.8	7.2	7.5	6.1	7.8	8.2	8.7
CI (±)	0.4	0.4	0.4	0.4	0.5	0.4	0.3	0.5	0.4	0.4	0.5	0.5
MOR (N/mm^2)												
$f_{m,k}$	14.7	18.8	14.1	21.5	19.7	17.3	20.8	20.5	15.6	18.2	19.3	18.9
Mean	26.9	38.9	26.7	32.7	30.0	30.7	31.2	34.4	25.8	34.9	32.1	35.6
CI (±)	3.1	4.4	2.8	2.6	2.6	2.6	1.9	2.5	2.2	2.8	3.3	3.0
$Density_{384}$ (kg/m^3)												
ρ_k	313	367	333	358	372	332	331	324	312	378	407	389
Mean	346	405	376	403	419	386	366	363	348	440	438	450
CI (±)	7	9	9	9	13	9	11	11	7	11	9	12
SC MOE_L	C14[2]	C20	C14	C20	C18	C16	C16	C16	C14[3]	C16	C16	C20
SC MOE_{PB}	C14[4]	C20	C14	C20	C18	C16	C16	C16	C14[5]	C16	C16	C20[6]

Sites: S, south; M, middle; N, north; CI: confidence interval of α = 0.95 for the mean;
$E_{0,mean}$, $f_{m,k}$ and ρ_k are the characteristic values for stiffness, strength and density respectively;
SC: Strength class for the basic grade (100% of the population in the strength class).
[1] Noble fir was 30 y/o and 38 y/o in south and north sites respectively, and western red cedar 35 y/o in south site;
C14[2] Yield = 97%; C14[3] Yield = 87%; C14[4] Yield = 91%; C14[5] Yield = 96%; C20[6] Yield = 95%

The allocation of sites and species to strength classes was done on the basis of the results of the destructive tests, and is referred to as optimum grading. The properties were ranked in ascending order, and the mean (for stiffness) or the 5th percentile (for bending strength and density) of the entire population calculated.

Overall, Norway spruce and western hemlock achieved higher basic grades than noble fir and western red cedar. However, noble fir in the middle site competed with the best plantations of Norway spruce or western hemlock, and even achieved 96% yield for the strength class C22. The potential yields obtained for strength classes C14 to C27 each by species are reported in the appendixes.

Table 3-10 shows the wood properties for the four species studied restricting age to 45 years. The stated characteristic values determine the basic grade. In order to capture the variation of wood properties, the characteristic values were determined for a one-tailed test at a confidence level of α = 0.75 using a non-parametric calculation as described in the statistical analysis (see §3.3.3). As well as the mean and characteristics values, the Table 3-10 shows the confidence adjusted characteristic values. This biased the characteristic value towards the safe side.

Table 3-10. Properties of timber for a rotation length of 45 years. The characteristic values for bending stiffness (kN/mm²), bending strength (N/mm²) and density (kg/m³) are given by MOE_{PB}, $f_{m,k}$ and ρ_k, respectively.

	Noble fir	Norway spruce	Western red cedar	Western hemlock
Property\pieces	126	128	115	138
Mean MOE_{PB}	7.7	8.6	7.0	8.5
CoV (%)	29	19	22	23
$E_{0,mean}$,75%, CI	7.6	8.5	6.9	8.4
Mean MOR	31.1	31.1	30.1	34.5
CoV (%)	42	29	27	31
$f_{m,k}$	14.8	19.1	16.3	18.2
$f_{m,k,75\% CI}$	13.7	18.2	15.6	17.3
Mean $Density_{384}$	378	401	358	444
CoV (%)	10	9	8	9
ρ_k	324	345	318	385
$\rho_{k,75\% CI}$	318	340	313	380
Strength class (Basic grade)	C14	C18	C14	C18

$f_{m,k,75\% CI}$ is a one tailed 75% confidence interval.

For allocation of timber to a certain strength class, all three properties must achieve the required values (Table 3-2). For example, Table 3-10 shows that MOR was the limiting property to grade to C16 for noble fir (for which $f_{m,k}$ should achieve 16 N/mm²). This was an exception, and for the data here investigated MOE was the main limiting property, with MOR and density values usually satisfying requirements of higher strength classes. Appendixes show in detail the variation of characteristic values for strength classes and species.

Grading allows to preferentially remove the worst material so that the remaining population achieves a higher strength class, at the expense of reducing the yields. Table 3-11 shows the yields for optimum grading to a single grade with a perfect grading machine (as described in EN 14081-2), and real grading yields may be considerably lower (because real machines have indicating properties with lower correlation to grade determining properties).

Yields are shown without considering visual override rejection due to twist. Noble fir was capable of producing a high yield of C16 timber, with Norway spruce and western hemlock achieving the requirements of C18 strength class, and even producing high yields of C20. Western red cedar also produced high yield of C16 timber but less than the other three species.

Table 3-11. Comparison of the optimum yields of timber for a rotation length of 45 years.

		Pieces	C14	C16	C18	C20	C22	C24
Noble fir	Overall	126	100%	96%	78%	64%	52%	33%
	S[1]	34	97%	53%	24%	12%	3%	3%
	M	45	100%	100%	100%	100%	96%	69%
	N[1]	47	100%	87%	57%	45%	30%	11%
Norway spruce	Overall	128	100%	100%	100%	84%	66%	37%
	S	42	100%	100%	100%	100%	79%	43%
	M	35	100%	100%	100%	94%	74%	46%
	N	51	100%	100%	84%	67%	51%	24%
Western red cedar	Overall	115	100%	96%	62%	45%	33%	17%
	S[1]	32	100%	100%	81%	59%	44%	19%
	M	37	100%	100%	92%	73%	57%	32%
	N	46	87%	48%	17%	11%	7%	2%
Western hemlock	Overall	138	100%	100%	94%	80%	67%	41%
	S	49	100%	100%	71%	55%	39%	14%
	M	33	100%	100%	85%	67%	52%	27%
	N	56	100%	100%	100%	100%	89%	68%

Sites: S, south; M, middle; N, north. [1] Noble fir was 30 y/o and 38 y/o in south and north sites respectively, and western red cedar 35 y/o in south site. Yield calculated using MOE_L.

3.4.3.2 Indicating properties (IP) for grading

Perfect grading machine as IP

In order to grade timber it is important to find a strong relationship between indicating properties (IP) that can be measured, and grade determining properties.

Grading machines can operate on many different IPs. Here, a selection of representative IP types were examined and compared to the optimum grading.

The possibility of grading the four species together was also explored, as this would have practical advantages for industry. The pieces were ranked in ascending order of IP measured, and the mean (for stiffness) or the 5th percentile (for bending strength and density) of the population above each IP value was calculated. This allowed to set up thresholds of the IP and the correlation with the characteristics values. This is the same approach used before for optimum grading (see §3.4.3.1).

Figure 3-11 illustrates the optimum grading of MOE_G using the results from the destructive tests. The graph shows the mean MOE_G of the portion that passes the threshold given on the abscissa axis. The graph illustrates that the mean of the whole population of Norway spruce and western hemlock is above the C16 requirement. It also shows that to grade C16 western red cedar a MOE_G of 7 kN/mm^2 is at least required in a piece so that the rest of the population can average to 8 kN/mm^2. The lines coinciding indicates that the species might be gradable together.

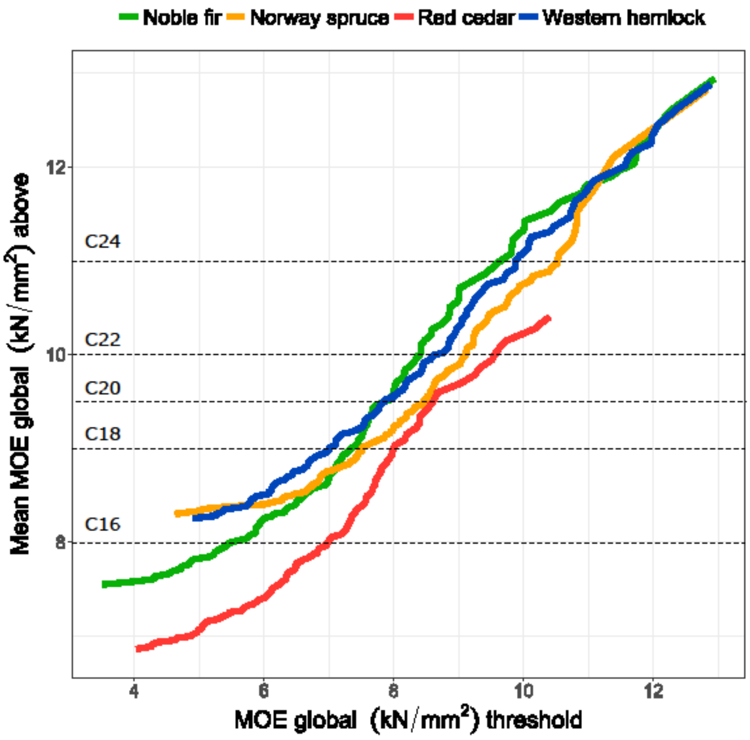


Figure 3-11. Performance of the species using MOE_G as IP.

For machine grading most of the current machines operate based on one or several of the following properties: mechanical stiffness, dynamic stiffness (measured with acoustic techniques), density, size and position of knots.

Chapter 5 will address in more detail the relationship of dynamic stiffness in sawn timber. For now, it is only necessary to know that dynamic stiffness refers to that obtained using the equation $MOE_{dyn} = \rho \times v^2$, where ρ is the wood density (kg/m^3) and v is the speed of sound (m/s) measured in the specimen.

Two widely used IP are the resonance speed and $Density_{timber}$. They were used individually, and in combination to obtain a third IP, dynamic stiffness (MOE_{dyn}).

Dynamic stiffness as IP

Figure 3-12 shows the grading of bending stiffness using MOE_{dyn} and the acoustic speed squared.

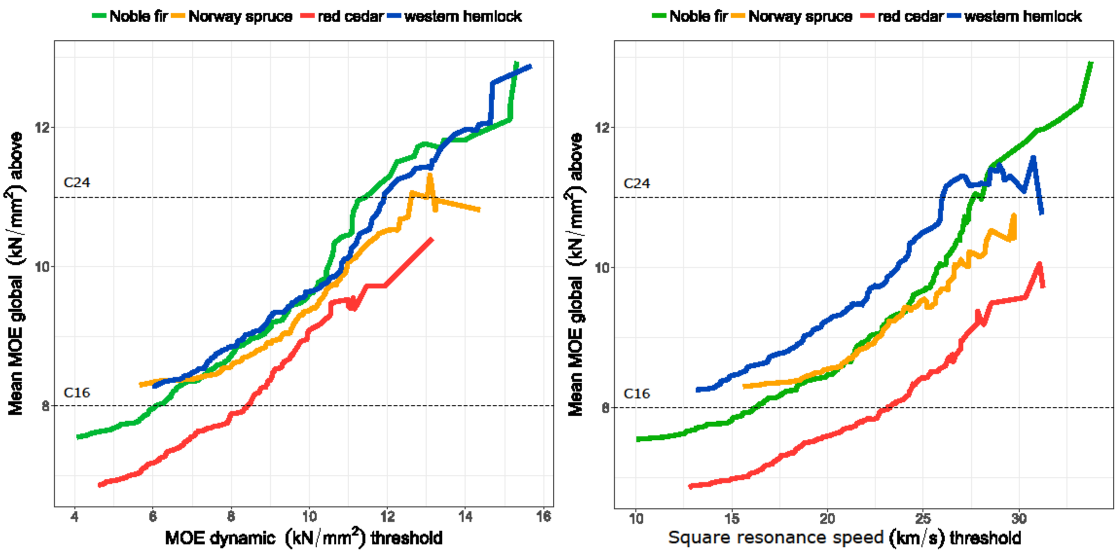


Figure 3-12. Performance of the species using MOE_{dyn} (left) and speed of sound in wood (right) as indicating property to grade timber based on stiffness.

Comparing Figure 3-12 with the optimum grading (Figure 3-11), the use of MOE_{dyn} offered more similar results than the use of speed alone. Using MOE_{dyn} for grading C16 timber (mean of 8 kN/mm^2), it would be possible to grade efficiently noble fir, Norway spruce and western hemlock together establishing for this dataset a minimum of 6 kN/mm^2 in a piece so that the rest of the population can average to 8 kN/mm^2. Western red cedar had a lower mean stiffness than the other three species, and the grading of the four species together would require of a higher threshold, and consequently very conservative grading that would penalise the yield of the other three species.

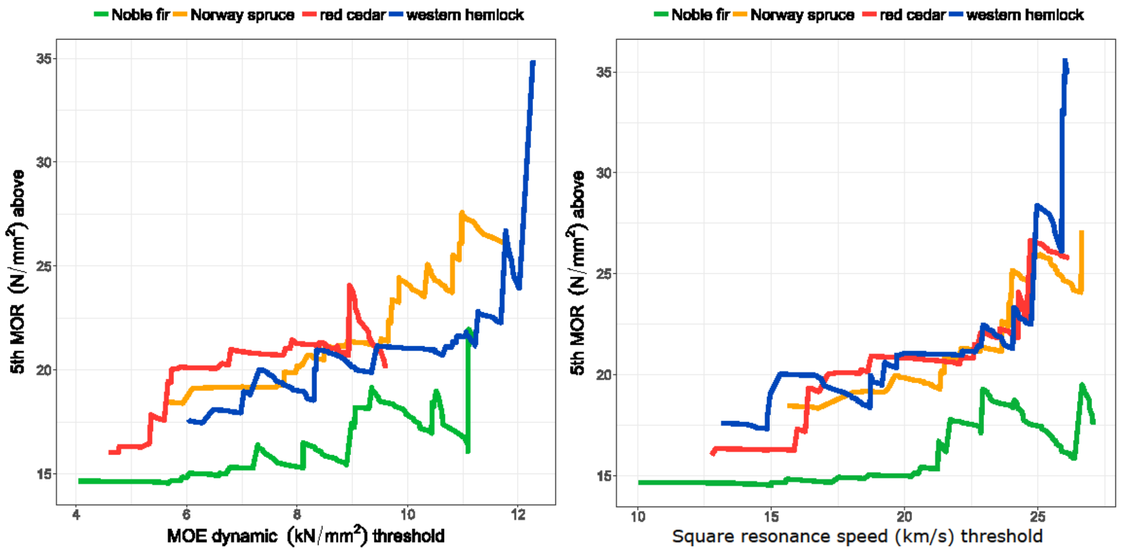


Figure 3-13. Performance of the species using MOE$_{dyn}$ (left) and speed of sound in wood (right) as indicating property to grade timber based on strength.

Table 3-10 and appendixes showed that stiffness was limiting in most cases, but MOR might limiting in some circumstances, in which case the difference in MOR between species becomes more important. The use of MOE$_{dyn}$ and resonance speed as IPs indicated that the four species differed when grading MOR (Figure 3-13). Grading of density showed a big variation between the species (Figure 3-14).

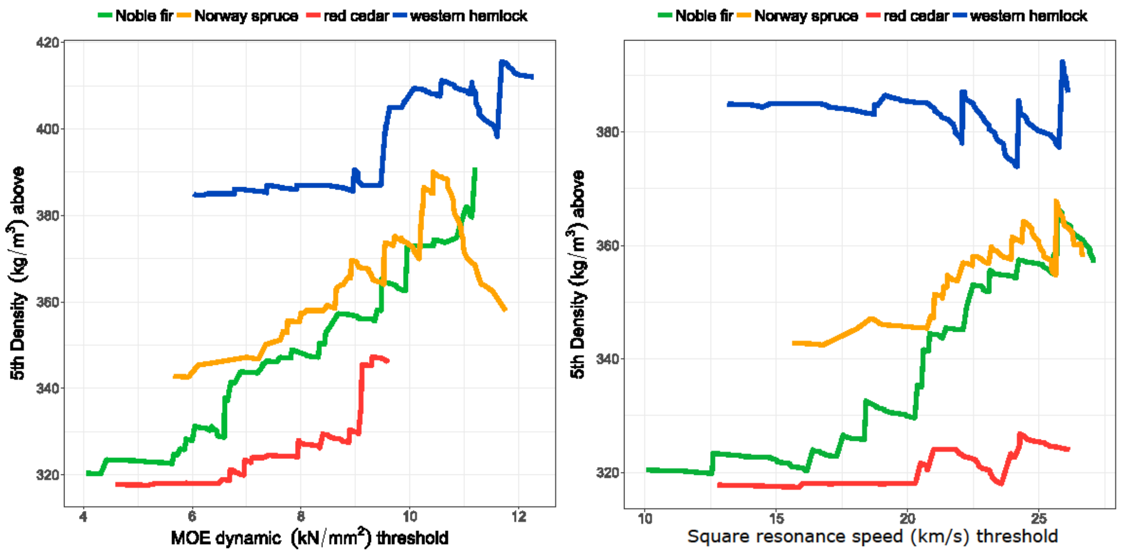


Figure 3-14. Performance of the species using MOE$_{dyn}$ (left) and speed of sound in wood (right) as indicating property to grade timber based on density.

The comparatively higher density of western hemlock, and lower of western red cedar might may make difficult the grading of the two species together, especially if density was the limiting property for grading. Noble fir and Norway spruce on the other hand were more comparable.

Density timber as IP

The use of $Density_{timber}$ as IP was also investigated. Table 3-6 showed that density had a good correlation with MOE in noble fir and Norway spruce, and it was very strong between $Density_{384}$ and $Density_{timber}$ in the four species. Before examining the use of density as IP for grading, the relationship between $Density_{timber}$ and $Density_{384}$ was examined.

ANOVA of a linear model concluded that species affected the intercept term ($F_{3\ 642}$ =13.6, $P<$ 0.001) of the relationship, but not the slope ($F_{3\ 639}$ =1.4, P= 0.24). Figure 3-15 showed that $Density_{timber}$ was slightly higher than $Density_{384}$, and the relationship between them very strong (R^2 = 0.88). Including the categorical variable species did not improve the relationship importantly. The 95% confidence range on slope was between 0.95 and 1.01, and therefore included the relationship 1:1. Figure 3-15 also showed that the $Density_{384}$ can vary in more than 50 kg/m^3 for a certain $Density_{timber}$.

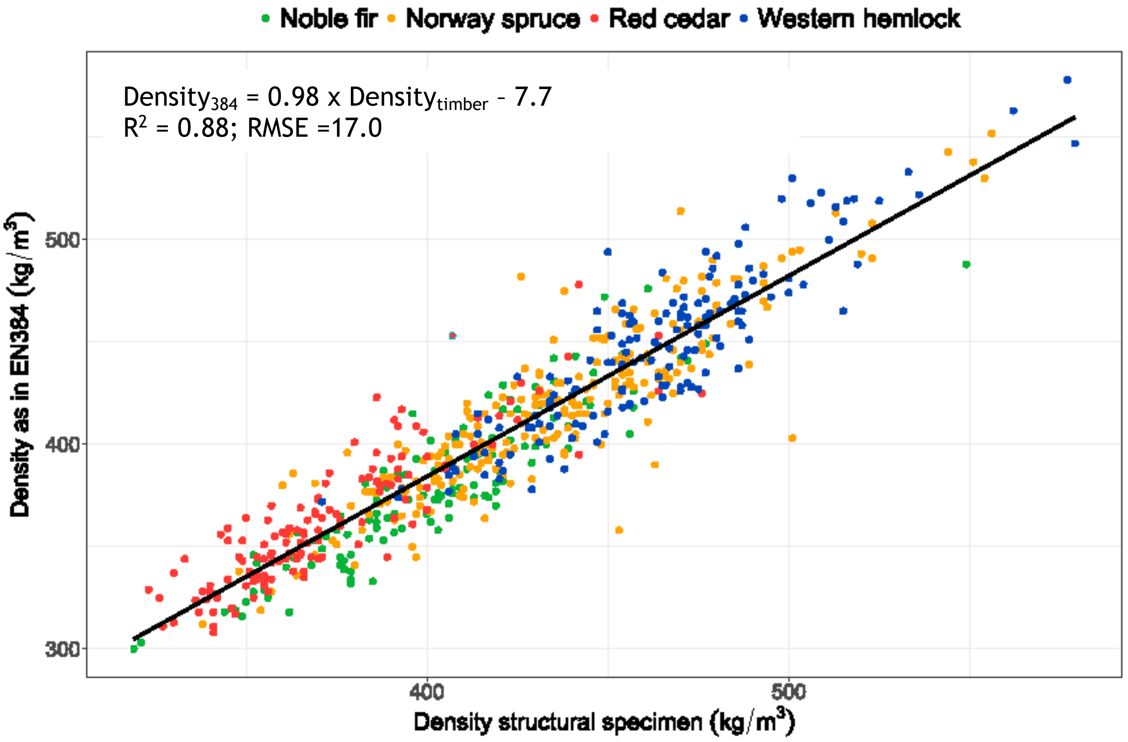


Figure 3-15. Relationship between $Density_{384}$ and $Density_{timber}$.

The higher values of $Density_{timber}$ compared to $Density_{384}$ could be caused by the knots. In order to improve the prediction of $Density_{384}$, additional variables were investigated: *mknot*, *tknot*, *nknot* and age. Only *tknot* (P<0.001) and age (P<0.05) were significant, but they barely improved the prediction of the model. The interaction of species with the variables fit in the model was not significant. The linear model [3-16] was finally chosen, and the resulting values reported in Table 3-12:

$$Density_{384} = \alpha_0 + \alpha_1 Density_{timber} + \alpha_2 Species + \varepsilon \quad [3\text{-}16]$$

Table 3-12. Summary of the chosen model for $Density_{384}$ prediction (kg/m^3).

	Species	Estimate	Std. Error	*P*-value
Intercepts	Noble fir	-26.5	7.7	<0.001
	Norway spruce	-21.3	2.0	0.011
	Western red cedar	-13.0	2.2	<0.001
	Western hemlock	-20.7	2.5	0.019
	Slope	1.01	0.02	<0.001
Equation: $Density_{384}$ = Slope x $Density_{timber}$ + Intercept + error				

If density was the limiting property for grading, the use of $Density_{timber}$ would be a good indicator.

Figure 3-16 shows how the use of $Density_{timber}$ as sole IP for grading performed in the dataset. The same methodology than grading based on acoustic IPs was applied. Western hemlock showed a higher density than the other three species which did not directly translate in higher MOE, in line with results in the chapter. As a result, this species may not fit well with the other three species for grading using density as sole IP.

The four species differed when grading MOR, although western red cedar and Norway spruce showed some similarity, as did noble fir with western hemlock.

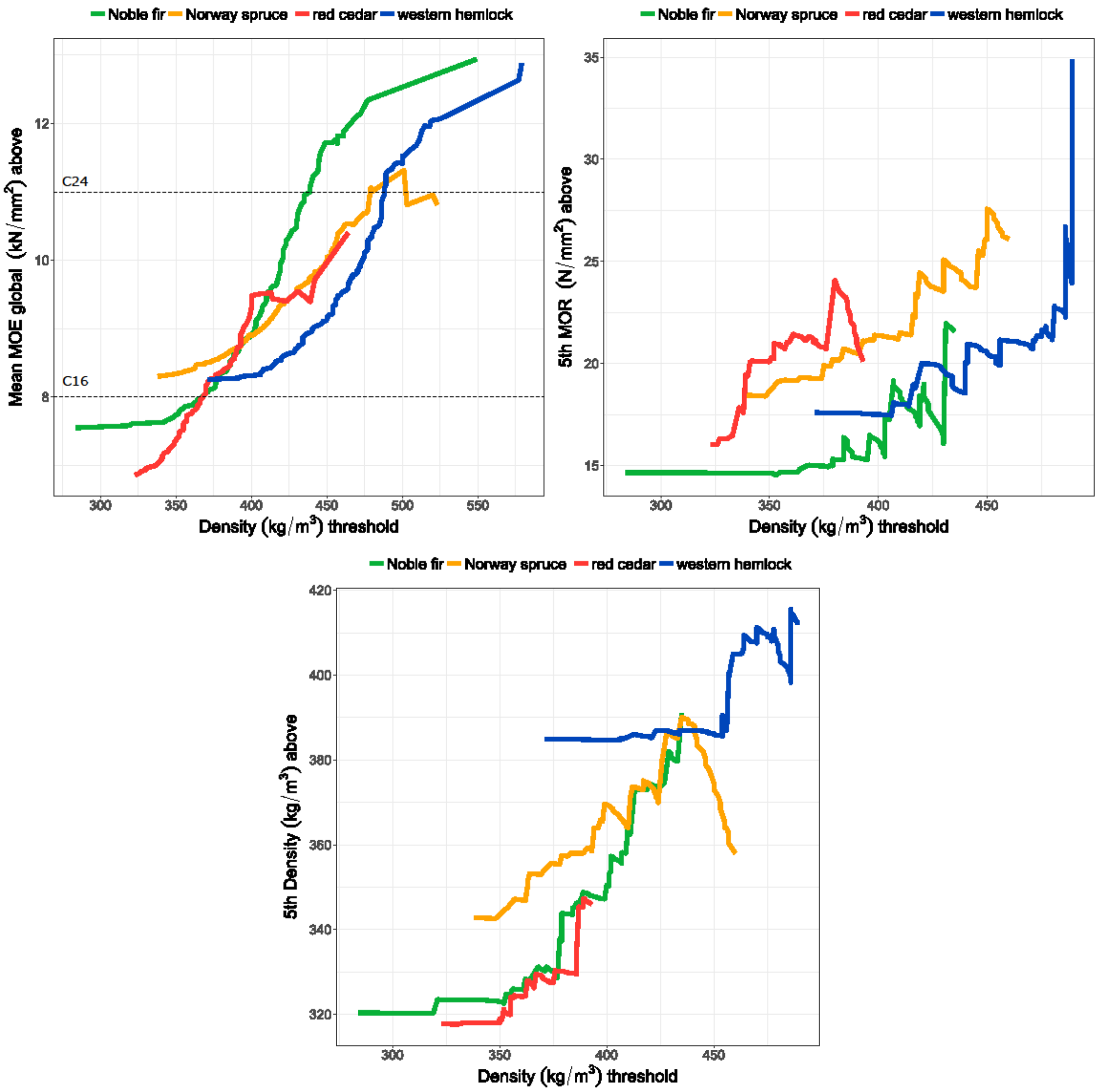


Figure 3-16. Performance of the species using Density_{timber} as IP for grading.

Noble fir and western red cedar showed similar trends for grading density based on Density_{timber}. For the same IP Norway spruce graded higher Density_{384}. The initial flat trend of western hemlock was due to the few number of pieces in that range of values.

3.4.4 Distortion. Twist.

The standard EN 14081-1:2016 specifies the requirements for strength graded structural timber with rectangular cross-sections. The standard refers to a maximum mean m.c. of 20% at the time structural timber is graded for distortion. The pieces in the current study were dried to 12%, and the pieces of western red cedar in the north site to 20% m.c. As a result of the different drying m.c. results of distortion for western red cedar must be considered with care. In terms of twist the 2016 version of the standard establishes a maximum twist of 2 mm per 25 mm width, but sawmills may choose to apply more stringent limits. The previous version of EN 14081 had two limits for twist (2 mm and 1 mm for 25 mm width), and those are used here for comparison with literature, equating to eight and four millimetres for a standard 100 mm width. British sawmills usually apply these distortion limits at about 18% m.c., and so the results here presented reflect the distortion by the time the customer gets it, and do not directly compare to rejection in the mills. The study aimed to compare across the species for a relative judgement, and sawmills may have difference experience and practice.

Only the pieces up to a cambial age of 45 were considered in order that the four species could be compared to current commercial production. A total of 126 pieces of structural timber of noble fir, 128 of Norway spruce, 94 of western red cedar (46 from the north site) and 138 of western hemlock were analysed for distortion. On 21 pieces of western red cedar the collapse suffered during drying caused grooves or corrugations that made impossible to measure twist.

Noble fir showed a wider range and higher twist values than the other three species (Figure 3-17, left). ANOVA test showed that the mean twist was not equal ($P<0.001$) on the four species. The following posthoc Tukey test indicated that there were differences between all pairs except western red cedar-western hemlock (Figure 3-17, right).

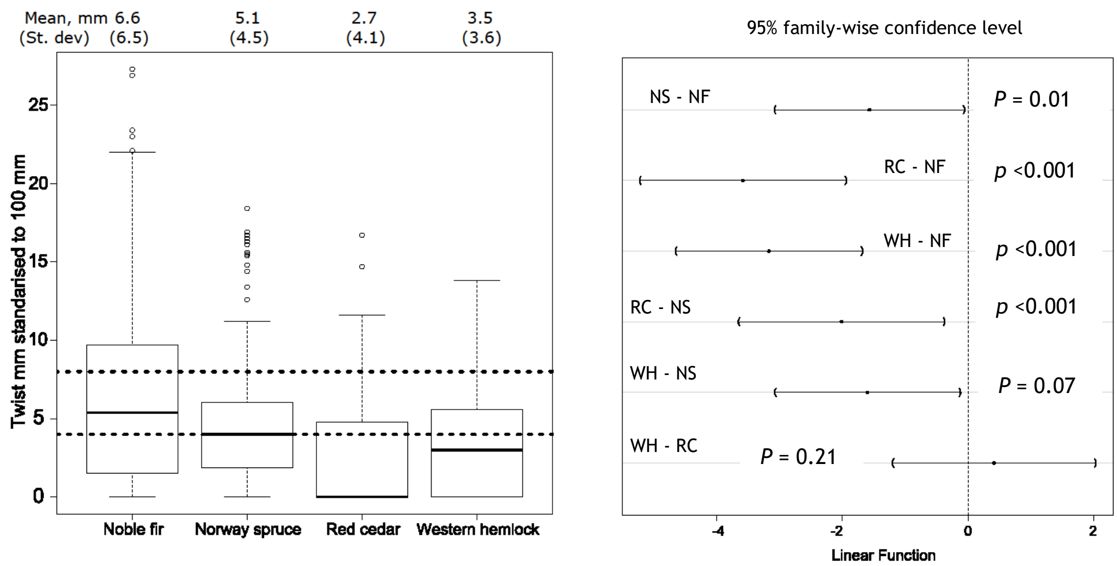


Figure 3-17. Left: Distribution of twist by species with limits 1 and 2 mm/25 mm width. Right: Tukey's HSD confidence interval at the 95% family-wise confidence level.

Twist was not present in 38 pieces of western red cedar from the north site (kiln dried to 20% m.c.), and the other eight pieces had less than four mm of twist. Between the other three species, western hemlock was the one less prone to twist and noble fir the most. Outliers of Norway spruce (ten pieces) corresponded to pieces from near the pith (nine specimens containing the pith and another one in radial position 2). A significant difference in twist was observed between radial positions (*P*<0.001). Figure 3-18 shows the influence of the radial position in the appearance of twist (position 5 is not shown due to the low number of pieces).

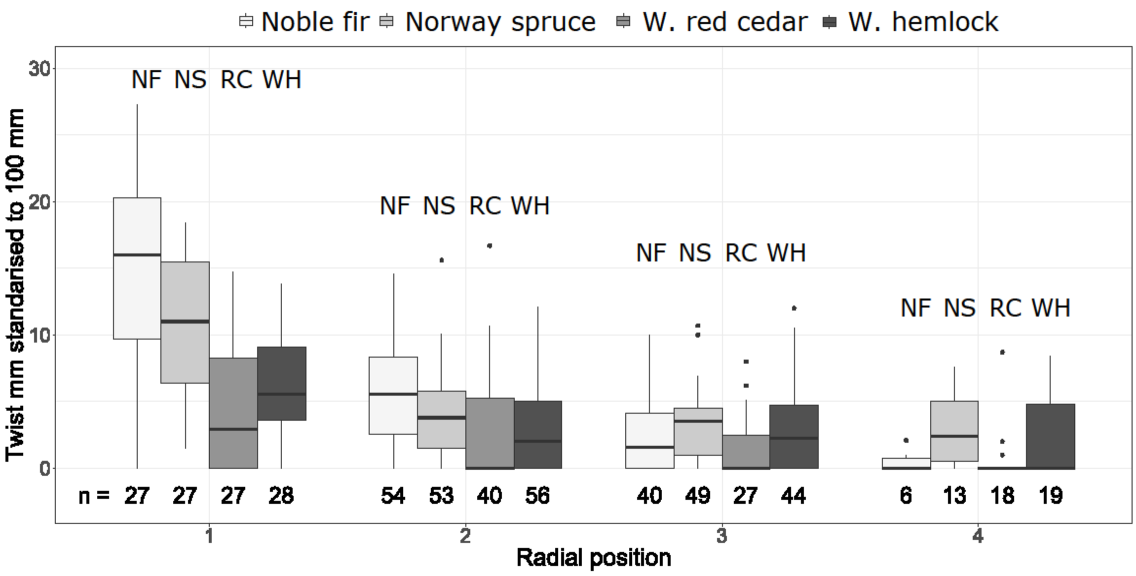


Figure 3-18. Presence of twist on structural pieces by radial position; "n" is the number of pieces.

Table 3-13 shows the passing rates of structural-size timber for twist according to EN 14081 for the data studied. By removing the samples containing the pith the passing rate increased, particularly in noble fir.

Table 3-13. Pass rates of timber pieces up to 45 y/o for twist.

	2 mm / 25 mm width		1 mm / 25 mm width	
	All	No Pith	All	No Pith
Noble fir, 12% m.c.	67 %	83 %	43 %	54 %
Norway spruce, 12% m.c.	83 %	95 %	49 %	61 %
Western red cedar, overall	86 %	93 %	69 %	80 %
12% m.c.	73 %	80 %	40 %	47%
20% m.c.	100 %	100 %	100 %	100 %
Western hemlock,12% m.c.	87 %	92 %	61 %	66 %

Once again, it must be stressed that the presence of collapse in some pieces of western red cedar affects these results. This lead to discard thirteen and eight pieces from radial positions 2 and 3 respectively, although it must also be noticed that none of the pieces from radial position three dried to 12% m.c. had more than eight mm of twist.

3.5 Discussion

This chapter showed that wood properties and twist varied for the four species investigated, but also that there exist an important influence of radial variation within a tree. For the data collected, the study determined that, overall, noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. can produce timber capable of meeting the quality required for structural construction.

In general, older stands achieved higher values in the wood properties studied, and they tended to increase outwards in the radial direction. Therefore, trees produced in general material with properties more suitable for timber construction as they grew. This was consistent with other studies (Kliger et al., 1998; Moore et al., 2012; Moya et al., 2013) that investigated the influence of rotation length in timber quality.

Although age was important there were other factors having an influence. Overall, Norway spruce and western hemlock had higher values of the wood properties studied. In the middle region, and comparing only pieces for a rotation length of 45 years, noble fir performance was comparable to Norway spruce, although the sites were different. The other two sites of noble fir were very young, and properties would probably be better had it been possible to sample trees of a comparable age to the other species investigated. On the other hand, western red cedar performed less well for structural purposes, and in particular the northern site achieved considerably lower values than the other two sites despite being an older stand. The reasons for this are unknown, and can be due to a latitude effect, genetics, or some other factors. Nevertheless, in its native land western red cedar has also low bending strength and very low stiffness, and it is not widely used as structural components (Minore, 1983; USDA, 2010).

Another feature than changed with radial position, and that may have particularly an influence in the increase of MOR was the decrease of knots content, both in number and total knot area. A study on Sitka spruce with a similar cutting pattern (Moore et al., 2012) observed this difference comparing a piece containing the pith, and a piece from the outerwood. The current study found significant differences between most of the radial positions. Norway spruce had more knots than the other three species, mostly due to the knots near the pith, and there was no significant difference in the total area compared to noble fir and western hemlock. This must be understood as Norway spruce having a smaller size of knots.

The analysis of the variation of the mechanical properties due to the different stratum in the experiment found that within tree variation was the most important attribute governing the differences in mechanical properties. Other studies studying one species also attributed most of the differences in mechanical properties to within tree variation (Table 3-14). A study on 12 sites of Sitka spruce (Moore et al., 2013) found a higher variation of the site attribute compared to a study on Scots pine (Moore et al., 2008) or in general in the present study, both on three sites. However, the influence of site in noble fir was very high, particularly for density. One reason explaining the higher effect of site in noble fir may be the age of the stands, as the two youngest crops (30 and 38 years old) were stands of noble fir, and the average of only three sites were heavily influenced by each site. This could have resulted in a bigger proportion of corewood compared to the older noble fir forest (58 years old), and therefore provoking the difference between sites. It could also be hypothesised it was due to the use of different provenances, but this thesis could not collect information on the origin of the seed lots. A study on the effects of genetics on the wood properties of Sitka spruce (Moore et al., 2009d) observed differences in density between two seed lots growing in the same region, but did not find differences in the mechanical properties.

Table 3-14. Variation in wood properties attributable to different stratum in Sitka spruce (Moore et al., 2013) and Scots pine (Moore et al., 2008).

		MOE_{PB}	MOR	Density[1]
Site	Sitka spruce	26.3%	18.3%	22.7%
	Scots pine	6.0%	3.4%	<0.01%
Plot	Sitka spruce	n/a	n/a	n/a
	Scots pine	1.0%	<0.01%	0.5%
Tree	Sitka spruce	36.2%	25.2%	51.1%
	Scots pine	24.9%	8.0%	9.8%
Log	Sitka spruce	2.2	1.4	4.5
	Scots pine	14.7	30.2	43.2
Piece	Sitka spruce[2]	35.3	24.9	51.9
	Scots pine[2]	53.9	58.5	46.5

[1] Specific gravity in Scots pine; n/a: effect of plot was not measured.

The properties studied for grading (MOE, MOR and density) kept in general a good correlation. MOE_G and MOE_L had a very strong correlation, and an empirical conversion equation was derived [3-3] to convert MOE_G to MOE_{PB}. The equation fits better to British timber, typically of low stiffness, than the general one [3-1], and provided a shear-free or true pure bending modulus (MOE_{PB}). MOE_G is more likely to be measured than MOE_L in relation to grading because MOE_L is more susceptible to errors in measurement and more time consuming, but it needs to be stressed that the equation presented here may not be translatable to the whole country, and the relationship may depend on the test machine and set-up. Density also had a good correlation with mechanical properties, stronger with MOE than MOR, and better in noble fir and Norway spruce.

The performance of the wood properties determined that timber produced from noble fir, Norway spruce, western red cedar and western hemlock were capable of producing high yields of the most commonly used strength class in G.B. C16, comparable to the performance of Sitka spruce and Douglas fir (Table 3-15).

Table 3-15. Wood properties for Sitka spruce (Moore et al., 2013) and Douglas fir (Drewett, 2015) in G.B.

	MOE_{PB} (kN/mm^2)	MOR (N/mm^2)	$f_{m,k}$ (N/mm^2)	Density (kg/m^3)	ρ_k (kg/m^3)	S.C.
Sitka spruce	8.3	32.7	19.6	387	330	16
Douglas fir	9.2	34.1	17.2	455	370	16

Age range was 35-45 for Sitka spruce and 42-58 for Douglas fir; S.C.: Strength class

These yields are based on destructive tests, but the lack of a perfect correlation between wood properties measured by a grading machine implies that actual yields achieved in practice could be lower than those reported in Table 3-11, as those are optimum yields calculated from measurements in a laboratory.

The use of some of the most common IPs was investigated, and despite the differences observed in the performance of the species, it was raised the possibility of grading the four species together. This would be a good way to get the four species into industrial use as a minor component added to an already well-established species mix. Special attention was put on MOE because it was the main limiting property for grading. MOE_{dyn} resulted a very good IP for grading MOE, offering very close results to the measurements of MOE in bending. The results indicated that grading the four species together may be possible under conservative settings, which would limit the potential of some of the species.

$Density_{timber}$ was also investigated as IP because it was found to have a strong relationship with $Density_{384}$, that could almost be described as 1 to 1. The measurement of knots did not add any useful information for prediction of $Density_{384}$, and so density measured in small clears may give a good indication of density in structural-size timber, which will be examined in Chapter 4. Despite the strong relationship between both densities, grading the four species together for MOE using density as sole predictor variable may not offer good results because MOE in western hemlock was not comparatively as high as it could have been expected from the high density values.

Regardless of the wood properties, timber can be rejected due to an excessive drying twist. Twist correlated weakly with wood properties, except noble fir that showed a moderate correlation with MOE. A study on Norway spruce (Johansson et al., 2001) also found a weak relationship between density and twist (R^2=0.12). A recent PhD thesis (Canavan, 2017) found strong correlations (r=0.73 to 0.83) between twist and acoustic velocity (used as indicator of dynamic MOE) in pieces of Sitka spruce using a relatively small number of pieces (36 specimens from six trees). Whether results would be representative of a larger population, and due to a difference behaviour of species would require a further investigation. Western red cedar showed a positive correlation of twist with the wood properties, but this could be influenced by the higher m.c. of drying.

Despite the lack of correlation, in line with the wood properties twist was also influenced by the radial position. The higher the quality of the piece of timber the less prone to twist it was, that is, material containing the pith was more prone to distortion, and outer pieces met higher wood quality and twist was lower. This was consistent with findings in Sitka spruce, both comparing radial positions (Moore et al., 2012), and inner and outer wood (Moore et al., 2009a) for which mean values of twist were one third lower in the outerwood (5.6 mm) than in the corewood (8.5 mm). A study on Norway spruce (Perstorper et al., 1995b) found for a similar cutting pattern a passing rate of 49% for a 5 mm limit when drying samples to 12% m.c., similar to results in this chapter (49.2%) for the 4 mm limit.

Comparing British grown species dried to 12% m.c., a study on Douglas fir (Drewett, 2015) found 90% of pieces passing the 8 mm threshold given in EN 14081, whereas other on British spruce (Searles, 2012) found 57% of pieces passing the 8 mm threshold. The four species investigated in the current thesis showed higher passing rates than Sitka spruce, with Norway spruce and western hemlock similar to Douglas fir. Results for western red cedar must be treated with care because pieces from the northern site (46) were kiln dried to 20% whereas the rest of specimens from the four species (491) were dried to 12%, lower than what the sawmills would normally dry to. It must be noted that a full study of twist would need to also include the effects of cutting patterns and kilning conditions.

This chapter has shown evidence that the wood properties of the four species studied perform comparatively well to British spruce for a similar rotation length, and they could be a good option to diversify and broaden the timber resource in G.B. Efforts now must address the replication of planted forest in the same sites so that different silviculture regimes can be assessed, particularly for Norway spruce to identify possible differences with Sitka spruce, as well as noble fir and western hemlock. Western red cedar may be consigned to non-structural uses.

3.6 Conclusions

This chapter has demonstrated for the first time that in addition to the already used Norway spruce, it is possible to grow British timber capable of meeting the most common quality required for structural construction from noble fir, western red cedar and western hemlock. In particular Norway spruce and western hemlock arose as a good complement to diversify and increase the timber resource in G.B.

The variation of wood properties with radial position ruled the difference between pieces. The key structural wood properties of stiffness, strength and density were examined, as well as the distribution of knots and the potential influence of twist in grading. The four species were potentially capable of producing high yields of C16 (the basic customary strength class used in the United Kingdom) for a rotation length of 45 years. In particular, Norway spruce and western hemlock produced high yields of C18 showing in addition lower twist than Sitka spruce. On the other hand, noble fir and western red cedar achieved a lower performance, but still capable of achieving C16 strength class in favourable sites. The outerwood timber of the species studied showed high performance of the wood properties associated with a lower twist, making this timber more suitable for structural applications.

Overall, timber stiffness resulted the limiting property for strength grading. Grading machines based on measurement of MOE_{dyn} appeared as potentially capable of grading the four species together for C16 or higher under conservative settings. With a shift towards continuous cover forestry in G.B., this opens the possibility to grade timber of different species like Norway spruce and western hemlock together. The material collected for this thesis was limited, compared to what would be required for grading machine settings.

Further research is required in order to investigate the performance in different growing regions and produce grading machine settings and possible species combinations.

Chapter 4. Wood properties. Clears.

4.1 Introduction

Clears are pieces typically sawn to dimensions of 300 x 20 x 20 mm in the longitudinal, tangential and radial directions. They lack of defects, and their mechanical properties represent the best potential performance of wood for a tree, stand or species in a growth area.

Compared to structural pieces, clears enable the study of the variability of wood by assessing the change in properties as trees age, without the complicating influence of defects, mainly knots, and with a higher resolution with respect to annual growth rings. This allows to produce guidance on the rotation length of forest plantations. Clears can also help to determine the effect of silvicultural treatments and genetic assessments on natural and planted forests even from early years (Ivković et al., 2009; McLean et al., 2016). In addition, clears are easier to produce, condition and test.

There is little data on the mechanical and physical capabilities of noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. This chapter examined the bending stiffness, bending strength and density on clears. The variation of wood properties between species, the performance and the variation with age was investigated. Previous studies (Auty et al., 2014, 2016; Gardiner et al., 2011) have modelled the radial variation of properties of one species, but this chapter aimed to build models that can be used simultaneously for different species. Finally, results of clears and structural-size pieces were compared to investigate the relationship between both.

Results help examining at which stratum of the experiment the variation between wood properties occurs, and then explore it with a higher resolution with respect to annual growth rings than structural pieces. Ultimately, results help understanding the effects of rotation length on the species.

4.1.1 Objectives

The aims of this chapter for the four species investigated are:

1. The variation in wood properties between and within trees.

   Quantify the variation of bending stiffness, bending strength and density due to species, sites, plots and trees.

2. The performance of wood properties.

   Examine and compare the performance the three wood properties and the relationships between them.

3. To model the radial variation of wood properties.

   Model the variation of wood properties with age.

4. Prediction of structural quality timber from clears.

   Examine the relationship between the wood properties of clears and structural timber at piece, tree and population level.

4.2 Literature review

Table 4-1 presents some data on the performance of the species in their native lands, where like with structural pieces there is a more extensive experience on clears than in G.B.

Table 4-1.Values published in literature for small clears from trees in their native lands.

	MOE (kN/mm^2)	MOR (N/mm^2)	Specific gravity
Noble fir[1]	11.9	74.0	0.39
Norway spruce[2]	10.4	71.8	395[3]
Western red cedar[1]	7.7	51.7	0.32
Western hemlock[1]	11.3	78.0	0.45

[1] published in (USDA, 2010); [2] published in (Haartveit and Flæte, 2006); [3] Density (kg/m^3) at 12% m.c.

There is only one major publication (Lavers, 2002) reporting values for British grown material (Table 4-2), of which first edition dates back to 1967. This publication provides values based on small clears, but the amount of data is limited, and the site, age and silviculture methods are unknown.

Table 4-2.Values published in literature (Lavers, 2002) for small clears.

	n	MOE (kN/mm^2)		MOR (N/mm^2)		Density (kg/m^3)
Lavers		Mean	CoV	Mean	CoV	Mean[1]
Noble fir	42	8.1	0.18	63	0.13	368
Norway spruce	1382[2]	8.5	0.20	66	0.16	400
Western red cedar	107	7.0	0.26	65	0.16	368
Western hemlock	125	8.0	0.22	76	0.19	433

n: number of pieces; Density at 12% m.c.; [1]Standard deviation no published for density; [2]MOR was obtained from 1383 pieces.

Chapter 3 examined the variation of wood properties with radial position, but the use of clears allows to compare wood free of defects, exclusively assessing the change in properties with age, and in more detail with respect to annual growth rings due to the smaller sample size.

It is widely accepted that slow-growth softwood plantations, associated with a longer rotation length tend to produce timber of higher quality for structural purposes compared to fast-growth and younger crops (Butterfield, 2003; Kliger et al., 1998; Moore et al., 2012; Moya et al., 2013; Zhang, 1995). This is largely a consequence of a higher volume of outerwood in comparison to corewood, of poorer mechanical performance. Efforts to increase the understanding on the correlation and variation of wood properties are necessary to improve the management for timber production.

Different indicators and the correlation with wood properties have been examined in order to model this variation, for example ring width due to the confounding effect with age and wood properties. Microfibril angle has been also widely used. Density has been stated *is most likely the best single predictor of mechanical properties of clear, straight-grained defect-free wood* (Zink-Sharp, 2003). It relates to changes in the wood structure and it is easy to be measured, making density a common indicator of wood quality (Desch and Dinwoodie, 1996; Savidge, 2003). In addition, some authors found that density is well correlated with many other properties (Saranpää, 2003), in particular MOR (Alteyrac et al., 2007a; Dinwoodie, 2000).

Mechanical properties commonly relate well with age, and they tend to increase as trees ages, but the increment can happen at different rates. The change in wood properties from corewood to non-corewood occurs over several years, and the transition may be more abrupt or smooth depending on the particular wood property and species. The rate of change can be more pronounced in the first years of growth from the pith, and subsequently slow down, levelling out to a constant maximum value at a certain point.

Density on the other hand may show different trends. In some species like loblolly pine (Mora et al., 2007), radiata pine (Kimberley et al., 2015) and Scots pine (Auty et al., 2014) density consistently increase from the pith outwards. Other species like Douglas fir (Bawcombe, 2012), and the most important conifers for structural purposes in the Pacific Northwest of North America show a low inflection point in the first years. The same pattern was observed in Sitka spruce in G.B. (Gardiner et al., 2011)

At the time of writing there is not much literature published on the radial variation of MOE and MOR for the four species studied. Only one study was found, and described the MOE_C and MOR_C of western hemlock (Kennedy, 1995)[1]. Most of the examined literature available studying the radial variation of wood properties focused in density, particularly for Norway spruce (Jyske et al., 2008; Mäkinen et al., 2007; Saranpää, 1994, 2003), and less for western red cedar (Cown and Bigwood, 1978) and western hemlock (Jozsa et al., 1998; Middleton and Munro, 2001). The three species described a profile with high density near the pith, decreasing for the first years, and increasing thereafter. The location of this inflection point varies between species, and it has been speculated that a more shade tolerance behaviour delays the time at which the minimum value is reached (Kennedy, 1995). No literature was found concerning the variation of wood properties with age in noble fir.

Some authors have modelled the wood properties of different species using density and age together, or as sole predictor variables. Leban and Haines (1999) modelled dynamic stiffness in larch as a non-linear function of age, and using a linear regression with age and density as sole independent variables. In

[1] Work by Ellis, S., Faculty of Forestry, University of B.C.

the same line, studies on Scots pine (Auty and Achim, 2008; Auty et al., 2016) and Douglas fir (Drewett, 2015) described the mechanical properties with density, and as a non-linear function of age.

Whether the mechanical properties are better modelled with density or age, may depend on the species, and the profile described in the radial direction, particularly for density. This chapter aimed to know how wood properties develop over time, adding knowledge about the rotation lengths required to achieve certain wood quality.

Due to the advantages that producing and testing clears offer this is frequently a previous step to testing structural pieces. However, the estimation of the possible performance of structural pieces from small clears values is complicated. In order to convert values from small clear pieces to working stresses of timber heuristic reduction factors are typically used (Dinwoodie, 2000), due to the presence of defects. Values of MOE_C are not typically reduced to estimate structural timber values (Desch and Dinwoodie, 1996) because knots are believed to have only a slight effect on MOE (Kretschmann, 2010), and so it is expected to be very similar in both structural timber and clears. Butler (2016) compared the wood properties of individual clears and structural pieces of loblolly pine. The clears were 25 x 25 x 410 mm and had been obtained from near the failure point of structural pieces previously tested to destruction. The clears were separated and tested into categories depending on the orientation of the growth rings. The direct comparison of results between the mechanical properties of both sample size was poor, and comparing the densities was moderate. The relationship between mechanical properties improved when both specific gravity and radial location were considered.

Prior to this thesis, a study in G.B. (Ramsay and Macdonald, 2013) used a small amount of published data for small clears (Table 4-2), and based on assumptions and experience with Sitka spruce in G.B. estimated the possible performance of structural prices (Table 4-3). The estimates gave values close to those measured for structural timber in Chapter 3 (Table 3-4), although underestimated the mean MOE_G of western hemlock by 12%, and used smaller coefficients of variation to calculate the 5th percentiles than those obtained in the current dataset.

Table 4-3. Estimates for structural size timber in Ramsay and Macdonald, 2013.

	MOE (KN/mm^2)	MOR (N/mm^2)		Density (kg/m^3)	
	Mean	Mean	5th percentile	Mean	5th percentile
Noble fir *	7.7	31.5	21.1	388	324
Norway spruce	8.08	33	22.1	412	344
Western red cedar	6.65	32.5	21.8	388	324
Western hemlock	7.6	38	25.5	447	373

* Estimates not published. Values calculated from the same model and assumptions.

In summary, the aim of this chapter is to investigate the bending stiffness, bending strength and density of clearwood in the four species studied grown in G.B. Particular focus is put in the change of properties with tree age, in more detail with respect to annual growth rings compared to structural pieces. The results help showing some evidence of the variation of the properties with age between species, and in particular the models suggested can help stand growth simulations, and in the decision-making of the forest management.

4.3 Material and methods

4.3.1 Material and methods

The methods of sampling, processing and testing of small clears were fully described in Chapter 2 Material and methods. A summary is provided below.

- Three even-aged single species planted stands from different latitudes.
- Nine trees per species and site, except ten western hemlock in the north.
- One log of roughly 1.6 m per tree, with the bottom part above the log processed for structural pieces, at approximately 4.5 metres height.
- A central slab containing the pith was sawn along the length of each log, for each of which a series of clears was processed from the pith to the bark.

A total of 878 small clears were tested: 200 noble fir, 244 Norway spruce, 214 western red cedar and 220 western hemlock. In some trees more than one clear per radial position was obtained, which accounted for 133 additional samples out of the 878 pieces. All the clears were considered in the analysis unless otherwise stated.

Table 4-4. Specimens obtained by species. In brackets extra samples obtained.

Species	South	Middle	North	Total
Noble fir	49 (+4)	63 (+13)	61 (+10)	173 (+27)
Norway spruce	57 (+29)	65 (+25)	67 (+1)	189 (+55)
Western red cedar	48 (+13)	53 (+18)	81 (+1)	182 (+32)
Western hemlock	64 (+6)	49 (+13)	88 (+0)	201 (+19)

Some clears (17), generally those containing the pith, contained some type of defect, primarily small knots of generally less than 5-mm. These defects did not coincide with points of failure of the clears and so their data were maintained within the analysis. Three samples contained abnormally low values, however there was no objective reason to discard them. In one sample the age was not recorded. The structural pieces used for comparison of wood properties were the same samples described in chapter 3.

4.3.2 Methods

The sampling method was designed so that the variation of wood properties with age could be studied. The rings number from the pith were identified, and recorded for every clear. After bringing the clears to a constant mass (20 °C and 65 % relative humidity) the density was measured, and destructively tested in three-point bending tests to calculate bending stiffness and bending strength. The three-point bending tests followed the methodology established in the standard BS 373.

4.3.3 Statistical Analysis

The statistical analysis was carried out with the R open-source statistical programming environment (R Development Core Team, 2016).

1. <u>To quantify the variation of wood properties between and within trees</u>.

For each property, a random effects model was used to estimate the variance components of the hierarchical data structure as explained in equation [2-6]:

$$y_{ijklm} = \mu + Sp_i + S_{j(i)} + P_{k(ij)} + T_{l(ijk)} + \varepsilon_{m(ijkl)} \quad [2\text{-}6]$$

where y_{ijklm} is the individual observation (measurement) of the variable investigated (MOE_C, MOR_C or density) on an individual sample, μ is the overall mean and the random effects (*Sp, S, P* and *T*) are assumed to be independent and to follow a normal distribution.

2. To examine the bending stiffness, bending strength and wood density.

The distribution of clears and wood properties by age group were investigated. This gave a preliminary insight into of the evolution of wood properties with age. Sub-samples of similar ages were established to compare the properties between species, minimising the influence of older stands. A single one-way ANOVA analysis examined the differences between species in the mean values of the wood properties. Pearson's correlation measured the strength of relationships between variables. In order to test if the relationship between properties was affected by species, a GLM was examined:

$$WP_1 = \alpha_0 + \alpha_1 WP_2 + \alpha_2 Species + \alpha_3 WP_2{:}Species + \varepsilon \qquad [4\text{-}1]$$

where WP_1 is the dependent variable, α_0 is the regression coefficient of intercept, α_1 is the regression coefficient of slope, α_2 represents the additive effect of the species studied and α_3 is the interaction term between WP_2 and species, and ε is residual error not explained by the model. ANOVA was conducted on this model in order to test if species was significant, and therefore a different relationship between properties (WP_1 and WP_2) exists per species.

3. To model the radial variation of wood properties.

Different functions, both linear and non-linear, were investigated to model the variation of wood properties with age. The models were compared using the Akaike's information criterion (AIC) and likelihood ratio tests. The best model was fitted again using the maximum likelihood method for parameter estimation using a mixed-effects modelling approach. The random effects always consisted of site, plot and tree. The models took into account the nested structure of the data collection in the experiment. The inclusion of random slopes was tested with the lme4 package in R (Bates et al., 2014). Parameters were considered significant when $P<0.05$.

4. To predict structural quality timber from clearwood.

MOE_C in clears was compared to MOE_G in structural-size timber because both cover the whole length of the piece and both are subjected to shear stresses. Due to the differences in dimensions and to cover a similar age-range of wood, it was considered that two clears should be fit per structural piece. The mean of the two clears was compared with the corresponding structural piece. To account for the practical limitations of this method, such as the kerf created by the cut saw, the following scheme was estimated (Figure 4-1):

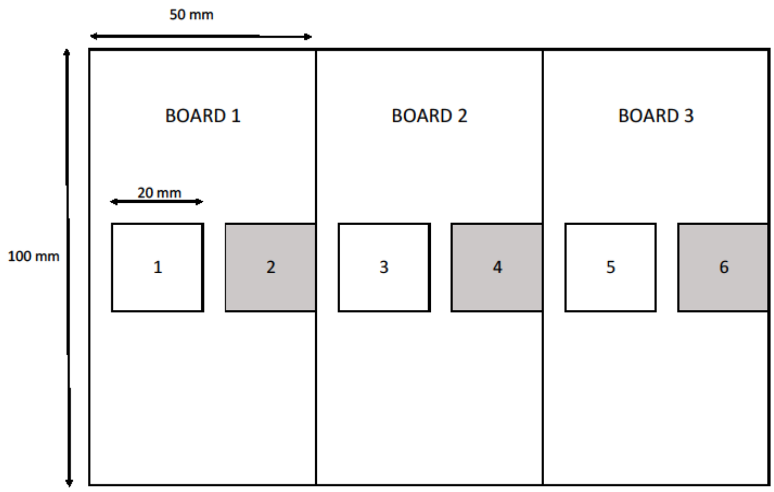


Figure 4-1. Scheme of clears contained per structural piece.

The clears were obtained at a higher position in the standing height of the tree than the structural pieces, and so the radial section covered was smaller. For this reason the outermost structural pieces were not represented by clears. Some structural pieces which contained the pith did not have an equivalent clear and were removed for the analysis. Similarly, structural pieces were removed from the analysis where the number of clears obtained per tree was uneven. A total of 327 structural pieces were compared with associated pairs of clears. The mean values of clears and structural pieces per tree were also studied.

4.4 Results

4.4.1 Variation in wood properties

The variation attributable to the different strata in the data indicated that most of the overall variation occurred within trees (Table 4-5). Variation attributed to differences between species was more important for density. There was not much variation between plots within the same site.

When considering species individually, between 67% and 93% of variation was attributed to differences within trees, depending on the species and property investigated. The second-largest source of variation was generally between trees within a plot. Noble fir was an exception showing a larger variation due to site than the other three species. Interestingly, western hemlock showed minute variation in density due to site. Plot was, in general, the stratum causing the lowest variation, particularly western red cedar showed barely any difference due to plot for any of the wood properties investigated.

Table 4-5. Percentage of total variation in MOE, MOR and density values attributable to each stratum in the experiment.

	Species	Site	Plot	Tree	Within tree
MOE					
Overall	17.0%	6.8%	0.3%	3.0%	72.8%
Noble fir		14.1%	<0.01%	<0.01%	85.9%
Norway spruce		4.0%	3.9%	11.4%	80.7%
Western red cedar		7.3%	<0.01%	8.3%	84.4%
Western hemlock		4.9%	<0.01%	1.7%	93.4%
MOR					
Overall	27.6%	6.3%	1.2%	12.3%	52.6%
Noble fir		20.9%	3.3%	3.9%	71.9%
Norway spruce		5.6%	3.1%	15.9%	75.5%
Western red cedar		10.6%	<0.01%	22.6%	66.7%
Western hemlock		3.4%	2.8%	21.1%	72.6%
Density					
Overall	39.9%	4.1%	2.5%	9.5%	44.2%
Noble fir		21.3%	2.7%	0.0%	76.0%
Norway spruce		5.6%	3.1%	15.9%	75.5%
Western red cedar		3.5%	<0.01%	10.4%	86.1%
Western hemlock		<0.01%	10.4%	14.8%	74.7%

These results highlighted the importance of the radial variation in the modelling of wood properties. The next section moved on to discuss the relationship between wood properties and the variation with age.

4.4.2 Performance of wood properties.

4.4.2.1 Comparison of wood properties.

Firstly, the distribution of data across age classes was explored using the annual ring of the clear from the pith (Figure 4-2). The interval of four years was chosen based on the common rule of dividing the range of the variable studied, in this case 60 years, by the square root of 200 pieces, which was the smallest number of pieces obtained for one species.

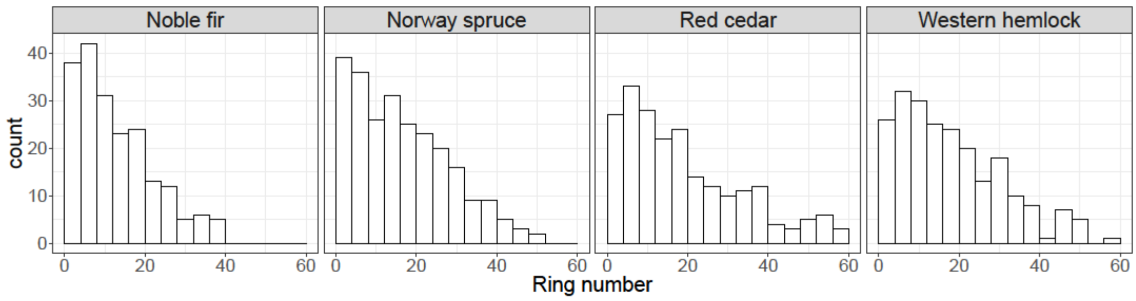


Figure 4-2. Distribution of cambial age by species. Numbers indicate the upper limit of the class.

Most of the data corresponded with clears younger than 24 years, with few of them over 40 years. The variation and range of wood properties with ring number can be seen in the following boxplots, which indicate the number of samples per group (n).

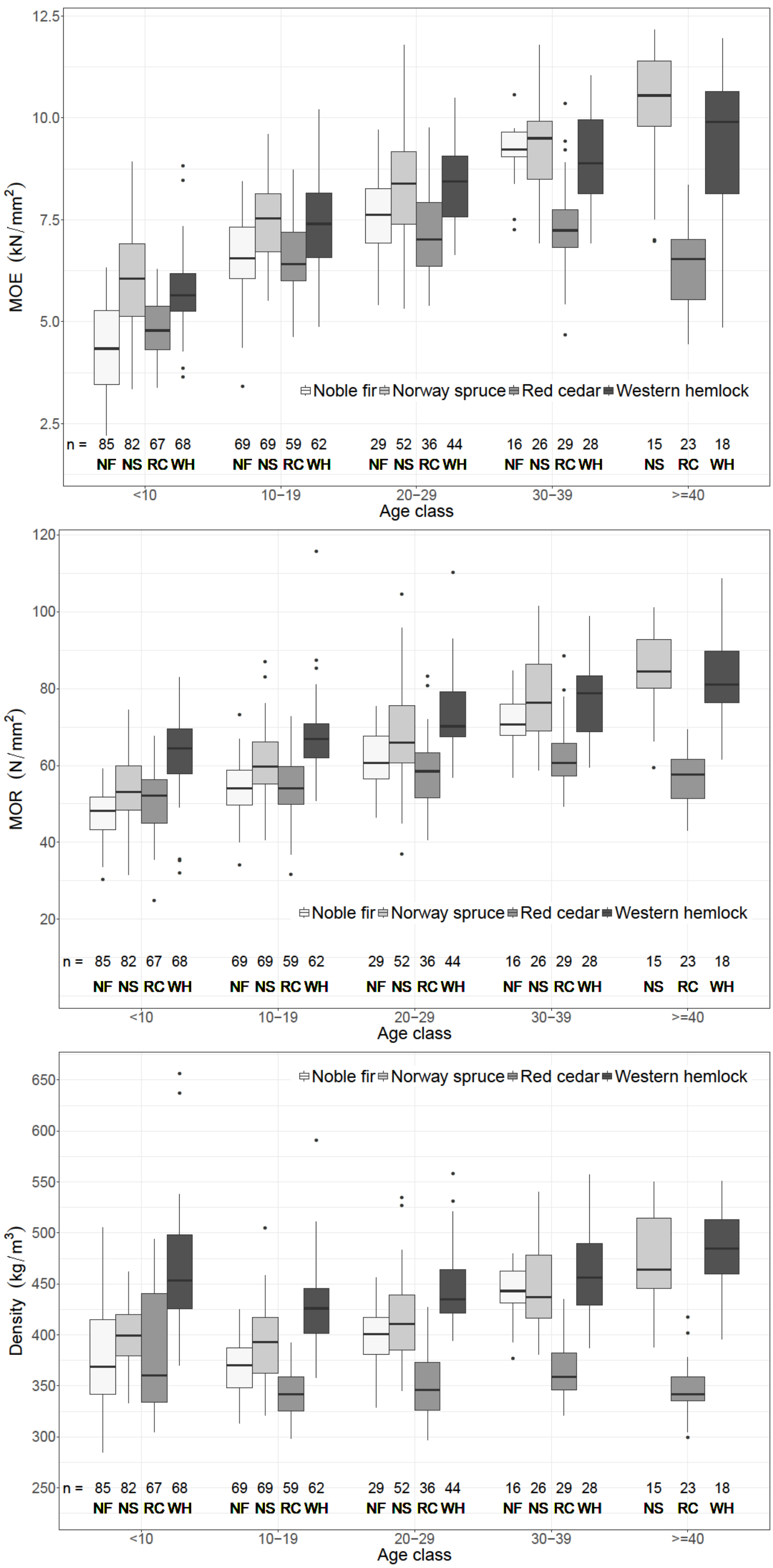


Figure 4-3. Range of MOE, MOR and Density in clears for categorical age and species.

Both MOE_C and MOR_C showed a general trend of increasing with age. Density also generally increased with age although there was a drop at the 11-20 years group. Only Norway spruce in the middle site, and western red cedar and western hemlock in the north produced clears older than 40.

To make fair comparisons of wood properties between species, data were discerned into two groups (younger and older than 40). The mean age of the group should be understood as the mean ring number of the clears. Additional clears were not included in Table 4-6 to avoid giving a major influence to those radial positions.

Table 4-6. Summary of wood properties by species up to and from (shaded) 40 years old.

Species	n	Clears mean age	MOE mean	MOE sd	MOE median	MOE min	MOE max
Noble fir	173	13	5.9	1.9	5.9	2.2	10.6
Norway spruce	180	16	7.3	1.6	7.2	3.4	11.5
Western red cedar	161	16	6.1	1.4	6.1	3.4	10.4
Western hemlock	187	17	7.4	1.7	7.4	3.7	11.2
Norway spruce	9	44	10.1	1.8	10.6	7.0	12.2
Western red cedar	21	51	6.4	1.1	6.5	4.5	8.4
Western hemlock	14	48	9.3	1.9	9.9	4.9	11.9
Species	**n**	**Clears mean age**	**MOR mean**	**MOR sd**	**MOR median**	**MOR min**	**MOR max**
Noble fir	173	13	53	10	52	30	85
Norway spruce	180	16	62	13	60	32	102
Western red cedar	161	16	56	10	55	25	89
Western hemlock	187	17	69	12	68	32	116
Norway spruce	9	44	85	13	84	66	101
Western red cedar	21	51	56	7	58	43	69
Western hemlock	14	48	83	12	83	62	109
Species	**n**	**Clears mean age**	**Density mean**	**Density sd**	**Density median**	**Density min**	**Density max**
Noble fir	173	13	382	44	379	285	495
Norway spruce	180	16	405	42	399	321	540
Western red cedar	161	16	363	44	353	297	494
Western hemlock	187	17	450	47	442	361	656
Norway spruce	9	44	479	60	495	388	550
Western red cedar	21	51	349	24	342	305	417
Western hemlock	14	48	481	43	486	396	551

n: number of samples; noble fir did not contain samples older than 40 years

Norway spruce and western hemlock gathered higher mean values of the mechanical and physical properties in the material older than 40 in comparison to younger pieces. Western red cedar showed a slight improvement of the mechanical properties in clears older than 40, but density decreased.

4.4.2.2 Correlation between wood properties

The strength of the relationship between two variables was measured with Pearson's correlation. The clears were restricted to a maximum of 40 years old so that the four species had the same age-span (the oldest sample of noble fir was 39). Table 4-7 reports the correlations between the wood properties investigated (all the pieces were used).

Table 4-7. Pearson's correlation (r) between variables.

	Overall	Noble fir	Norway spruce	Western red cedar	Western hemlock
Age - MOE_C	0.64***	0.87***	0.75***	0.49***	0.72***
Age - MOR_C	0.50***	0.74***	0.68***	0.29***	0.52***
Age - Den	0.11**	0.27***	0.44***	-0.22**	0.08 (ns)
Den - MOE_C	0.40***	0.20**	0.71***	-0.07 (ns)	0.17*
Den - MOR_C	0.71***	0.57***	0.81***	0.52***	0.53***
MOE_C- MOR_C	0.82***	0.84***	0.92***	0.67***	0.76***

P value: '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 'ns' not significant.

Correlation of age with mechanical properties was very strong or strong, except in the case of western red cedar. The correlation of age with density was only moderate in the best case, negative for western red cedar and not significant for western hemlock. Density related better with MOR_C than with MOE_C, which was not significant for western red cedar, and indicated a low significance for western hemlock. The strongest correlation of density was with MOR_C in Norway spruce. ANOVA of a linear model (equation [4-1]) showed that both the intercept and slope of the relationship between MOR_C and MOE_C varied with species ($F_{3\ 873}$ = 27.7, P<0.001 and $F_{3\ 870}$ = 14.5, P<0.001) as Figure 4-3 illustrates. A general regression line for all the pieces resulted in R^2 = 0.68.

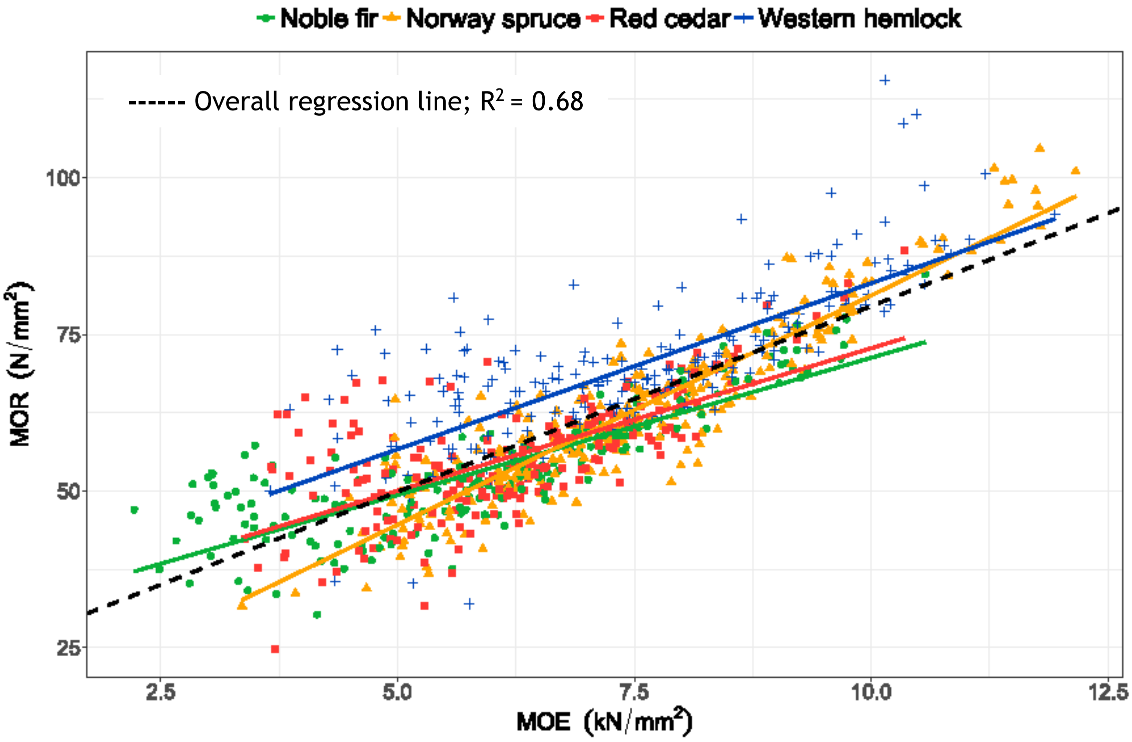


Figure 4-4. Relationship between MOE_C and MOR_C with the linear regression line for the four species together.

Figure 4-3 showed the radial group between 10 and 19 years old was an inflection point in the trend of density. In order to gain a better indication of how density relates to MOE_C and MOR_C, Figure 4-5 plotted the data in two groups. The graphs showed that samples younger than ten (corewood) were much more widely spread than samples older than ten (outerwood), especially for the MOE_C -Density relationship.

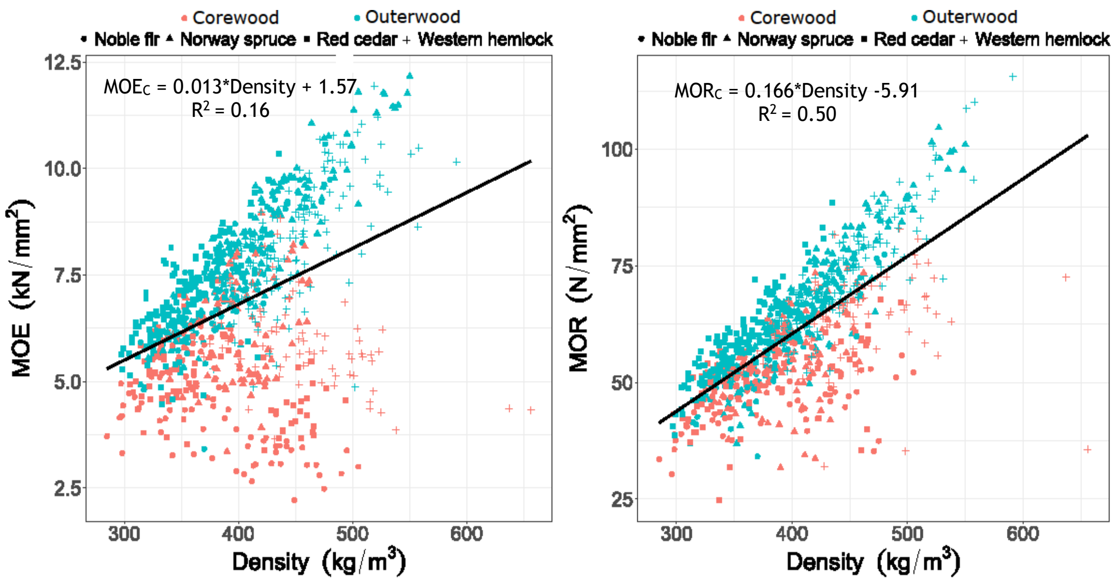


Figure 4-5. Relationship between Density with MOEc (left) and MORc (right) with the linear regression line for the four species together. Corewood <=10 years old.

ANOVA of a linear model (equation [4-1]) indicated that the relationship of density with MOE_C and MOR_C was different between species, affecting both the intercept and slope ($F_{3\ 873}$ = 21.3, P <0.001 and $F_{3\ 870}$ = 30.2, P=<0.001 for MOE_C, and $F_{3\ 873}$ = 18.2, P <0.001 and $F_{3\ 870}$ = 25.1, P <0.001 for MOR_C).

4.4.3 Radial variation of wood properties. Models

4.4.3.1 MOE model

As indicated in Table 4-5, most of the total variation in MOE_C was attributed to variation within trees, that is, influenced by age. The strong correlation of the mechanical properties with age (Table 4-7) made this an adequate predictor variable for building models. Figure 4-6 plots the values of MOE_C with age.

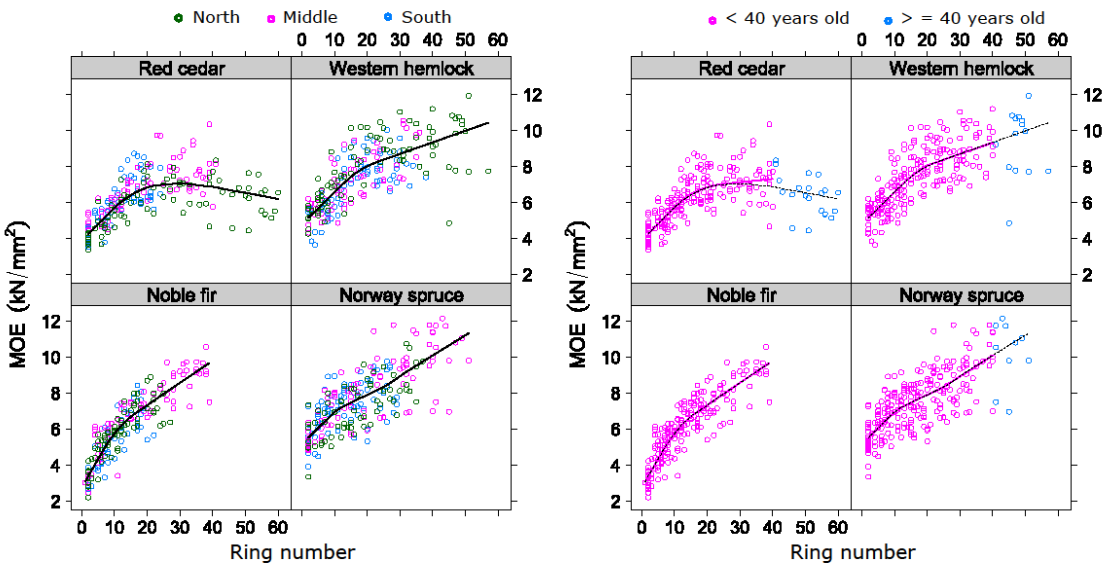


Figure 4-6. LOESS trendlines for the relationship of MOE with age by species, with indication of site (left), and splitting data up to and from 40 years old (right).

The MOE_C increased with age, more accentuated during the first 10-15 years. Western red cedar levelled out between 25 and 35 years old, with material apparently losing stiffness afterwards. Noble fir did not have specimens older than 40. For the other three species, there were only a few pieces older than 40, and came from only one site, so the material studied was restricted in further models to a range of age representative of the three sites and for the four species. In terms of descriptive statistics Table 4-8 presents a summary for MOE_C by site (extra pieces are not included).

Table 4-8. Summary of MOE_C by species and sites.

MOE_C (kN/mm^2)	Noble fir			Norway spruce			Western red cedar			Western hemlock		
Site	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**
Stand age	30	58	38	44	76	44	35	61	78	44	49	78
Pieces	49	63	61	57	65	67	48	53	81	64	49	88
Mean	5.2	6.7	5.7	7.2	8.0	7.1	6.0	6.7	5.9	7.1	7.3	8.0
Sd	1.5	2.1	1.6	1.4	2.0	1.5	1.3	1.5	1.2	1.5	1.6	1.9
CV (%)	29	31	29	20	25	22	22	22	21	21	22	24
Median	5.1	7	5.8	7.3	7.8	7.0	6.1	6.7	6.0	7.3	7.3	8.0

Sites: S, south; M, middle; N, north.

Results show that MOE_C varied from species to species but also with stand age. Stands of similar age can have similar mean values for different species (Norway spruce in south and north sites, and western hemlock in south site were 44 y/o), but besides the general increment of MOE_C with age younger stands can produce stiffer material than older ones (e.g. Norway spruce in the south and north compared to noble fir in the middle site).

After observing the pattern of MOE_C with age in Figure 4-6, various exponential functions were screened and analysed. The following function gave the best fit:

$$\boldsymbol{MOE_{ijklm}} = \alpha_{1,i} \times -e^{(-\alpha_{2,i} \times Age_{ijklm})} + \alpha_{3,i} + A_{3,ij} + A_{3,ijk} + \varepsilon_{ijklm} \qquad [4\text{-}2]$$

where MOE_{ijklm} and Age_{ijklm} were the bending stiffness and mean ring age respectively of the *m*th clear in the *l*th tree in the *k*th plot at the *j*th site of the *i*th species. The fixed-effects parameters to be estimated were α_2 for the rate of change; α_3 for the maximum value; and $\alpha_3 - \alpha_1$ for the starting value for each *i*th species. Parameter α_3 had both fixed and random components; hence $A_{3,ij}$, $A_{3,ijk}$ and $A_{3,ijkl}$ represented the random effects affecting α_3 at site, plot and tree levels, respectively. The random effects were assumed to be independent and normally distributed with mean zero and variance σ^2. The residual error was ε.

The model without the inclusion of species explained 58% of the variation in MOE_C. The model including species, site, and plot as random effects (model 1) explained 83% of the variation. A mixed model including species as fixed effects (model 2) and sites, plots and trees as random effects affecting the parameter α_3 (maximum value), which was closely related to α_1, explained 85% of the variation in MOE_C, reducing the information-based criteria (Table 4-9).

Table 4-9. Degrees of freedom, AIC, Log-likelihood and error statistics

	R^2	df	AIC	logLik	*E*	|*E*|	*E%*
Model 1	0.83	8	2131	-1057	2.2E-10	0.6	9.0
Model 2	0.85	17	2033	-997	6.6E-7	0.5	8.3

Although α_2 (rate of change) could also be thought to be influenced by the random effects, the model did not converge. The random effects affecting α_3 per species were also tested, but the model failed to converge due to increasing model complexity. Table 4-10 reported the parameters resulting from the selected model.

Table 4-10. Values for MOE prediction using [4-2].

	Fixed parameters			
	α_1	α_2	α_3	Var. Residual
Noble fir	6.56	0.07	9.15	0.63
Norway spruce	5.70	0.04	10.82	0.83
Western red cedar	4.20	0.08	7.74	0.59
Western hemlock	5.39	0.07	9.45	0.77

For a 40 years rotation length Norway spruce reached the highest MOE_C out of the four species studied (α_3 =10.8 kN/mm^2) with the highest starting value (α_3 - α_1= 5.12 kN/mm^2) but the lowest increase rate of MOE_C (α_2 = 0.04 kN/mm^2). Western hemlock performed similarly well, with a lower starting value (4.06 kN/mm^2), but a higher rate of increase which however was not enough to achieve the maximum values of Norway spruce. Noble fir performed slightly worse than western hemlock, with the lowest starting value (2.6 kN/mm^2) but still achieving more than 9 kN/mm^2 at the maximum. Finally, MOE_C in western red cedar only reached up a maximum of 7.7 kN/mm^2 although it showed the highest rate of change. Figure 4-7 represents the prediction models of MOE_C.

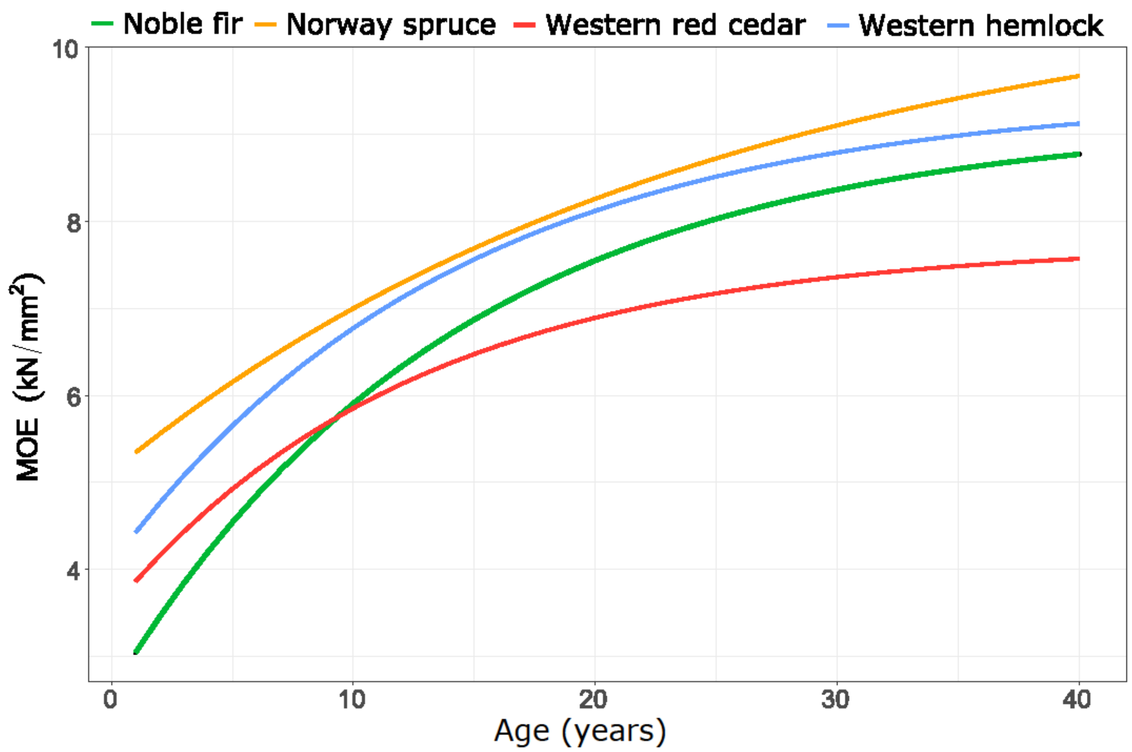


Figure 4-7. MOE predicted using the models fitted

Visual inspection of the residual plots did not reveal any pattern evidencing heteroscedasticity or lack of independence (see appendices).

4.4.3.2 MOR model

Figure 4-8 plotted the evolution of MOR_C with age showing two age groups.

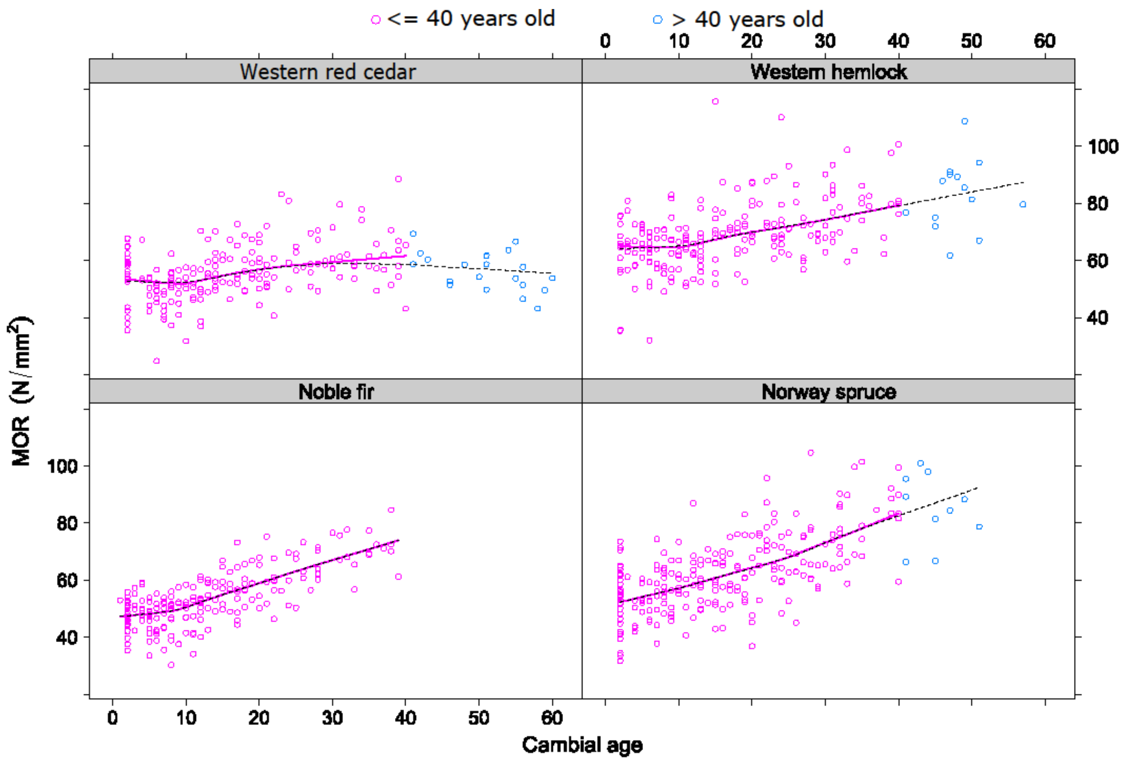


Figure 4-8. Overall LOESS trendline for the relationship of MOR with age by species.

Overall, MOR_C increased with age, although western red cedar had a more subtle increase in comparison to the other three species. The material for the analysis was restricted to a maximum age of 40 years old.

Table 4-11. Summary of MOR_C by species and sites (extra pieces not included)

MOR (N/mm^2)	Noble fir			Norway spruce			Western red cedar			Western hemlock		
Site	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**
Stand age	30	58	38	44	76	44	35	61	78	44	49	78
Pieces	49	63	61	57	65	67	48	53	81	64	49	88
Mean	48	58	52	59	68	61	53	60	54	68	67	74
Sd	8	10	8	11	16	12	8	10	9	9	9	15
CV (%)	17	17	15	19	24	20	16	16	16	13	14	20
Median	47	58	52	60	65	60	52	59	54	68	68	72

Sites: S, south; M, middle; N, north.

Table 4-11 presents a summary of MOR_C. Stands of similar age performed similarly well within species (e.g. Norway spruce in south and north sites), but variation of approximately 15% was found between species (notice western hemlock in south site). Although exponential models were investigated in an attempt to model the slight curvature observed within the first years of growth, a linear model between MOR_C and cambial age gave the best fit.

The effect of species was tested first. The inclusion of species and its interaction with age was significant (P<0.001), with R^2 = 0.49 (model 1). When site, plot and tree were included as random effects (model 2) the model explained 71% of the total variance. Model 3 (equation [4-3]) was a random slope model that investigated the effect of ring number on sites, plots and trees using the lmer library (Bates et al., 2014). The effect of age varied with the random effects, and the model explained 76% of the total variance.

$$\boldsymbol{MOR_{ijklm}} = \mu + \alpha_{0,i} \times Age + S_{j(i)} + P_{k(ij)} + T_{l(ijk)} + (A_{Age,ij} + A_{Age,ijk} + A_{Age,ijkl}) + \varepsilon_{ijklm} \quad [4\text{-}3]$$

where MOR_{ijklm} was the prediction of MOR_C on the mth clear, μ was the intercept, $\alpha_{0,i}$ was the slope for age of the ith species, and $S_{j(i)}$, $P_{k(ij)}$ and $T_{l(ijk)}$ were the random effects of the jth site, kth plot and the lth tree respectively. Parameters $A_{Age,ij}$, $A_{Age,ijk}$ and $A_{Age,ijkl}$ represented the random effects affecting Age at the site, tree and plot levels, in the ith species respectively. ε was the residual error. The random effects and residual errors were assumed to be independent and normally distributed.

Table 4-12. Degrees of freedom and measures of the fit of different models of MOR.

	R^2	df	AIC	logLik	p value χ^2	E	|E|	E%
Model 2	0.71	12	5839	-2908		1.5E-15	5.2	9.0
Model 3	0.76	18	5812	-2888	<0.001	-4.9E-14	12.2	8.5

In summary, the best model to predict MOR_C used age and species with interaction terms as fixed effects. As random effects, there were random intercepts for sites, plots and trees, as well as random slopes for the effect of age. The results in Table 4-13 shows the different regression coefficients, and Figure 4-9 plots the prediction for the four species within the first 40 years.

Table 4-13. Fixed parameters for MOR prediction using [4-3].

	Noble fir	Norway spruce	Western red cedar	Western hemlock
Intercept	44.6	50.0	50.1	61.2
Slope	0.67	0.76	0.34	0.48

The model indicated that western hemlock had the highest intercept term. Norway spruce and western red cedar had an almost identical intercept, but the slope was double for Norway spruce.

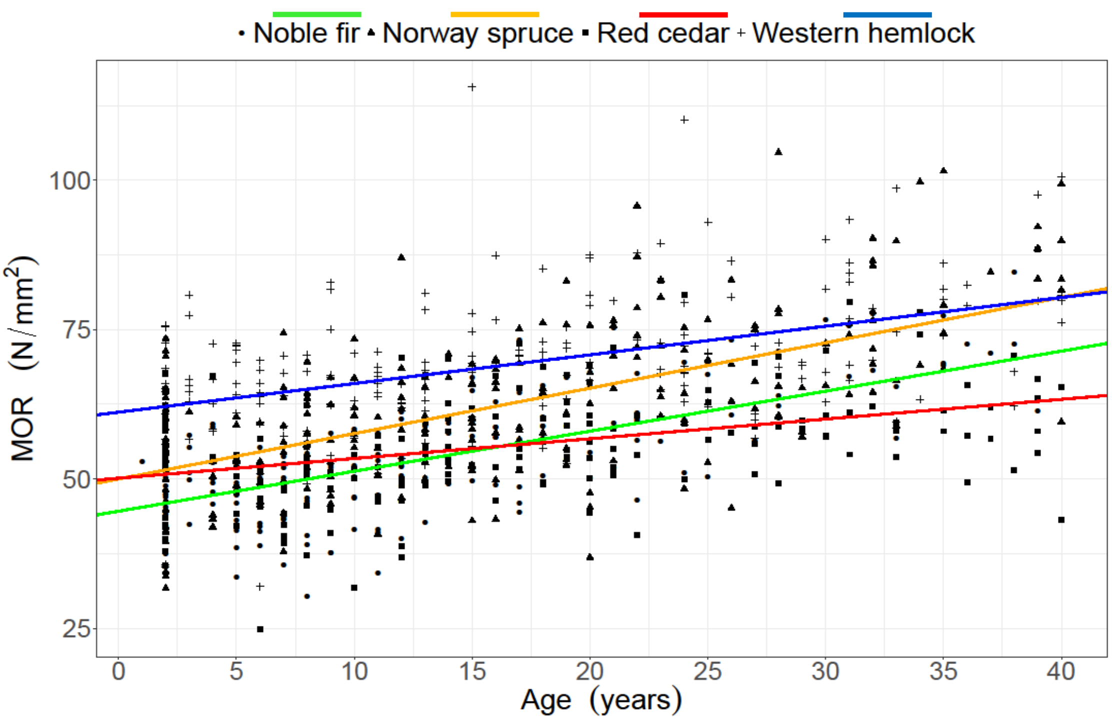


Figure 4-9. MOR predicted using the models fitted.

Visual inspection of residual plots did not reveal any obvious deviations from homoscedasticity or normality (see appendices).

4.4.3.3 Density model

As indicated in Table 4-7, the correlation of density with age was generally weak for the species investigated, slightly better for Norway spruce. Density followed two different trends depending on the range of annual rings considered (Figure 4-10).

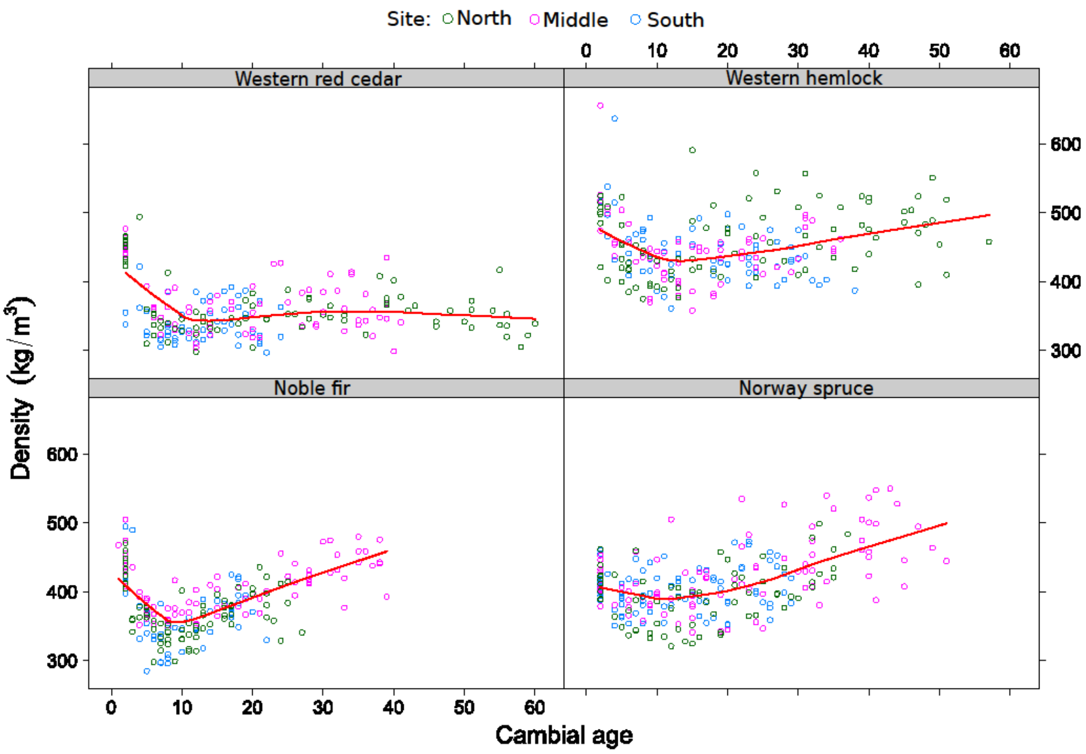


Figure 4-10. LOESS trendline for the relationship of density with age by species.

Density decreased from the pith, reaching a minimum around the tenth ring, more marked in noble fir. After this point, density increased linearly. Likewise with MOE_C and MOR_C, density in western red cedar did not notably increase after certain age. In this case, the LOESS line remained nearly flat after achieving the minimum value, although the pieces from the south, and the middle site showed a slight increment. The LOESS line of western hemlock was smoother than that of Norway spruce and noble fir, the latter having the sharpest change. Table 4-14 summarises the density data per site.

Table 4-14. Summary of density by species and sites (extra pieces not included).

Density (kg/cm^3)	Noble fir			Norway spruce			Western red cedar			Western hemlock		
Site	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**	**S**	**M**	**N**
Stand age	30	58	38	44	76	44	35	61	78	44	49	78
Pieces	49	63	61	57	65	67	48	53	81	64	49	88
Mean	366	407	370	403	427	395	351	373	361	445	448	459
Sd	47	36	40	33	52	42	43	42	41	44	48	49
CV (%)	13	9	11	8	12	11	12	11	11	10	11	11
Median	363	404	363	398	415	395	337	363	351	436	444	455

Sites: S, south; M, middle; N, north.

Table 4-14 generally shows higher values for older forest plantations except for the already mentioned western red cedar. It can be seen that within species, stands of similar age performed similarly well (e.g. Norway spruce in south and north sites), but there was also variation between species for the same age (notice western hemlock in south site) of approximately 13%.

The modelling of density restricted material to samples up to 40 years old, and addressed the two trends separately named as first and second section. The inflection point was located at eight years from the pith for noble fir, and at eleven years for the other three species. Pearson's correlation of density with age improved when sections were considered separately (Table 4-15) compared to Table 4-7.

Table 4-15. Pearson's correlation (r) between age and density.

	Noble fir	Norway spruce	Western red cedar	Western hemlock
First section	-0.74	-0.33	-0.77	-0.63
Second section	0.73	0.53	0.31	0.29

Due to the differences between the cambial ages of the points of inflection, the four species were modelled separately. A linear mixed model with random intercept for sites, plots and trees, as well as a random slope for the effect of age was investigated per species and section. The inclusion of a random slope for age on density did not have the same effect for all the sections and species. The following linear model investigated the evolution of density with age.

$$\boldsymbol{Density_{ijklm}} = \mu + \alpha_{0,i} \times Age + S_{j(i)} + P_{k(ij)} + T_{l(ijk)} + (A_{Age,ij} + A_{Age,ijk} + A_{Age,ijkl}) + \varepsilon_{ijklm} \quad [4\text{-}4]$$

where $Density_{ijklm}$ and Age_{ijklm} were the density and ring age respectively of the *m*th clear, μ was the intercept, and the parameter α_0 was the slope for age of the *i*th species in each section. The random effects of *Age* at site, plot and tree levels ($A_{Age,ij}$, $A_{Age,ijk}$ and $A_{Age,ijkl}$) were included when they were statistically significant. The random effects and residual errors were assumed to be independent and normally distributed. Table 4-16 shows the *P*-value for each case and the coefficient of determination (R^2).

Table 4-16. *P* values (χ^2) of the effect of age on random effects and the correspondent coefficient of determination (R^2) of the fixed and mixed models.

	First section			Second section		
	Fixed effects	Mixed effects		Fixed effects	Mixed effects	
		Intercept model	Slope model		Intercept model	Slope model
Noble fir		*P* value = ns			*P* value <0.01	
	63%	81%		51%	78%	90%
Norway spruce		*P* value <0.02			*P* value = ns	
	11%	53%	72%	28%	78%	11%
Western red cedar		*P* value = ns			*P* value = <0.05	
	60%	75%		9%	82%	89%
Western hemlock		*P* value = ns			*P* value = <0.01	
	40%	64%		8%	67%	81%

ns: effect not significant of age on random effects.

The use of age as the sole predictor of density did not always explain much of the variation. Overall, age explained a higher percentage of the variation in density in noble fir than in the rest of species, where data were more widely spread (Figure 4-10), with the exception of the first section of western red cedar. Particularly low resulted the relationship in Norway spruce, especially considering it showed the highest correlation (Table 4-7). It is also striking the weak value of R^2 in the second section of western red cedar and western hemlock. The use of random effects of age increased the coefficient of determination importantly. Table 4-17 shows the fixed parameters of the best models (the random parameters and residual error are given in the appendices).

Table 4-17. Fixed parameters for density models ([1]Mixed model with random effects on the intercept; [2]Mixed model with random effects on the slope).

	Fixed parameters	
Noble fir	**Intercept (Std error)**	**Slope (Std error)**
Noble fir		
First section[1]	465 (8.6)	-18 (1.3)
Second section[2]	315 (16.9)	3.9 (0.8)
Norway spruce		
First section[2]	418 (7.9)	-3.9 (1.8)
Second section[1]	349 (9.7)	2.9 (0.3)
Western red cedar		
First section[1]	458 (9.1)	-13.7 (1.1)
Second section[2]	344 (15.6)	0.2 (0.9)
Western hemlock		
First section[1]	525 (11.7)	-11.5 (1.3)
Second section[2]	427 (16.4)	0.8 (0.7)

Figure 4-11 shows the prediction models of density.

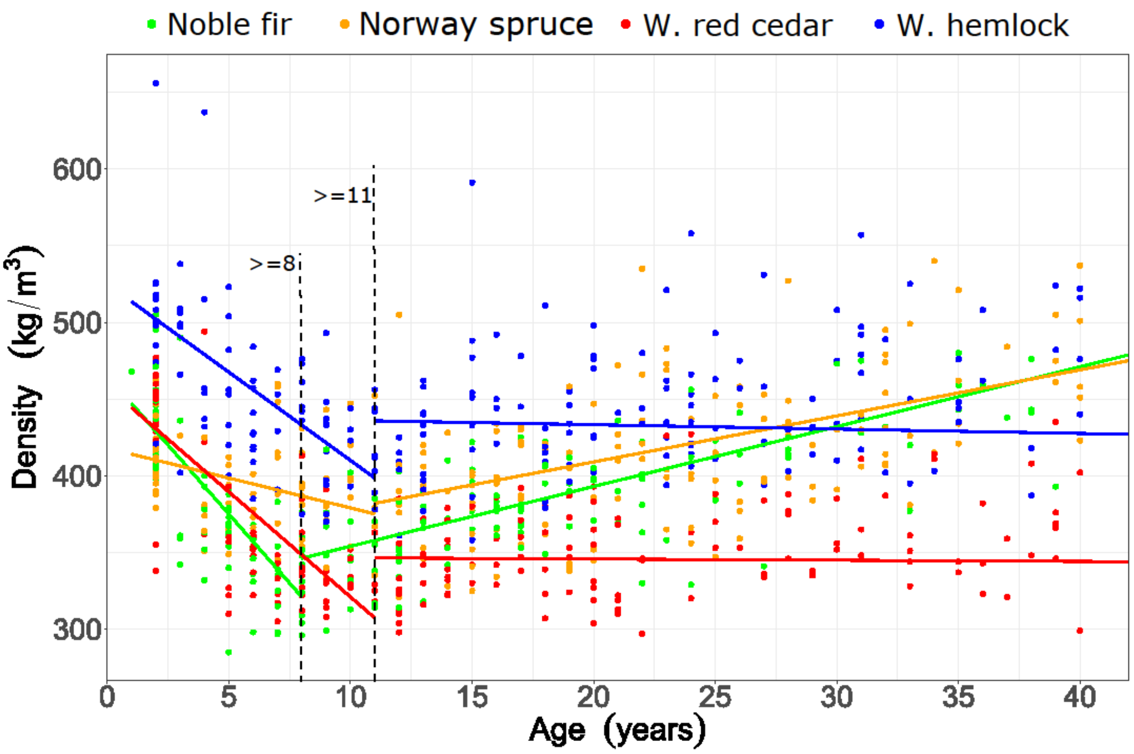


Figure 4-11. Density predicted using the models fitted.

In the second section, noble fir and Norway spruce had a higher slope than western red cedar and western hemlock. As a result, clears older than 30 years old achieved lower density in western hemlock than in noble fir or Norway spruce, even though Table 4-6 showed that western hemlock had the highest mean values for density overall.

4.4.4 Prediction of structural quality timber from clearwood.

This section focusses on the differences between the wood properties of clears and structural-size pieces. It must be pointed out that the properties in clears were not adjusted to the standard 12%, whereas the data used for structural timber were adjusted. Nevertheless, the difference between the mean MOE_C with and without moisture content adjustment was 0.001 kN/mm^2 since the small clear specimens were well conditioned.

Density was almost identical in timber (Table 3-4) and clears (Table 4-14). This section particularly compares the MOE between both material size, because whilst there were obvious differences in MOR due to the presence of defects, differences in MOE were not as straightforward.

Previous sections of this chapter examined the trend of wood properties with age. Interestingly, for bending stiffness a similar trend was observed in structural pieces, with values consistently around 1.25 KN/mm^2 higher (Figure 4-12).

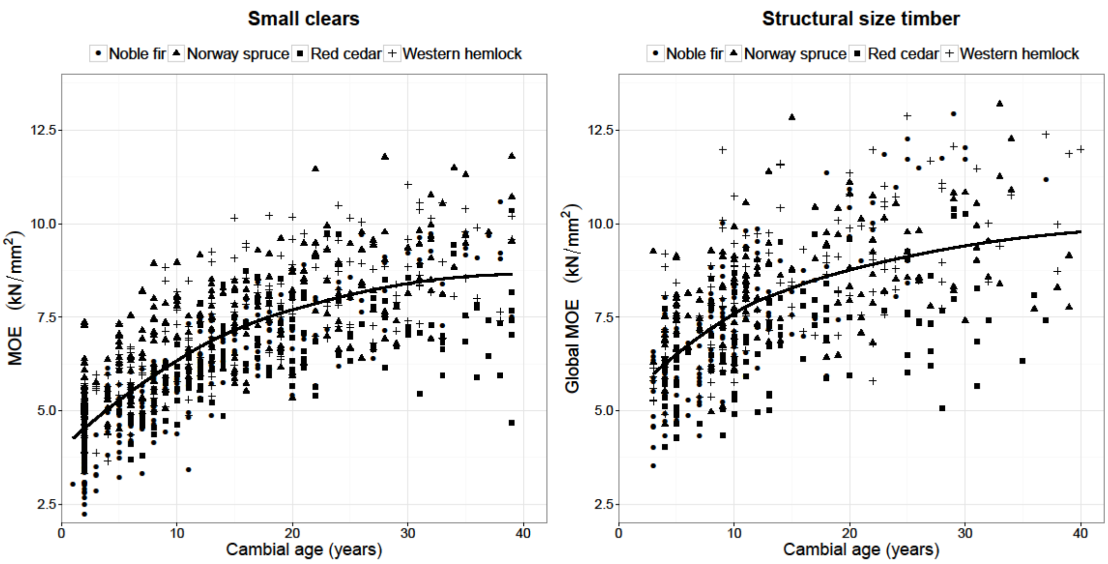


Figure 4-12. Variation of MOE with age and LOESS trendline.

Considering the difference in dimensions, the mean values of every pair of clears was compared to the equivalent structural piece (Figure 4-1). A total of 327 structural pieces were compared. ANOVA of a linear model showed that the relationship of MOE in clears and in structural pieces depends on species, affecting both the intercept and slope ($F_{3\ 322}$ = 11.4, *P*= <0.001 and $F_{3\ 319}$ = 2.9, *P*= <0.05) as Figure 4-13 illustrates.

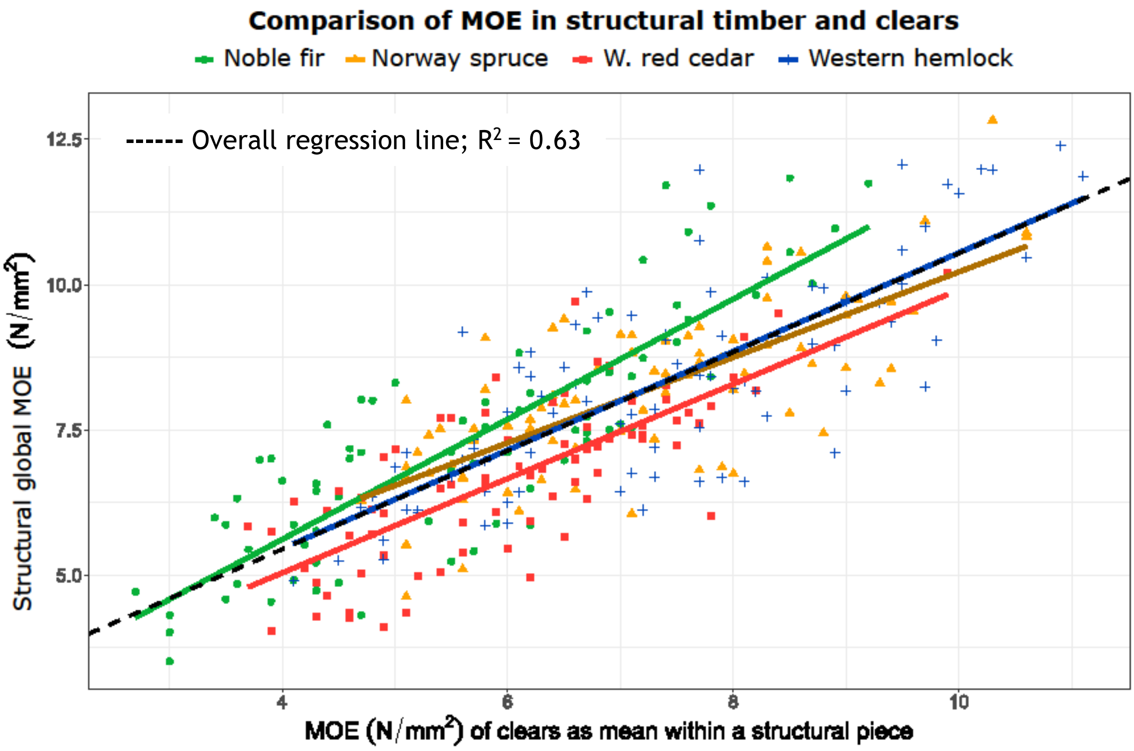


Figure 4-13. Comparison of MOE measured in structural pieces and averaging clears within structural pieces.

The overall relationship of MOE in structural pieces with the mean MOE of clears within the correspondent structural piece was good (R^2=0.63). The MOE of structural pieces were on average 18% higher than the mean calculated for the clears. Differences were bigger in noble fir (30%), with similar values for Norway spruce, western red cedar and western hemlock (15%, 12% and 14%).

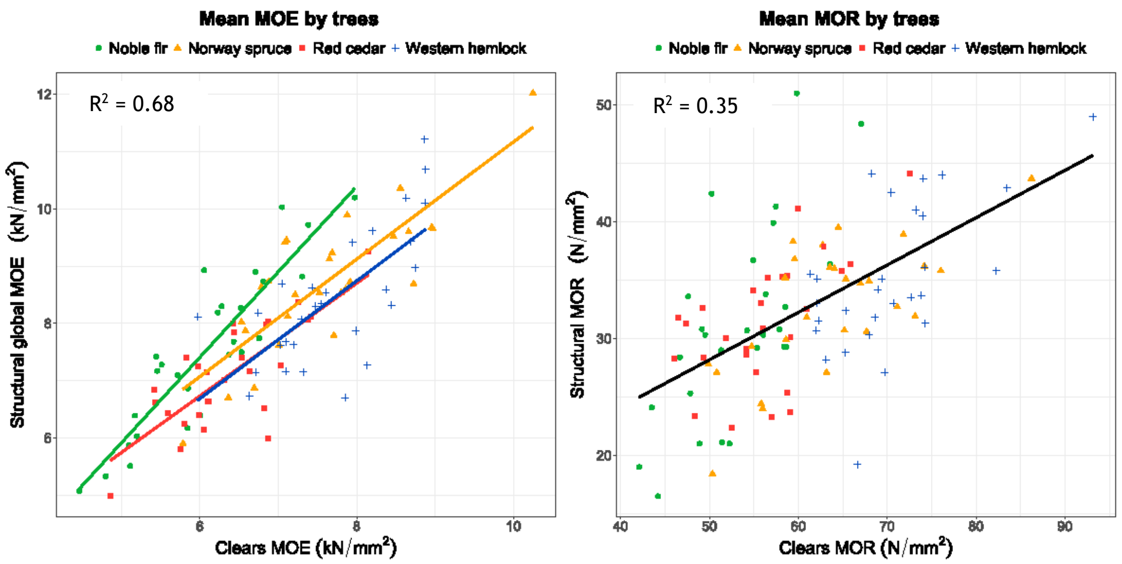


Figure 4-14. Relationship of mechanical properties of clears and structural pieces per tree.

The relationship between MOE in structural pieces and in clears improved slightly at a tree level (R^2=0.68, Figure 4-14 left), but still differences were bigger in noble fir similarly to the comparison in individual pieces. ANOVA of a linear model supported that the relationship of MOE in clears and in structural pieces depends on species, affecting both the intercept and slope ($F_{3\ 104}$ = 7.4, P<0.001 and $F_{3\ 101}$ = 2.2, P<0.1). Table 4-18 shows that except for noble fir, the slope of the relationship was around 1 to 1.

Table 4-18. Regression coefficients between the mean MOE of clears and structural pieces per tree.

	Noble fir	Norway spruce	Western red cedar	Western hemlock
Intercept	-1.55	0.92	0.82	0.52
Slope	1.49	1.02	0.99	1.03

The comparison of MOR in clears and structural pieces at tree level (Figure 4-14, right) showed a poor relationship (R^2=0.35), likely due to the difference in the presence/absence of knots in timber/clears.

In order to make sets of clears more comparable to the cutting pattern of structural pieces, a bark-to-bark cutting pattern of clears was simulated. Clears not containing the pith were given double weight (i.e. they were counted twice in the average). Table 4-19 summarises the values of the simulation.

Table 4-19. Clear values for a simulated radial variation bark-to-bark compared to structural timber.

			MOE (kN/mm^2)		MOR (N/mm^2)		Density (kg/m^3)	
Clears	**n**	**Age**	**Mean**	**CoV**	**Mean**	**CoV**	**Mean**	**CoV**
Noble fir	319	13	6.1	0.29	54	0.18	378	0.11
Norway spruce	351	17	7.6	0.22	64	0.21	408	0.11
Western red cedar	182	20	6.3	0.21	56	0.17	356	0.10
Western hemlock	201	19	7.7	0.22	71	0.17	449	0.10
Structural timber								
Noble fir	127	11	7.6	0.26	31	0.42	379	0.10
Norway spruce	143	17	8.5	0.18	32	0.29	406	0.10
Western red cedar	138	19	7.0	0.20	31	0.26	363	0.09
Western hemlock	150	16	8.5	0.22	35	0.31	447	0.09

n: number of pieces estimating each clear on both sides of the pith; pith sample was not obtained in two western red cedar and two western hemlock; Age refers to the mean age of the clears; Density at 12% moisture content. MOE global in structural pieces.

MOE_C was lower than MOE_G, 24% for noble fir, 19% for Norway spruce and 10% for the other species. MOR was considerably lower in structural pieces than in clears, with an average reduction of 53%. Mean values of density estimated for both clears and structural pieces were very similar.

4.5 Discussion

This chapter used clears pieces to investigate the properties of bending stiffness, bending strength and density in the four species studied. The first section stressed the importance influence of radial variation within a tree. The chapter continued to describe the wood properties, and the relationships between them and with age. Both results highlighted the importance of age on wood properties, and so it was used to model the radial variation. Finally, the differences between the wood properties of clears and structural-size pieces were investigated.

Chapter 3 highlighted that the largest source of variation in MOE and MOR of timber was attributed to within-stands differences. This chapter used clears for a higher resolution with respect to annual growth rings. Results concluded that even when dealing with different species the variation within trees was larger than that due to species. This is important as variation within trees will influence the proportion of the corewood compared to the outerwood, which will influence the determination of the rotation lengths for timber quality (Kliger et al., 1998; Moore et al., 2012; Moya et al., 2013). This chapter quantified the variation in MOE_C and MOR_C within a tree as 59.3% and 51.1% respectively, higher than due to species (24.7% and 30.1% respectively). Species was a more important variance component for density (41.5%). Within species, the three properties showed a variation within trees between 67% and 93%. It is possible that more sites for each species, with different growing conditions would increase the variability due to site. These results were in line with variation quantified in structural-size timber in Chapter 3, although variation of MOE and density within trees was much higher for clears than timber.

These variations led to the examination of the performance of wood properties with radial positions, grouped in age classes. Results showed a general improvement in wood quality from pith outwards.

For the dataset collected Norway spruce and western hemlock performed better than noble fir and western red cedar for the same age-span. A direct comparison with previous publications for British grown material was not possible, as the only data published for the four species studied (Lavers, 2002) did not provide the age of the pieces tested. The mechanical properties reported by Lavers were higher, and density was lower than that found in the current study, both at 12% m.c. This may be due to different methods of sample selection. Lavers selected samples at random, *in such a manner that the probability of obtaining a stick at any distance from the centre of a cross-section of a bolt was proportional to the area of timber at that distance*. As a result, it was more likely that pieces from the outerwood (with higher mechanical properties) were selected. The method of sampling for this chapter focused on obtaining information about the radial variation of properties so samples nearer the pith had the same weight in the mean, even though they represent a smaller percentage of the cross-sectional area than samples nearer to the bark.

In order to understand better the radial variation, the correlation between wood properties, and particularly with age was investigated. The correlation between MOE_C and MOR_C was high (r=0.82), suggesting that these two properties are somewhat bound together. Density related better with MOR_C than MOE_C, in line with other studies on clears (Auty et al., 2016; Cown et al., 1999). The correlations varied by species, and between density and MOE_C it was non-significant for western red cedar. On black spruce, Alteyrac et al (2007a) also found that MOE and density did not correlate significantly. A study of Sitka spruce (McLean et al., 2016) observed a strong relationship between density and MOE_C in the outer clears (R^2=0.77), but did not find a significant relationship for clears within sourced from corewood, resulting the overall relationship weak (R^2=0.16).

This thesis observed that the correlation of density with MOE was more spread in the corewood than in the outerwood, but did not investigate the correlation further. Age correlated mostly well with the mechanical properties, but weakly with density. The three wood properties were modelled in function of age, because most of the variation of wood properties occurred within trees, and to understand how the three wood properties are influenced by the rotation lengths.

The radial variation of MOE_C with age showed a non-linear increase in the four species, and it was described as an exponential function of age. The function is biologically meaningful, and includes approximations to the rate of change, maximum value and, indirectly, the starting value of the material near the pith as parameters. The exponential model was able to explain 58% of the variation using age as single predictor variable, increasing to 85% of the variation in MOE_C by using a mixed effects model with site, plot and tree as random effects. The results indicated that noble fir had the lowest value for MOE_C near the pith (2.6 kN/mm^2). Norway spruce the highest value for MOE_C near the pith (5.1 kN/mm^2), the rate of change was roughly half (0.04 kN/mm^2) than the other three species, and reached the highest value (10.8 kN/mm^2) out of the four species at the age of 40. The starting value for western red cedar was about 1 kN/mm^2 higher than noble fir, but it attained the lowest asymptotic maximum value. Finally, western hemlock produced material which was only less stiff than Norway spruce.

The same function had explained 56% of the variation on Douglas fir (Drewett, 2015), and 45% and 70% on Scots pine for a fixed and mixed model respectively (Auty et al., 2016). Another study on Scots pine reported values of R^2= 0.58 using only age as predictor variable in a non-linear model (Auty and Achim, 2008). In the same line, Leban and Haines (1999) found that modelling dynamic stiffness in larch as a non-linear function of age produced better predictions (R^2 = 0.53) than using a linear regression with age or density as sole independent variable (R^2 = 0.39 and R^2 = 0.47). The authors used an exponential model to overcome the uncertainties of a linear model when extrapolating beyond the data collected by fixing a maximum attainable limit which would otherwise extend up to unrealistic values.

Timber in G.B. is typically graded to C16 strength class, for which MOE must achieve an average of 8 kN/mm^2. According to the models of MOE_C presented in Table 4-10 and Table 4-18 combined, noble fir would reach 8 kN/mm^2 after 12 years of growth, Norway spruce at 10, western red cedar at 28 and western hemlock at 13. A few more years would be required to achieve mean values of 8 kN/mm^2.

MOR_C showed a linear pattern with age for the range of years studied. A model using age and its interaction with species explained 49% of the variation in MOR_C. A random slope model where site, plot and tree had different intercepts, as well as different slopes for the effect of age explained 76% of the variation. On Douglas fir (Drewett, 2015), a linear regression with age as predictor variable explained 44% of the variation in MOR_C, and a non-linear function of age explained 47% of the variation in MOR_C. On Scots pine, a non-linear model explained 46% of the variation in MOR_C using fixed effects, and 83% including random effects (Auty et al., 2016), although another study explained 54 of the variation in MOR_C using fixed effects % (Auty and Achim, 2008). The results of the selected model indicated a higher MOR performance of western hemlock than in the rest of species for the first 40 years, but the higher slope of Norway spruce would exceed western hemlock afterwards.

Density decreased from pith to minimum values at ring 11th, earlier in noble fir, followed by a gradual increase in the following rings. This contrasting trend explained the overall weak relationship of density with age, and it was appropriate to subsequently analyse the two sections of the radial profile separately. The random effects improved importantly the prediction of the models. The mixed effects models selected explained between 64% and 81% of the variation in the decreasing section, and between 67% and 90% in the increasing section. These models explained a higher proportion of the density variation than the exponential mixed models built for other species with similar radial trend, such as Sitka spruce (Gardiner et al., 2011) based on ring number and ring width (R^2 = 0.55), or the model of Douglas fir (Drewett, 2015) using age and rings per sample in a fixed model (R^2 = 0.55). The model suggested in this study has the limitation of lacking an upper limit, although in the case of western red cedar and western hemlock it may not be a problem because they showed a very flat trend after reaching the lower values.

The trends of the wood properties can be compared to the behaviour of the species in their native lands, although very little literature was found on the radial variation of the wood properties of the four species, none on noble fir.

The pattern observed in density of Norway spruce was in line with research on the species in Finland (Saranpää, 2003) and Sitka spruce both in its native land (Kennedy, 1995) and in G.B. (Gardiner et al., 2011).

The only study found on the radial variation of MOE_C and MOR_C for western hemlock (Kennedy, 1995)[2], described a similar trend in MOE_C to the current thesis. The values at 8% m.c. were between 7.2 kN/mm^2 near the pith and 14 kN/mm^2 at 40 years, higher than in the current study, tested at 12% m.c. The same study reported an increment of 38% in MOR_C over the first 40 years, slightly higher than the 32% resulting in the current study. Middleton and Munro (2001) reported for trees 90 years old from three sites using a similar cutting pattern than in the present study values of MOE_C between 10.3 and 12.8 kN/mm^2, and MOR_C of 71 and 94 / mm^2.

A previous study on five sites (Jozsa et al., 1998), reported a mean relative density of 0.426 with a general declining occurring from the pith to minimum values at ring 12th, followed by a rapid increase in ring density between years 15 to 35. The same author had reported in a different study (Jozsa and Kellogg, 1986) a relatively high density for the first years of growth, with low density from age 10 to 20 and a rapid increase from 20 to about age 40. This was in line with work from (Kennedy, 1995) who indicated as general trend for western hemlock a near constant minimum values persisting for several years with a recovery thereafter. Even though the density model presented here did not show that trend, the presence of older clears from the north site suggested a pattern similar to Canada.

More important resulted the overall drop in the performance of western red cedar in clears older than 40 years, mostly coming from the north site. The reasons for this are unknown. Whether the declining was due to a site effect, or inherent to the species could not be determined in the present study. A study on ten rapidly grown second-growth western red cedar in Canada (Jozsa and Kellogg, 1986) found a relative high density near the pith, and a decrease for the first 15-20 years, more sharply in the first ten years, followed by a flat trend thereafter. In non-native lands, a study on 15 western red cedar growing

[2] Work by Ellis, S., Faculty of Forestry , University of B.C.

in France (Polge, 1964) found the highest density occurring adjacent to the pith decreasing outwards for about 20 years, and thereafter remaining constant. In New Zealand Cown and Bigwood (1978) compared radial density trends in material from four sites, and found a different pattern in each site (Figure 4-15).

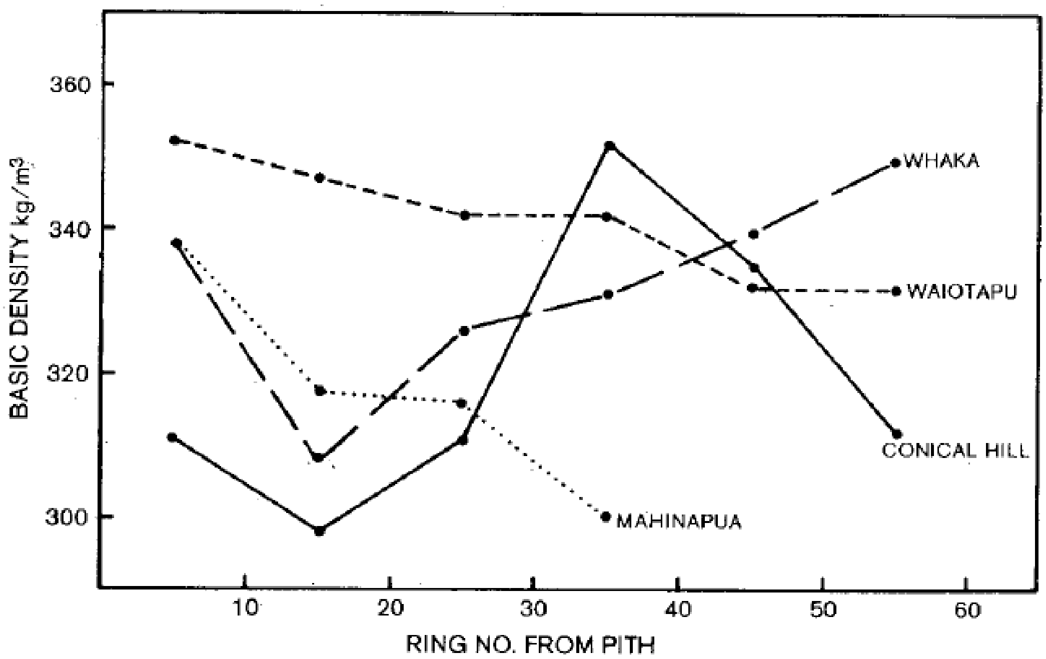


Figure 4-15. Comparison of radial density trends in western red cedar at four locations in New Zealand (Cown and Bigwood, 1978).

The relationship between the wood properties of clears and structural-size timber was investigated. Both type of pieces described a similar trend of MOE with age, but the performance of structural pieces was systematically around 1.25 kN/mm^2 higher. This had not been anticipated. Traditionally, values of MOE_C are not reduced to estimate structural timber values (Desch and Dinwoodie, 1996) or by very little to take into account the slight influence of knots (Kretschmann, 2010; Ramsay and Macdonald, 2013). However, a recent study on loblolly pine (Butler et al., 2016) compared MOE of structural pieces and clears obtained from near the failure point in the same pieces, and reported reduction factors from structural timber to clears, bigger as the quality grade decreased.

Averaging clears within structural pieces showed a good linear relationship for MOE (R^2=0.63), but the relationship changed by species, with bigger differences in noble fir, both likening the size of clears to the structural pieces, and a tree level simulating the same cutting pattern bark-to-bark. The differences in MOE can be possibly explained by: 1) the dimension of the structural pieces that includes a wider span of growth rings; 2) possibly more embedment for the small clears; 3) different testing method, inducing the three point bending test a bigger shear effect than the four point bending test; 4) testing of structural pieces based in the location of the “critical section” to failure, which is not necessarily the less stiff. The low relationship in MOR is mostly expected due to the presence of knots that reduce MOR in structural pieces compared to clears. This could be influenced by the species, management and age of the crop. The biggest reduction in this study occurred in western hemlock (50%), which may indicate a bigger size of knots. The size of branch diameter is examined in Chapter 6. Density in clears was a good predictor of the density samples used in structural timber for grading, as they both are free of defects.

Variation in the wood properties between clears and structural pieces can be also expected due to the different sampling height, but the variation may depend on species. On Scots pine, the mechanical properties decreased with height (Auty et al., 2016), but on Norway spruce MOE increased and MOR decreased (Vestøl et al., 2012). The influence of sampling height in this thesis was not observed for density, although it has been shown to vary with stem height for a given cambial age, decreasing in Scots pine (Auty et al., 2014) and increasing in Norway spruce (Jyske et al., 2008; Vestøl et al., 2012). It was not an aim of this chapter, and the relative short distance may not be enough to reach a conclusion.

Understanding the variations of wood properties in noble fir, Norway spruce, western red cedar and western hemlock will favour the production of material with higher wood properties within the most appropriate rotation length. In particular stiffness, which is usually the property penalising the grading in G.B., described a similar trend with age for the fours species, mainly varying the values near the pith.

4.6 Conclusions

This research found that variation in wood properties was larger within trees than between species. Even though, differences were observed between species, and it was found that Norway spruce and western hemlock performed similarly well to Sitka spruce in G.B. in terms of mechanical properties and density, with noble fir and western red cedar achieving lower values.

Overall, the three properties investigated improved with age. Mixed-effects models were developed to predict the wood properties as functions of age. Stiffness and strength used species as fixed effect, which enabled to build only one model for each mechanical property. The mixed models explained 85% of the variation of MOE_C and 76% of MOR_C.

Density decreased in the four species from the pith outwards for roughly the first ten rings. Differences were observed between species afterwards, leading to model density separately for each species. The different models chosen for density were able to explain between 64% and 90% of the variation depending on the species and section.

The performance of MOE in clears was lower than in structural pieces, but it described a similar exponential trend with age in both. A good overall relationship was found likening the width of structural pieces and clears (R^2 = 0.63), but the relationship varied with species. MOR was approximately double in clears than in structural pieces possible due to the presence of knots in the latter, and the relationship was worse. Density was very similar in clears and structural-size timber.

The use of clears was useful as a first approach, but more samples per tree are required for making confident predictions of structural timber performance, preferably making the sampling more similar, and including the ring number. Adjusting for the differences between testing methods for small clears and full size pieces, including the different shear effects in three and four point bending, would make the results more comparable to the four point bending test.

Chapter 5. Acoustic assessment of timber quality

5.1 Introduction

Previous chapters have shown how bending stiffness, bending strength and density are measured. Yet the determination of mechanical properties by bending tests is time consuming and the equipment required may not be accessible to everybody. The use of non-destructive techniques (NDT) are now widely accepted for wood quality assessment. Of common use are those based on speed sound propagation to predict dynamic wood stiffness (MOE_{dyn}), as they are relatively inexpensive and easy to use. Acoustic techniques can be applied in sawn timber, logs and standing trees, although the predictive performance of the techniques differs.

Whereas acoustic measurements on clears and structural timber are most strongly correlated with mechanical properties in static bending (MOE_{sta}), logs and trees have a lower correlation. This is partially due to the large variation in wood properties within logs and trees, which makes wood quality assessments more difficult. In particular, the current techniques applied to standing trees are somehow limited, and results present relatively large uncertainties regarding the actual properties measured. Yet, prediction the wood properties of logs and trees prior to processing and drying of sawn timber is important for informing decisions about the most appropriate forest management and end-product.

This chapter focuses on the use of NDT to assess “acoustically” mechanical properties, in particular the stiffness of wood. This has been identified in the literature and in the previous chapters of the current thesis as the property that in G.B. typically limits timber to a strength class. This chapter covers the acoustic assessment of wood on small clears, structural-size timber, logs and trees, and compares the results with the bending mechanical properties measured in structural pieces and clears. Different measurements were compared at various levels: tree, plot, site and species. Finally, different time-of-flight distances in standing trees investigated the wave behaviour and the implications for predicting mechanical properties in standing trees.

The results improve our understanding of the shortcomings of acoustic techniques for wood quality assessment, by comparing which techniques are more suitable to discern wood quality at different scales.

5.1.1 Objectives

Specifically, the aims of this chapter are:

1. Prediction of mechanical properties with NDT.

   Evaluate the use of acoustic methods to assess MOE_{dyn} and estimate bending strength of wood.

2. Performance of NDT at tree, site and species level.

   Examine the capabilities of the most commonly used NDT to differentiate dynamic stiffness between trees, plots, sites and species.

3. Additional acoustic measurements on standing trees.

   Investigate the sound wave propagation in standing trees and examine the shortcomings for the most commonly measured one metre distance.

5.2 Literature review

Construction timber is one of the most valuable forestry products. Traditionally forest industries sorted trees and logs based on measurable parameters such as the diameter and taper, and more qualitative visual assessments of branching characteristics or the stem straightness (Macdonald and Gardiner, 2007; MacDonald et al., 2009). Although these factors can be related to timber quality (Macdonald and Hubert, 2002) they do not, *per se*, provide information about the mechanical properties.

Wood stiffness can be estimated acoustically because this property is closely related to the acoustic behaviour of a wave travelling through the material (Bucur, 2006). In addition, acoustic speeds relate well with the bending strength (Auty and Achim, 2008), and so MOE_{dyn} can be used in sawmills as the basis for grading as Chapter 3 showed (see §3.4.3.2).

Acoustic tools are now commonly used in the forest industry, and different techniques are applied for timber sorting, both in the sawmill, the forest or the laboratory, and applied to trees, logs or sawn timber (Mochan et al., 2009). These tools can be installed in the processing line of a sawmill, the head of a harvester or simply hand held. Prediction of mechanical properties from acoustics is based on the relationship described by the fundamental Newton-Laplace equation, which is also referred to as one-dimensional wave equation:

$$MOE_{dyn} = \rho \times v^2 \quad [5\text{-}1]$$

where MOE_{dyn} is the modulus of elasticity obtained with acoustic methods, ρ is the wood density and v is the speed of sound. Although different devices and models are available all of them are based on one of two principles, resonance or time delay (time-of-flight):

- The resonance method measures the frequency at which a log or piece vibrates when excited in a particular mode of vibration, commonly longitudinal. In this case, the stress wave is generated by the impact of a hammer on one end. The frequency (f, Hz) is related to the velocity (v, m/s) at which a stress wave travels along a particular specimen of using the following expression:

$$Speed = Wavelength \times Frequency \quad [5\text{-}2]$$

- Time delay is measured between two points by stress wave timers and it is referred as "time-of-flight" (TOF) technique. The propagation speed is obtained from the time delay and the assumed distance travelled. The TOF applied on trees usually uses two transducers which for practical reasons are generally placed one meter apart, generally on the same side of the tree, with the midpoint between the transducers at breast height. A hammer or ultrasonic pulse generates a stress wave in a probe and the time it takes for the induced stress wave to travel to the second probe is measured. Because the distance at which the probes are placed is known the speed can be estimated dividing distance by time delay.

Results can vary depending on the method used. Resonance is recognised to offer more accurate estimations of wood stiffness (Carter et al., 2007; Wang, 2013), but it requires that the piece can vibrate freely, and therefore it can only be applied to logs and sawn timber but not to standing trees. Assessments carried out using TOF instruments can be applied to sawn timber, logs and have the advantage of being also possible on standing trees.

For the same trees, TOF speeds are generally higher than the resonance speed (Chauhan and Walker, 2006; Dickson et al., 2004; Grabianowski et al., 2006; Lindström et al., 2009; Mora et al., 2009; Searles and Moore, 2009; Wang et al., 2007). Research has explored the effect of placement of probes for the TOF method. Some studies measured the TOF on one side of the tree (Auty and Achim, 2008; Mora et al., 2009). Some others averaged measurements on two opposite faces (Grabianowski et al., 2006; Lindström et al., 2009; Moore et al., 2009c) to balance out the influence of temperature and moisture content (Gao et al., 2013; Searles, 2012) and taper (Wang et al., 2004) in the speed of sound. Finally, other studies placed the probes diagonally on opposite sides of the stem, theoretically forcing the wave to cover the whole cross section of the tree (Dickson et al., 2004). The use of different techniques aimed to obtain a value representative of the whole section like the resonance method does.

Traditionally, it has been assumed that for probes placed on the same side of the tree, the stress wave moves through the sapwood in the outer part of the tree (Grabianowski et al., 2006; Lindström et al., 2009), which in softwoods is typically stiffer, and so causing higher values to be measured. However, recent studies postulated that there is a difference in the behaviour of an acoustic wave depending on whether the method applied is resonance or TOF.

Logs and sawn timber can resemble a rod-like structure where a longitudinal wave (compressive or P-wave) generated by impact (resonance method) travels the fastest. This wave behaves as a "plane" (Andrews, 2002), that is, the wave front moves over the entire section of the piece and so it is representative of the whole log section and the average properties of the material. Planar wave velocity can be calculated from the one-dimensional wave equation [5-1].

Propagation in trees is more complex. A wave in a tree is introduced from the side and spreads in three directions: longitudinal, radial and tangential. It is therefore a three-dimensional wave (Meyers, 1994; Wang et al., 2007) also called "dilatational". Figure 5-1 illustrates the hypothesis in which a sound wave propagates through the outer part of the tree or as a three-dimensional wave.

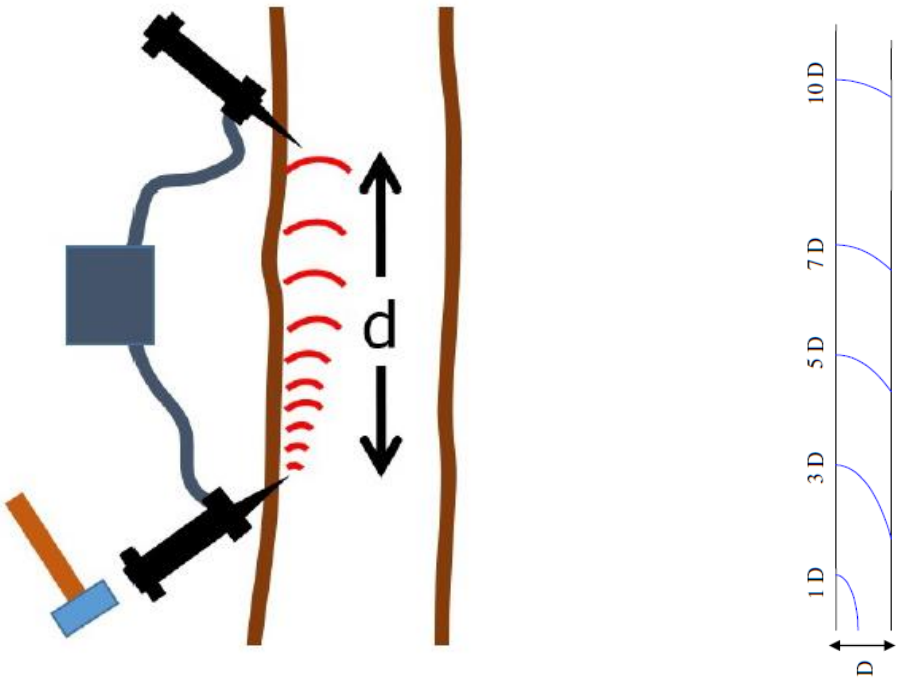


Figure 5-1. Hypothetical propagations of a sound wave in a tree. Left, reproduced from Legg and Bradley (2016), path in the outer part of the tree for a "d" known distance; right covering the whole section (Searles, 2012; Zhang et al., 2011) of diameter "D" at the impact point.

Regarding the wave behaviour, Andrews (2002) concluded that dilatational speed is dominant in standing trees, and its influence is more significant at short paths before it becomes in a plane front. Zhang et al (2011) quantified as 0.1 the diameter-to-distance ratio at which a dilatational wave begins to propagate as quasi one-dimensional wave. In other words, in order to apply the one-dimensional equation [5-1] in trees the distance must be at least ten times the diameter. Searles (2012) explained the wave shape as an elliptical propagation where the ellipse varies its eccentricity with variation in MOE, and concluded that: *If a quasi-plane wave behaves in a similar manner to a plane wave in that its speed is controlled by the entire area it covers, then the properties of a tree measured during a standing tree TOF test are not simply the area 20 – 30 mm wide, directly between the probes as is generally assumed.*

Therefore, there seem to be indications that due to a varying wave behaviour increasing the distance between the transducers could reduce the influence of the diameter size and the variation in properties across the section on the sound wave propagation. This may lead to an improvement in the relationship between MOE_{dyn} obtained from the TOF and MOE_{sta}. Despite the research conducted thus far on acoustics in wood, there still exist uncertainties on how to interpret the information obtained from acoustic tools and the reliability to predict wood properties. The studies by Zhang et al (2011) and Searles (2012) were carried out on logs and billets, and testing their hypothesis in standing trees will help to understand the limits of the current acoustic techniques and will contribute to a better interpretation of the measured values.

This chapter assesses the performance of different acoustic techniques to measure the stiffness of trees, logs, structural-size timber and clears, the last two tested both acoustically and mechanically, which very few studies have had the chance to evaluate. The use of acoustic methods to estimate wood strength is also examined. The capabilities of several methods are examined at a number of scales: tree, plot, site and species. Finally, the chapter aims to improve the performance of acoustic methods in standing trees by testing the effect of lengthening the measuring distance between probes.

5.3 Material and methods

5.3.1 Material and methods

Acoustic measurements were conducted on all the trees growing within the studied plots, on the logs of the felled trees and the structural-size pieces and small clears obtained from those. A list of the abbreviations used throughout the chapter is given in Table 5-1.

Table 5-1. Nomenclature and abbreviations used in Chapter 5.

Variable	Definition
$MOE_{dyn,MTG}$:	MOE_{dyn} calculated on structural pieces with the MTG tool.
$MOE_{dyn,log}$:	MOE_{dyn} calculated on logs with the Hitman tool.
$MOE_{dyn,TOFx}$:	MOE_{dyn} obtained using x, where x is a TOF measurement.
$MOE_{dyn,109}$:	MOE_{dyn} calculated with $TOF1_{ave}$ with Fakopp tool on the selected trees for felling.
$MOE_{dyn,627}$:	MOE_{dyn} calculated with $TOF1_{ave}$ Fakopp on all trees within the studied plots.
MOE_{sta}	MOE obtained in bending test
$TOF1_N$, $TOF2_N$, $TOF3_N$	Time-of-flight at 1, 2 and 3 metre distance, respectively on the north side.
$TOF1_{NS}$ & $TOF2_{NS}$	Time-of-flight to travel a 1 & 2 m vertical distance from the north to south face in the stem
$TOF1_{ave}$	Average TOF1 measured on the north and south faces of a tree. It can refer to all trees measured ($TOF1_{ave,627}$) or to the felled ones ($TOF1_{ave,109}$).
mknot	Marginal knot index. See Section 2.4.1.3.
nknot	Number of knots within the test section.
tknot	Total knots index See Section 2.4.1.3

A summary of the acoustic measurements will be shown in Table 5-2.

5.3.1.1 Standing trees

A total of 627 standing trees were acoustically assessed using the device TreeSonic (Fakopp, Hungary). This is a hammer impact type of TOF device. The protocol was:

- For practical reasons the start transducer was placed at the bottom.
- The probes were inserted at an angle of around 45°, aligned at a vertical distance of approximately one meter measured with a tape measure, centring on breast height.
- The measurements were repeated until three consecutive identical readings were obtained, or otherwise nearly identical and averaged.
- Both the north and south side of each standing tree were measured.

Additional TOF measurements were taken in the 36 standing trees selected for felling at the northern site (Figure 5-2). This aimed to explore the stress wave behaviour travelling within a tree. The one meter distance on the north side was measured first, and with the start transducer fixed, the stop one was moved upwards to cover a distance of approximately two and three meters. Keeping the start at the same bottom position in the north side, the stop was attached to the south side one and two metres above. For analysis, the distance was calculated using the Pythagorean Theorem assuming the diameter does not change for the measured length, and using the dbh and the vertical distance between transducers as the catheti.

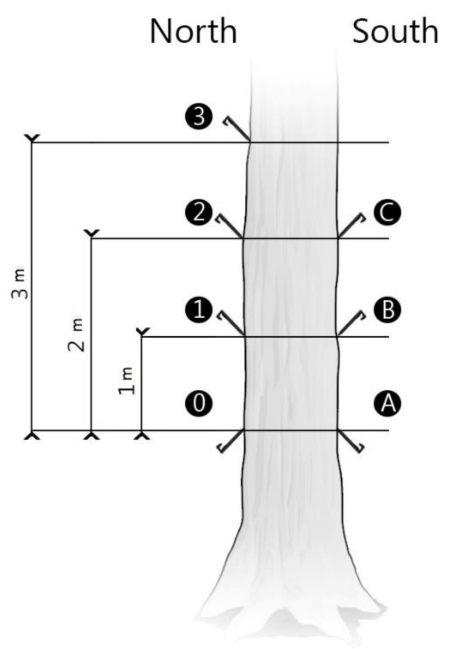


Figure 5-2. TOF measurements in standing trees. 0-1 and A-B was the common practise. 0-2; 0-3; 0-B and 0-C were additional measurements in the northern site: (illustration by Darío Pérez-Moreno). To the right, measurement in the field over 3 m distance.

5.3.1.2 Logs

A total of 109 logs, one per each of the felled trees, were acoustically assessed with the resonance method (Figure 5-3), including one extra log of western hemlock at the northern site. The logs were over five metres length with the bottom at breast height. Exceptionally, three logs of western red cedar felled in the northern site were 3.1 m in length. The tool used was a HM-200 “Hitman” (Fibre-gen, Auckland, New Zealand). It measures the frequency (*f*, Hz) of the vibration, which is converted to velocity (*v*, m/s) based on the length of the log using the expression [5-2]. The measurements were repeated until three consecutive readings were identical or otherwise nearly identical, and averaged.

Figure 5-3. Measurement of resonance in logs.

5.3.1.3 Structural-size timber

As described in Chapter 3, a total of 558 structural pieces were obtained in the radial transect, and 90 extra pieces of Norway spruce from the south and middle sites (see Table 3-3 for further details). The acoustic operating procedure consisted of:

- Measurement of the longitudinal resonance acoustic frequency with a timber grading machine MTG960 (Brookhuis Microelectronics BV, Holland) connected via Bluetooth with a laptop (Figure 5-4).
- Length was measured (nearest 1 mm) with a tape measure, and width and thickness (nearest 0.01 mm) with a digital calliper at three points along the length.
- Weighing of the piece with a balance plugged to the same laptop, which in combination with the dimensions allowed to obtain the piece density.

The speed was calculated for each piece using the frequency measured and applying the equation [5-2].

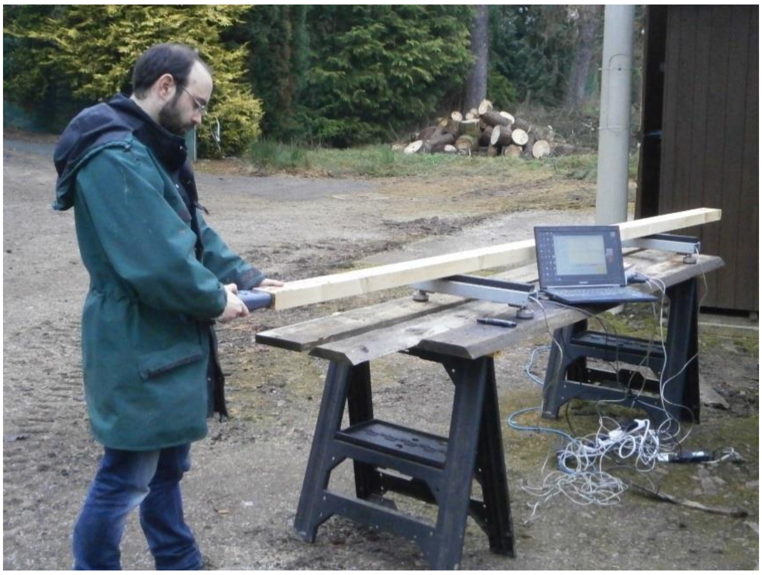


Figure 5-4. Acoustic measurement on sawn timber.

For density calculation, the dimensions of the cross sections of the specimens altered due to drying collapse (Figure 2-6) were measured on the basis of an approximation to the original (uncollapsed) dimensions.

5.3.1.4 Small clears

The small clears were brought to a moisture content of the order of 12%, and acoustically assessed prior to destructive bending tests (see §2.5.2.2). An ultrasonic pulse velocity test (Pundit Lab+, Proceq SA , Switzerland) determined the time delay (TOF method) as shown in Figure 5-5. The following settings and protocol was applied:

- Probe frequency 54 kHz.
- Pulse Amplitude (excitation voltage) 500V.
- Rx probe gain (amplifier) 200x.
- 30 measurements per clear (3 events, 10 readings per event).
- One transducer was held in a clamp stand to minimise the influence of the operator. If the arrival times varied noticeably within the 30 readings the test was repeated to get consistent readings, or manually adjusted if the arrival time was not automatically detected.

Five clears were not measured and eleven more were discarded in the analysis due to the use of the wrong settings. As a result, a total of 862 small clears acoustically assessed were analysed. The velocity of the acoustic stress wave was calculated from the travelled distance and the time delay measured. Wood density was obtained from mass and the average of three measurements of the cross section dimensions. Both sound velocity and density were used afterwards to obtain dynamic stiffness applying [5-1].

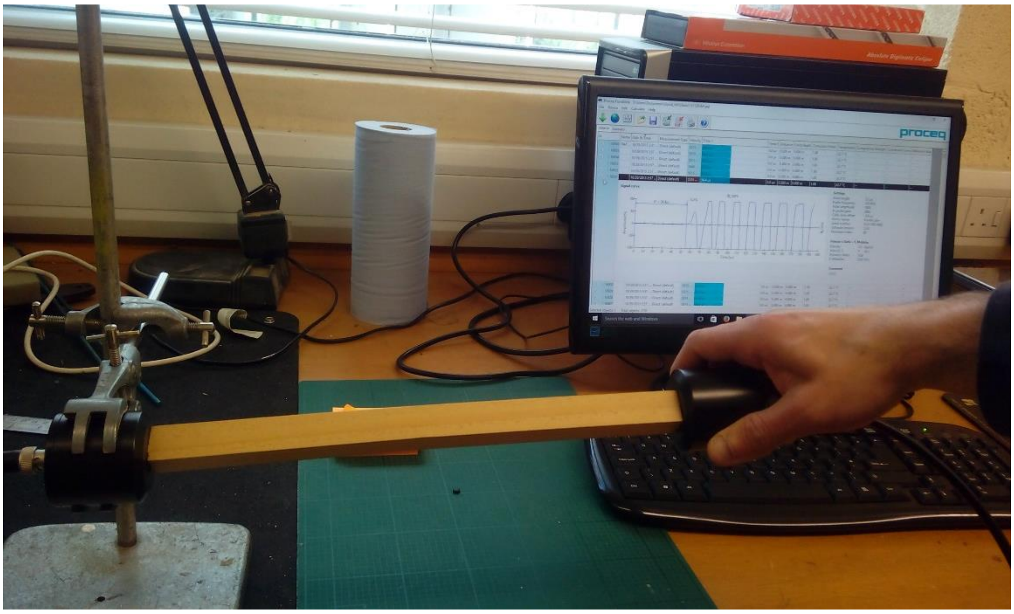


Figure 5-5. Acoustic measurement on a small clear. In the current project the transducers were wrapped with rubber textile to improve the contact between surfaces.

Table 5-2. Summary of acoustic measurements on standing trees with TOF1 and logs and sawn timber with resonance.

	Noble fir				Norway spruce				Western red cedar				Western hemlock			
	Overall	S	M	N	Overall	S	M	N	Overall	S	M	N	Overall	S	M	N
Age of stands		30	58	38		44	76	44		35	61	78		44	49	78
Number of trees	170	48	64	58	163	48	53	62	168	47	60	61	126	37	47	42
TOF 1 m (km/s)																
Mean	4.0	3.7	4.3	4.0	4.0	4.0	3.9	3.9	3.0	3.0	3.0	2.9	3.9	3.7	3.9	4.1
Sd	0.3	0.2	0.2	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.4	0.3	0.3	0.2	0.2	0.3
CV (%)	7.9	5.3	4.5	7.7	6.5	5.4	6.8	7.3	10.7	9.0	12.2	10.4	6.8	4.9	5.3	6.5
Resonance logs (km/s)																
Number of trees	27	9	9	9	27	9	9	9	27	9	9	9	28	9	9	10
Mean	3.1	3.1	3.3	3.0	3.3	3.3	3.3	3.4	2.9	2.9	3.1	2.8	3.3	3.1	3.3	3.4
Sd	0.2	0.1	0.0	0.2	0.1	0.2	0.1	0.1	0.3	0.2	0.3	0.3	0.2	0.1	0.2	0.1
CV (%)	5.9	3.0	1.5	6.0	4.4	4.7	4.3	4.0	8.8	5.4	9.7	9.4	6.1	4.7	5.9	3.5
Resonance in structural timber (km/s)																
Number of pieces	127	34	46	47	143	42	50	50	138	32	39	66	150	49	33	68
Mean	4.6	4.4	4.9	4.6	4.9	4.9	4.8	4.8	4.6	4.7	4.8	4.5	4.7	4.5	4.6	4.8
Sd	0.6	0.5	0.5	0.6	0.3	0.3	0.3	0.3	0.5	0.3	0.4	0.5	0.5	0.5	0.4	0.5
CV (%)	12.2	10.7	10.9	12.3	6.3	5.7	6.6	6.4	10.0	6.9	8.6	11.4	10.3	10.1	8.2	10.3
TOF in clears (km/s)																
Number of pieces	195	51	74	70	255	83	87	65	210	60	70	80	202	68	60	74
Mean	5.2	4.9	5.3	5.2	5.6	5.4	5.7	5.5	5.1	5.2	5.2	5.0	5.1	5.0	5.1	5.3
Sd	0.8	0.8	0.8	0.8	0.4	0.4	0.5	0.4	0.7	0.6	0.8	0.7	0.7	0.7	0.7	0.7
CV (%)	15	16	15	15	8	8	8	7	13	12	15	13	13	14	13	12

Sites: S, south; M, middle; N, north.

5.3.2 Statistical analysis

The statistical analysis was carried out with the R open-source statistical programming environment (R Development Core Team, 2016). The MOE_{dyn} was calculated using equation [5-1]. For the standing trees and logs the wood density was assumed to be 1000 kg/m^3 due to the difficulties of measuring density in the forest and the unlikeliness of that normally to happen. For structural pieces and clears the density was calculated from mass and volume of the whole piece. MOE_{dyn} in structural pieces was obtained using the speed calculated and the density measured of the full piece, and adjusted to a 12% m.c. for comparison with results in bending. Reversing the equation, it was possible to obtain the speed adjusted to a 12% m.c. In logs and trees, the resulting MOE_{dyn} was compared to the mean MOE_{PB} (see §3.2 for description of MOE_{PB}) per tree. Following it is described the specifics of the analysis for each of the aims:

1. Prediction of mechanical properties with NDT.

Both in small clears and structural pieces a linear regression was used to investigate the relationship between MOE_{dyn} and the mechanical properties. Clears were cut from pith to bark. In order to represent the radial section (bark-to-bark) they were given double weight (i.e., they were counted twice in the average) except for those containing the pith. The mean of the radial section was used as value per tree. The MOR in structural timber was modelled using MOE_{dyn} as main predictor variable in a multiple linear regression. In order to test if the relationship between mechanical properties and MOE_{dyn} was affected by species, a GLM with the form specified in the equation [5-3] was examined:

$$WP = \alpha_0 + \alpha_1 MOE_{\mathrm{dyn}} + \alpha_2 Species + \alpha_3 MOE_{\mathrm{dyn}}{:}Species + \varepsilon \qquad [5\text{-}3]$$

Where *WP* is MOE_{PB} or MOR, α_0 is the regression coefficient of intercept, α_1 is the regression coefficient of slope, α_2 represents the additive effect of the species studied, α_3 is the interaction term between MOE_{dyn} and species and ε is the residual error not explained by the model. ANOVA was conducted on this model in order to test if species was significant, and therefore a different relationship exists per species.

2. Performance of NDT at tree, site and species level.

A paired *t*-test investigated the differences between TOF1 in the north and south side measurements. A single one-way ANOVA analysis examined the differences in the mean values of TOF1 between species. A Tukey (HSD) test with $\alpha = 0.05$ investigated afterwards differences in the relationships between the species. Relationships among speeds, and with the MOE_{PB} were investigated using Pearson and Spearman's rank-order tests at sawn timber, tree, plot, site and species level. Whereas Pearson examined the linear association between two variables, Spearman's test (rho) measured the strength of association between two ranked variables.

3. Additional acoustic measurements on standing trees

The relationship between the speeds measured in resonance, and the TOF measured over 1, 2 and 3 metres on the north side ($TOF1_N$, $TOF2_N$ and $TOF3_N$) were examined. Afterwards, the MOE_{dyn} derived from the TOF measurements were compared to the MOE_{sta} of the outermost piece obtained to the north, as well as with the mean MOE_{sta} of the pieces in the tree. The relationships helped to understand which is the most likely spreading behaviour of a sound wave in a tree. Arrival times between transducers placed in opposite faces (north to south) were measured and compared to those between transducers placed in the same face (north to north). These measurements were replicated over a vertical distance of one and two meters and the speeds compared with resonance speed in logs.

All the acoustic measurements taken in the north site were compared with the mean of MOE_{PB} using a Spearman's rank test and Pearson's correlation.

5.4 Results

5.4.1 Prediction of mechanical properties with NDT.

5.4.1.1 Dynamic and static mechanical properties in clears.

In clears, the values of MOE_{dyn} were higher than MOE_{sta}, and the relationship between them very strong ($R^2 = 0.88$, RMSE = 0.63, Figure 5-6). MOR related moderately with MOE_{dyn} (R^2 = 0.57, RMSE = 8.62, Figure 5-6), which is only slightly worse than that reported in Chapter 4 with MOE_{sta} (R^2 = 0.68). Adding age and/or density in a multiple linear regression for prediction of mechanical properties was statistically significant (P<0.001), but did not usefully improve the coefficient of determination.

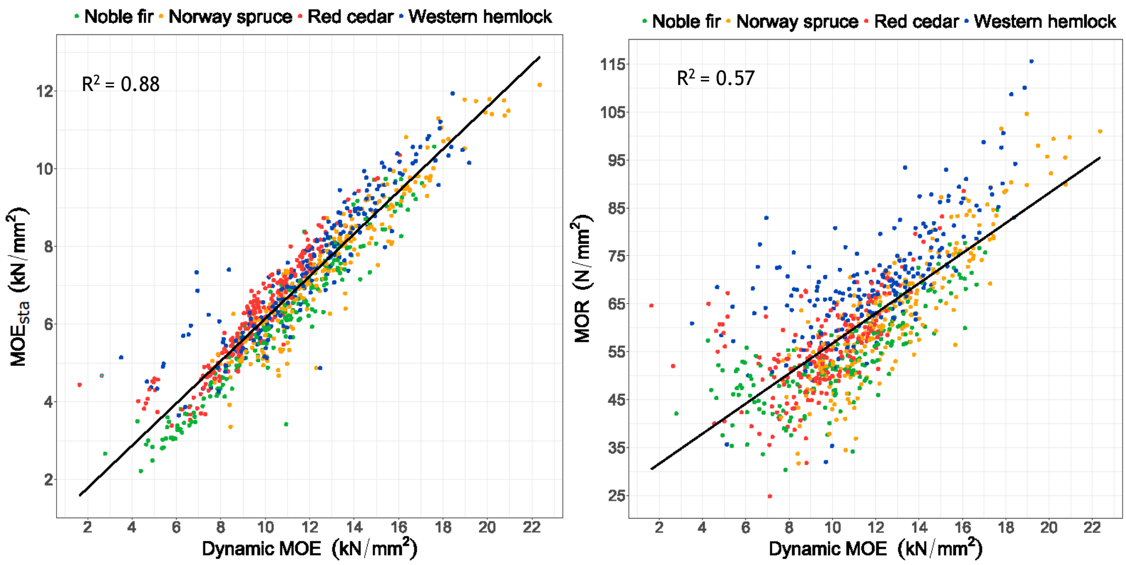


Figure 5-6. Linear relationship of MOE_{dyn} with MOE_{sta} (left) and MOR (right) in clears.

The next sections discuss the prediction of bending properties in structural pieces using acoustic methods and the influence of different factors in the prediction.

5.4.1.2 Dynamic and static mechanical properties in structural-size timber.

A total of 648 pieces were acoustically assessed by resonance. The distribution is shown in Figure 5-7, including the extra pieces of Norway spruce.

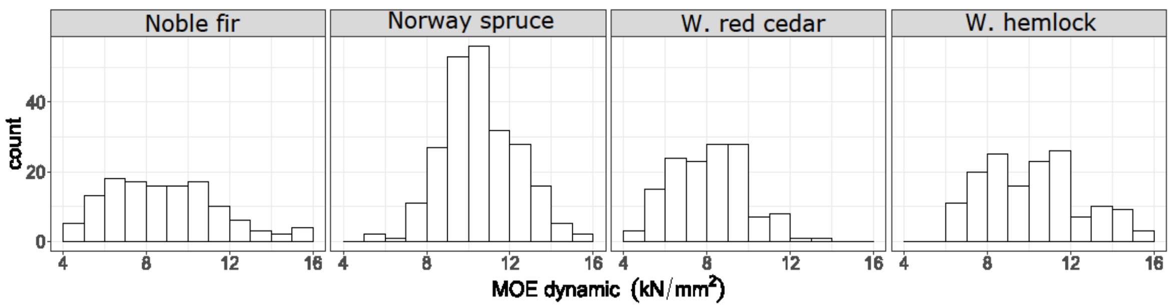


Figure 5-7. Distribution of MOE_{dyn}. Numbers indicate the upper limit of the class.

The MOE_{dyn} in the pieces of noble fir and western red cedar was lower than in Norway spruce and western hemlock. A summary of the MOE_{dyn} measured in structural pieces is offered in Table 5-3. Only the pieces cut in the radial transect are shown.

Table 5-3. Summary of MOE_{dyn} in structural pieces by species and sites.

	Noble fir			Norway spruce			Western red cedar			Western hemlock		
	S	M	N	S	M	N	S	M	N	S	M	N
Age of the stand	30	58	38	44	76	44	35	61	78	44	49	78
Pieces	34	46	47	42	50	51	32	39	67	49	33	68
$MOE_{dyn,MTG}$ (kN/mm^2)												
Mean	7.2	10.5	8.5	10.4	10.5	9.6	8.4	8.7	7.6	9.3	9.8	11.0
Sd	1.6	2.6	2.3	1.4	2.0	1.6	1.3	1.8	1.9	2.0	1.7	2.6
CV (%)	22	25	27	14	19	17	15	21	24	21	17	24
5th per	5.1	6.5	4.7	8.7	8.0	6.7	6.3	5.7	5.1	6.2	7.6	7.3
Median	7.0	10.4	8.7	10.3	10.1	9.7	8.5	8.5	7.2	9.6	9.5	11.1
95th per	9.9	15.1	11.9	13.2	14.3	11.7	10.3	11.5	10.6	11.9	12.6	14.7

Sites: S, south; M, middle; N, north.

These values are higher than those reported from destructive testing in Chapter 3. At an individual piece level, 90 % of the variation (RMSE = 0.64) in MOE_{PB} could be explained by $MOE_{dyn,MTG}$ (equation [5-4]).

$$MOE_{PB} = 0.183 + 0.854 \times MOE_{dyn,MTG} \qquad [5\text{-}4]$$

$MOE_{dyn,MTG}$ in structural pieces explained 43% of the variation in bending strength (RMSE = 7.9, equation [5-5]).

$$MOR = 2.96 \times MOE_{dyn,MTG} - 4.4 \qquad [5\text{-}5]$$

The extra pieces obtained for Norway spruce were also incorporated in the models ([5-4] and [5-5]) to account for the maximum variability. An ANOVA of a linear model (equation [5-3]) showed that species did not influence importantly the relationship between $MOE_{dyn,MTG}$ and MOE_{PB} ($F_{3\ 643}$ *=2.2, P= 0.09*), but they influenced the intercept of the relationship between $MOE_{dyn,MTG}$ and MOR ($F_{3\ 643}$ *=14.0, P*<0.001), although not the slope ($F_{3\ 640}$ = *0.28, P*=0.84). The relationships between $MOE_{dyn,MTG}$ and the bending properties are shown in Figure 5-8.

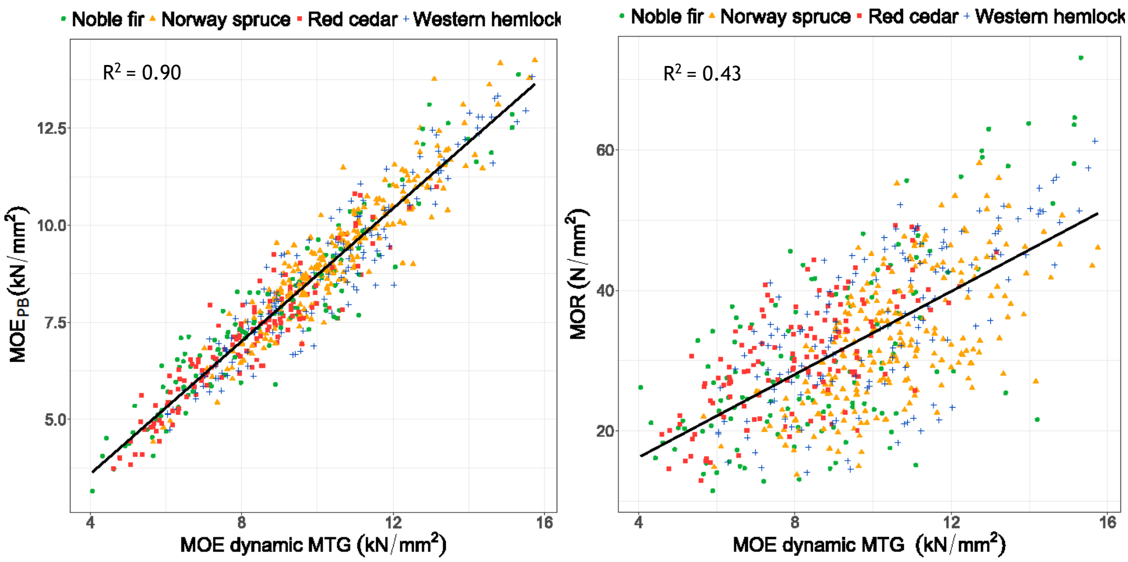


Figure 5-8. Relationship between MOE_{dyn} in structural-size timber and MOE_{PB} (left) and MOR (right).

In addition to $MOE_{dyn,MTG}$, other variables were studied in order to model MOR. The correlation between those variables potentially having an influence on the performance are reported in Table 5-4. Only the pieces cut in the radial direction were used because age and knots were only measured on those.

Table 5-4. Pearson's correlation (r) between variables.

	Overall	Noble fir	Norway spruce	Western red cedar	Western hemlock
$MOE_{dyn,MTG}$ - MOR	0.69	0.68	0.73	0.70	0.70
$Density_{384}$ - MOR	0.50	0.62	0.60	0.39	0.43
$Density_{timber}$ - MOR	0.44	0.54	0.52	0.32	0.36
Age - MOR	0.41	0.64	0.52	0.29	0.49
tknot - MOR	-0.45	-0.47	-0.52	-0.52	-0.63
nknot - MOR	-0.32	-0.22	-0.41	-0.41	-0.43
mknot - MOR	-0.48	-0.46	-0.56	-0.52	-0.62

All $P < 0.001$

The use of $MOE_{dyn,MTG}$ as sole variable was able to explain 47% of the variation in bending strength of the pieces cut in the radial direction. The additive effect of species was statistically significant ($P < 0.001$), but barely increased the prediction (R^2 = 0.50). Different variables were tested in the model: *mknot*, *tknot*, *nknot*, age and density of the full board. Only *mknot* and *tknot* were statistically significant. Adding the variable *tknot* did not usefully improve the prediction of the model, and the AIC of the model increased. Therefore, the selected final model only included the *mknot* index resulting a relationship of R^2 = 0.59 (RMSE = 7.0 N/mm^2). The interaction of species with the variables fit in the model was not statistically significant, and the following linear model was chosen:

$$MOR = \alpha_{0,Species} + \alpha_1 \times MOE_{dyn,MTG} + mknot + \varepsilon \qquad [5\text{-}6]$$

Table 5-5 reports the values resulting of the model [5-6] for each species.

Table 5-5. Summary of the chosen model for MOR prediction (N/mm^2).

	Noble fir	Norway spruce	Western red cedar	Western hemlock
α_0 Intercept	11.3	12.2	12.0	19.8
α_1 $MOE_{dyn,MTG}$	3.0	2.7	2.8	2.0
mknot	-8.9	-8.6	-6.2	7.6
RMSE	9.0	5.6	6.9	7.7
P-values	<0.001	<0.001	<0.001	<0.001

5.4.1.3 Dynamic properties in logs and trees.

The 109 trees from which clears and structural pieces were obtained were all acoustically assessed using the TOF1 method, and the subsequent logs using the resonance method. The resulting MOE_{dyn} was compared to the mean MOE_{PB} per tree (Figure 5-9).

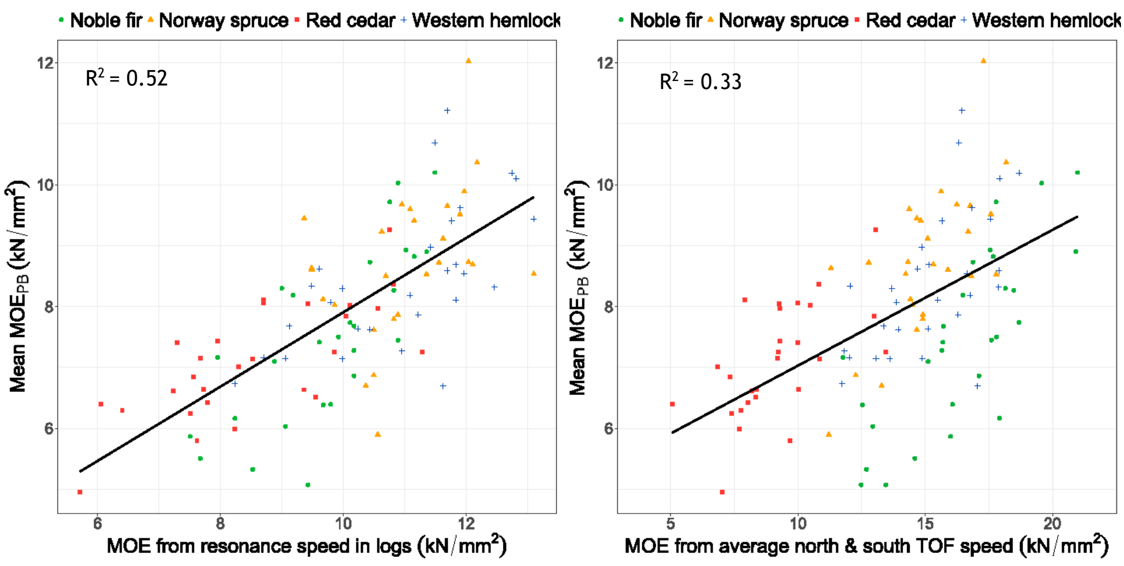


Figure 5-9. Relationship at tree level between mean MOE_{PB} and MOE_{dyn} on logs (left) and trees (right).

The MOE_{dyn} on logs ranged from 5.7 up to 13.1 kN/mm^2, with a mean of 10.1 kN/mm^2. The MOE_{dyn} on trees using TOF1 ranged from 5.1 up to 21.0 kN/mm^2, with a mean of 14.0 kN/mm^2. The mean value of MOE_{PB} per tree was moderately related to MOE_{dyn} on logs (R^2=0.52; RMSE=1.1 kN/mm^2), and weakly to MOE_{dyn} measured with $TOF1_{ave}$ (R^2=0.33; RMSE=1.27 kN/mm^2). The mean value per tree of MOE_{sta} in clears only obtained an overall relationship of R^2 = 0.16 with $MOE_{dyn,TOF1}$.

In summary, the performance of the acoustic tools tested in standing trees was poor compared to logs, structural pieces and small clears.

5.4.2 Performance of NDT at tree, site and species level.

The use of acoustic NDT was evaluated at different stages in the forest wood chain (species, site or tree).

A paired *t*-test found no significant difference (*P*=0.17) between the means of the speeds measured on the north and south side of the trees. A single one way ANOVA analysis determined that there were statistically significant differences (*P*<0.001) between species in the means TOF1 measurements. The posthoc Tukey (HSD) test found that western red cedar was different to everything else, with no statistically significant differences for the rest of possible combinations. Figure 5-10 shows the lower TOF1 speed measured in western red cedar compared to the other species.

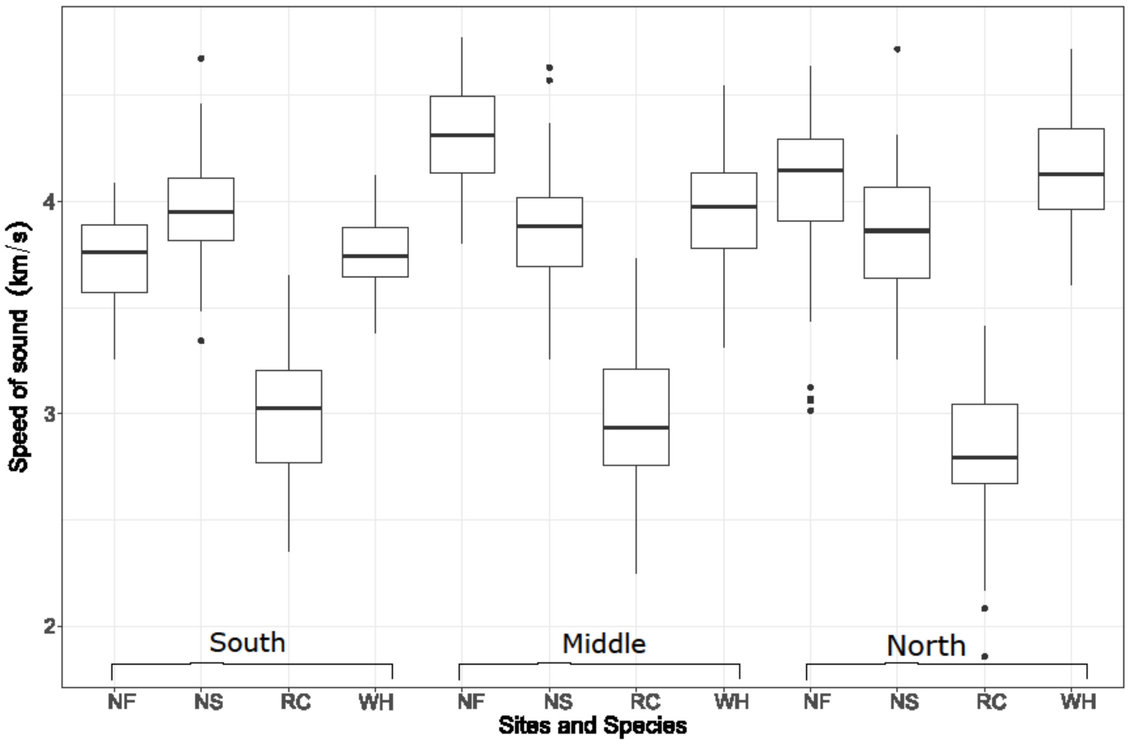


Figure 5-10. Distribution of speeds on the north face by site and species.

Overall, the acoustic measurements in trees gave higher values than those obtained in the logs (Figure 5-11). Norway spruce and western hemlock had the highest values for resonance speed with western red cedar again the lowest. The trees of western red cedar with TOF lower than resonance were investigated, but no particular pattern was found. The correlation between the speed measured in trees with $TOF1_{ave}$ and the resonance speed in the correspondent log was moderate (R^2 = 0.50).

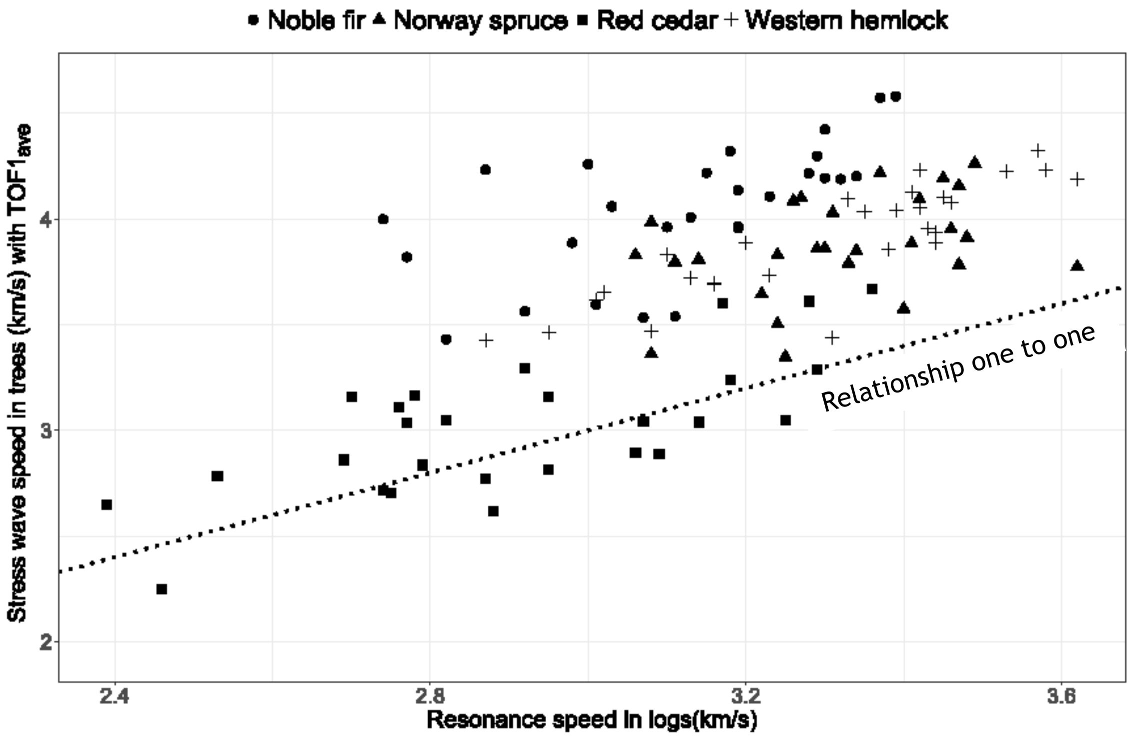


Figure 5-11. Relationship at tree level between resonance and $TOF1_{ave}$ speed.

Table 5-6 summarises the mean values per site for MOE_{PB}, $MOE_{dyn,log}$ and $MOE_{dyn,tree}$, both for the 109 felled trees and for the 627 standing trees assessed acoustically.

Table 5-6. Summary of mean MOE_{PB}, $MOE_{dyn,log}$, $MOE_{dyn,109}$, $MOE_{dyn,627}$. Results in kN/mm^2.

	Site	Age	MOE_{PB}	$MOE_{dyn,log}$	$MOE_{dyn,109}$	$MOE_{dyn,627}$
Noble fir	South	30	6.57	9.5	14.3	13.9
	Middle	58	9.40	11.0	18.6	18.1
	North	38	7.16	8.8	16.4	16.1
	Overall		7.71	9.8	16.4	16.1
Norway spruce	South	44	9.44	10.7	15.8	16.1
	Middle	76	9.77	11.0	15.2	15.6
	North	44	8.06	11.4	14.0	15.1
	Overall		9.09	11.0	15.0	15.7
Western red cedar	South	35	7.39	8.2	9.4	9.0
	Middle	61	7.75	9.3	9.3	9.0
	North	78	6.54	8.0	8.5	8.1
	Overall		7.23	8.5	9.1	8.7
Western hemlock	South	44	8.13	9.7	13.5	13.9
	Middle	49	8.61	11.2	16.1	15.5
	North	78	9.47	11.8	15.8	17.1
	Overall		8.76	10.9	15.2	15.4

According to Table 5-6, the stiffness would be correctly ranked by species using the acoustic measurements on logs, but not with those on standing trees, where noble fir ranked as the species with the highest stiffness. The lower quality of western red cedar compared to the other three species would be always correctly identified, whereas the ranking of Norway spruce and western hemlock would depend on the number of trees selected, ranking correctly when more trees are measured.

Within species, noble fir values at the tree, log and structural piece level fir were always higher in the middle site. On the other hand, the higher MOE_{PB} of the north site compared to the south found correspondence with the higher values of MOE_{dyn} in trees, but not in logs. In Norway spruce, the lower MOE_{PB} of the north site was not reflected by lower values of $MOE_{dyn,log}$, although it was by the measurements in the standing trees. However, the $MOE_{dyn,log}$ reflected better the difference in MOE_{PB} between the south and middle sites than the MOE_{dyn} in the standing trees. The MOE_{PB} values of western red cedar ranked like the $MOE_{dyn,log}$, but only the lower quality sites were correctly identified by lower MOE_{dyn} in the standing trees.

Table 5-7 shows the correlations at different levels. Both using the resonance and TOF methods, the linear association increased as the level of study (tree, plot, site and species) was more general.

Table 5-7. Pearson (r) and Spearman's rank-order correlation (rho) of MOE_{PB} with speed of sound at different levels of study. Speed in structural pieces was analysed with and without moisture content adjustment to 12%.

	Resonance		$TOF1_{ave,627}$		$TOF1_{ave,109}$	
Level	r	Rho	r	rho	r	rho
Structural piece	0.79	0.79				
Structural piece$^{m.c.}$	0.83	0.83				
Tree	0.72	0.74	0.57	0.59	0.57	0.59
Plot	0.79	0.76	0.56	0.62	0.58	0.60
Site	0.81^{1}	0.78^{1}	0.65^{2}	0.72^{2}	0.61^{2}	0.49^{3}
Species	0.97^{2}	1^{3}	0.70^{ns}	0.40^{ns}	0.62^{ns}	0.20^{ns}

P-values <0.001; except ^{1} *P*<0.005; ^{2} *P*<0.05; ^{3} *P*<0.1; *ns* = no significant; m.c. = adjusted to 12%.

The speed measured with the resonance method in the structural pieces was strongly related to MOE_{PB}, increasing the association when the speed was adjusted to a 12% m.c.

At site level, the mean MOE_{PB} ranged from 6.54 kN/mm^2 up to 9.77 kN/mm^2. It found a better relationship with $MOE_{dyn,log}$ (R^2 = 0.66; RMSE = 0.70 kN/mm^2) than with $MOE_{dyn,109}$ (R^2 = 0.38; RMSE = 0.95 kN/mm^2 , Figure 5-12).

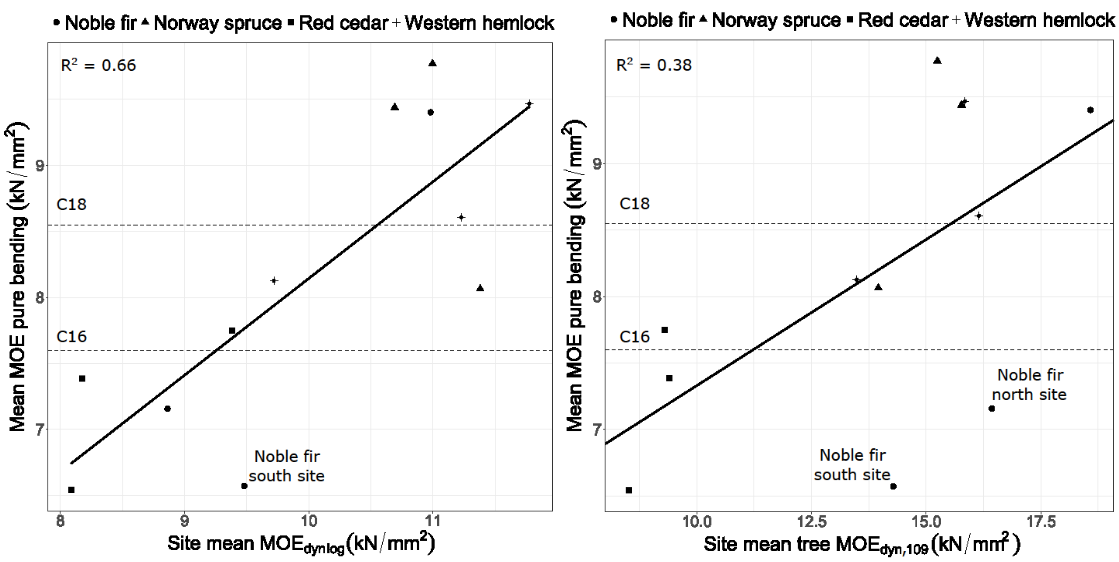


Figure 5-12. Relationship of mean MOE_{PB} per site with $MOE_{dyn,log}$ (left) and $MOE_{dyn,109}$ (right).

Overall, the resonance on logs was able to distinguish the higher quality sites from the lower ones. Yet, care must be taken. The south site of noble fir, 30 years old, had a relatively high $MOE_{dyn,log}$ compared to the low MOE_{PB} measured. If the aim was to obtain C16 strength class timber, an IP of 9.3 kN/mm^2 would segregate timber correctly. The TOF measurements in the standing trees discerned correctly the lower quality of western red cedar, but in the stands of noble fir in the south and north were high compared to the low bending stiffness measured, which would segregate timber for C16 erroneously.

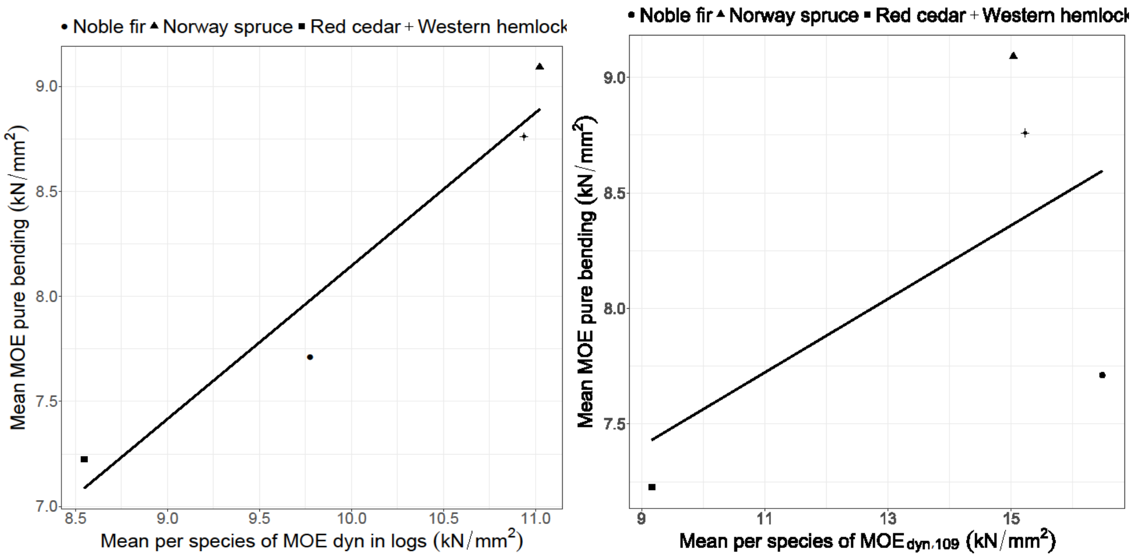


Figure 5-13. Relationship of mean MOE_{PB} per species with $MOE_{dyn,log}$ (left) and $MOE_{dyn,109}$ (right).

At a species level, bending stiffness correlated well with the acoustic measurements on logs, even though noble fir still offered a higher acoustic value than expected compared to the bending tests. The measurements on standing trees were not capable of discerning bending stiffness correctly with the exception of the lower quality in western red cedar.

The following section investigated alternative measurements in standing trees that help to understand the sound wave behaviour in wood and the shortcomings of acoustic techniques for wood quality assessment.

5.4.3 Additional acoustic measurements on standing trees.

The 36 trees selected for felling in the northern site were acoustically assessed with additional measurements before cutting.

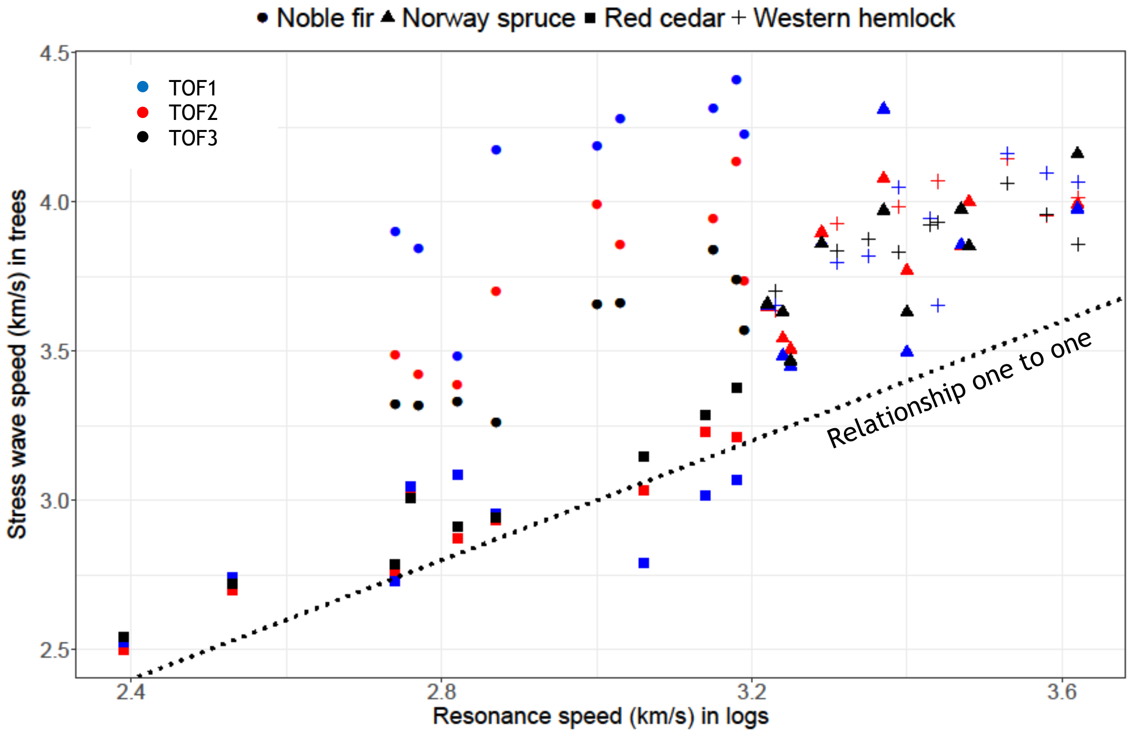


Figure 5-14. Relationship at tree between resonance speed and $TOF1_N$, $TOF2_N$ and $TOF3_N$ speed.

Figure 5-14 revealed that, in general, the measurements taken in standing trees recorded higher velocities than those using resonance on logs even when the distance covered is more than one metre. Yet, the correlation improved as the distance increased. The resonance speed measured in logs was moderate related to the $TOF1_N$ speed (r = 0.57), and very strong related to $TOF2_N$ (r = 0.81) and $TOF3_N$ (r = 0.91). Noble fir presented differences of near 14% between $TOF1_N$ and $TOF3_N$, larger than in the other three species. In western red cedar, particularly in the lower range, there were no important difference between $TOF1_N$ and $TOF3_N$ speed.

In order to understand the acoustic wave propagation within standing trees, and by extension the properties measured, the MOE_{dyn} calculated with different TOF measurements was compared to the MOE_{PB} from the immediately adjacent (north side) structural piece, and to the mean MOE_{PB} of all pieces per tree (Figure 5-15).

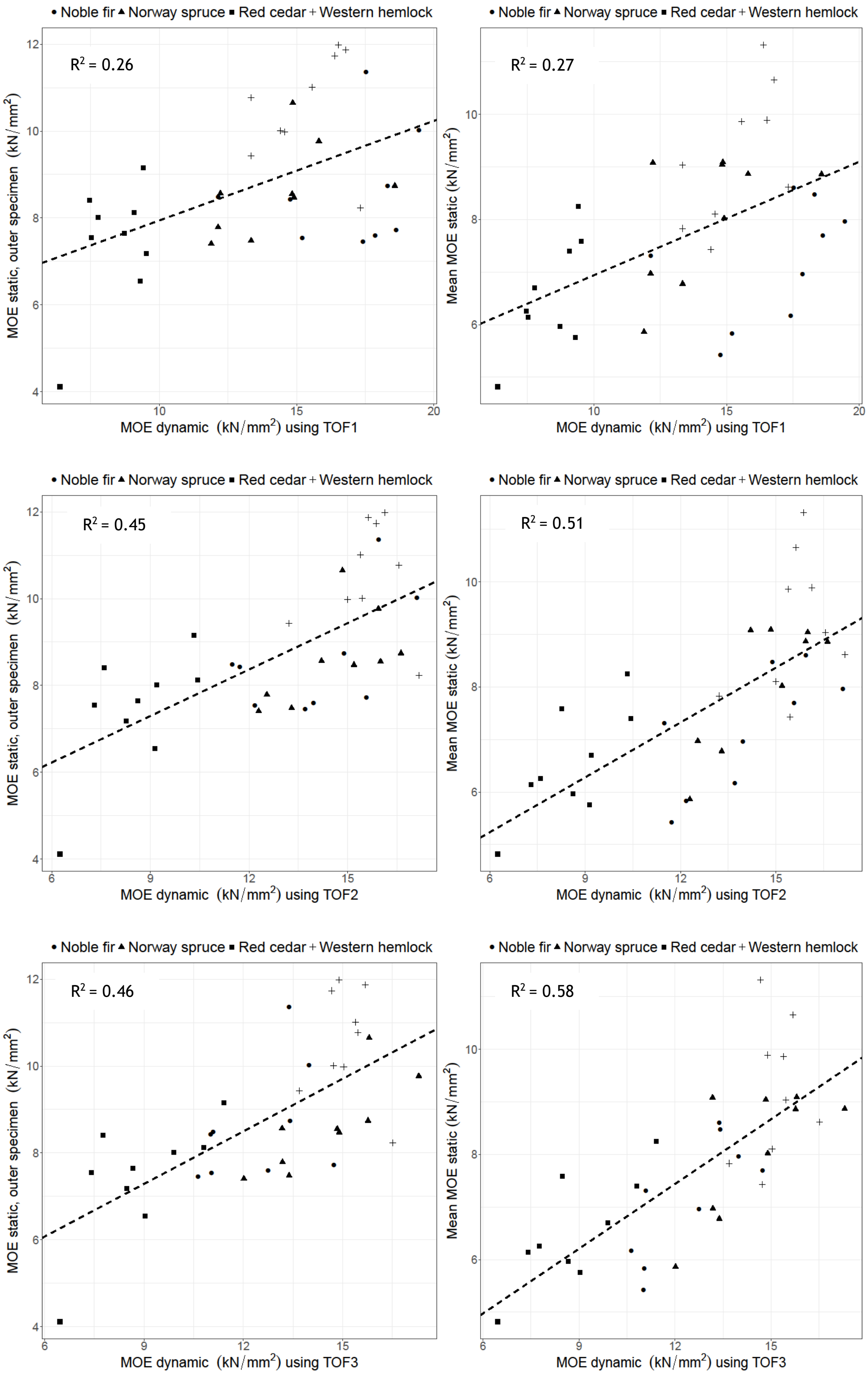


Figure 5-15. Comparison of MOE_{dyn} using $TOF1_N$, $TOF2_N$ and $TOF3_N$ with the MOE_{PB} of the outer piece to the north side and the mean MOE_{PB} per tree.

Figure 5-15 showed that the MOE_{dyn} calculated with TOF measurements related better with the mean MOE_{PB} per tree than with the outermost piece to the north side. The relationship was poor, and the differences small using $TOF1_N$ (R^2 = 0.27 and R^2 = 0.26), but increased lengthening the distance of measurement, more importantly compared to the mean MOE_{PB} per tree (R^2 = 0.58 using $TOF3_N$).

On clears, it was shown before (see §5.4.1.3) that $MOE_{dyn,TOF1}$ was weakly related to the MOE_{sta} (R^2 = 0.16 for the three sites). In the northern site the relationship was R^2 = 0.17, but using $TOF2_N$ and $TOF3_N$ it improved to R^2 = 0.44 and R^2 = 0.52. This is not surprising because clears were cut just above the top probe, and so $TOF1_N$ did not actually cover the properties at that height. The $MOE_{dyn,TOFx}$ related stronger with the MOE_{sta} of the outermost clear (R^2 = 0.34, 0.55 and 0.61) than with the mean MOE_{sta} of clears per tree (R^2 = 0.17, 0.44 and 0.52), but getting more similar as the distance increased. Similarly, the relationship of $MOE_{dyn,TOFx}$ with MOR_C also improved using $TOF2_N$ and $TOF3_N$ (R^2 = 0.31 and 0.38) in comparison to the R^2 = 0.14 obtained with $TOF1_N$.

The sound wave propagation between two opposite sides of trees was also examined. Comparing two paths with the same starting point, and stopping at the same height on opposite sides of the trunk (Figure 5-2, 0B-01, and 0C-02), it was found that the difference in the arrival time lessened measuring longer distances (Figure 5-16 left).

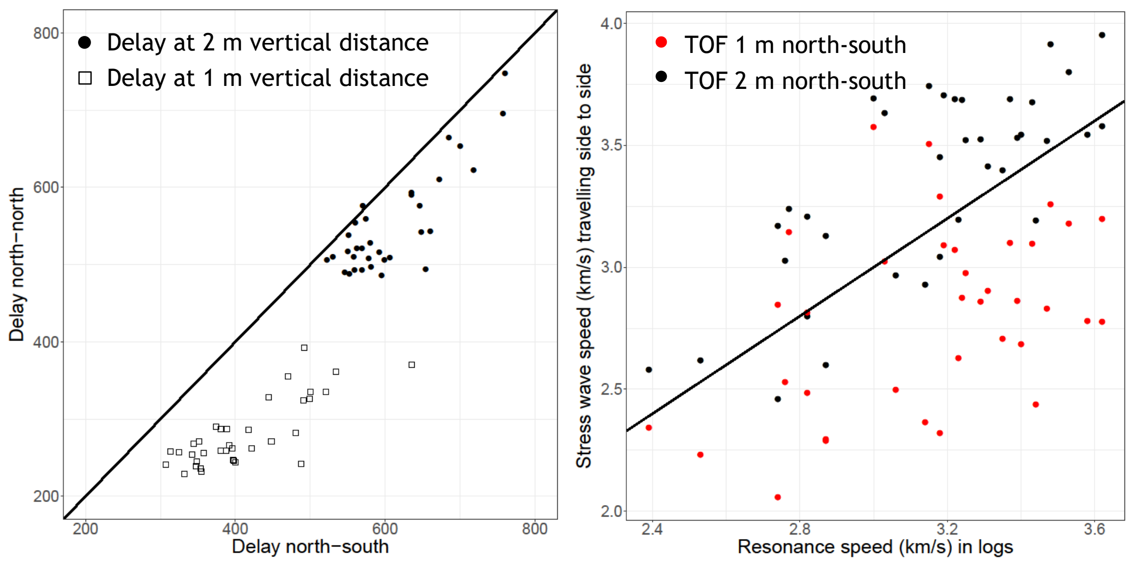


Figure 5-16. Delay differences (μs) between measurements on the north side and on opposite faces (left) and relationship between resonance and TOF speed measured over opposite faces (right). The solid line indicates a relationship one to one.

The resonance speed on logs was moderately related to the wave speed travelling between opposite sides over one metre vertical distance (r = 0.43), and strongly related travelling a two metre vertical distance (r = 0.76, Figure 5-16, right).

The correlation of the different acoustic measurements tested in the north site among themselves and with the mean MOE_{PB} per tree was assessed with Pearson's and Spearman's rank test (Table 5-8). Pearson aimed to examine the linear relationship and Spearman the rank order.

Table 5-8. Spearman and Pearson (italics and underlined) coefficients between MOE_{PB} and MOE_{dyn} per tree using different acoustic measurements in the northern site.

	MOE_{PB}	MOE dyn MTG	MOE dyn log	MOE dyn TOF3N	MOE dyn TOF2N	MOE dyn TOF2,NS	MOE dyn TOF1N	MOE dyn TOF1,ave	MOE dyn TOF1,NS
MOE_{PB}	1	0.98	0.82	0.79	0.75	0.56	0.50*	0.52*	0.31
$MOE_{dyn,MTG}$	*0.98*	1	0.85	0.83	0.79	0.60	0.54	0.55	0.36
$MOE_{dyn,log}$	*0.80*	*0.85*	1	0.88	0.77	0.66	0.43**	0.44**	0.39
$MOE_{dyn,TOF3N}$	*0.76*	*0.81*	*0.90*	1	0.88	0.73	0.65	0.64	0.58
$MOE_{dyn,TOF2N}$	*0.72*	*0.77*	*0.80*	*0.94*	1	0.76	0.80	0.82	0.67
$MOE_{dyn,TOF2,NS}$	*0.58*	*0.62*	*0.75*	*0.87*	*0.86*	1	*0.79*	*0.75*	*0.83*
$MOE_{dyn,TOF1N}$	*0.52*	*0.58*	*0.54*	*0.77*	*0.89*	0.73	1	0.95	0.72
$MOE_{dyn,TOF1,ave}$	*0.56*	*0.61*	*0.55*	*0.77*	*0.89*	0.66	*0.97*	1	0.62
$MOE_{dyn,TOF1,NS}$	*0.32*	*0.35*	*0.40*	*0.63*	*0.70*	0.85	*0.76*	*0.69*	1

P-values <0.001, except **<0.01 and *<0.05

The correlations of the mean MOE_{PB} per tree with the MOE_{dyn} calculated using the resonance speed were very strong (r = 0.98 in structural pieces, $MOE_{dyn,MTG}$, and 0.80 in logs, $MOE_{dyn,log}$). The correlation decreased slightly when using $TOF3_N$ (r = 0.76) and $TOF2_N$ (r = 0.72), and became only moderate using $TOF1_N$ (r = 0.52) and $TOF2_{NS}$ (r = 0.58).

The strongest correlation of $MOE_{dyn,log}$ was with MOE_{dyn} using $TOF3_N$ (r = 0.90). MOE_{dyn} using $TOF3_N$ correlated strongly with MOE_{dyn} using $TOF2_N$ or $TOF2_{NS}$ (r = 0.94, and r = 0.87). Finally, the correlation of MOE_{dyn} using $TOF1_{NS}$ was better correlated with MOE_{dyn} using $TOF2_{NS}$ (r = 0.83) than with MOE_{dyn} using $TOF1_N$ (r = 0.76).

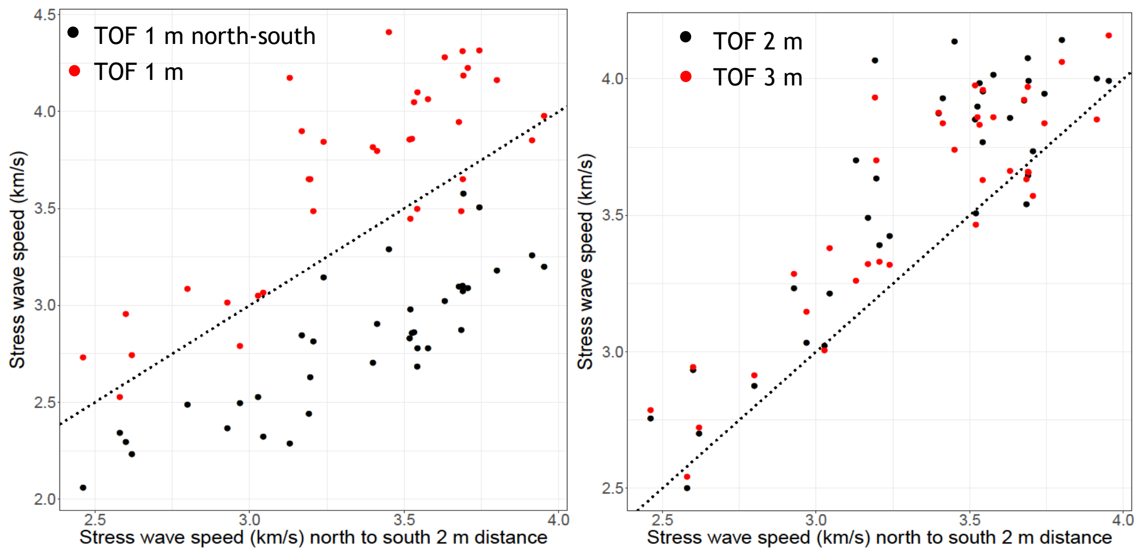


Figure 5-17. Comparison of speeds calculated using different distances.

Figure 5-17 (left) showed that an acoustic wave travelling side to side of a stem over a vertical distance of two metres was faster than travelling one vertical metre, and overall slower than travelling one metre vertical distance on the same side. Figure 5-17 (right) showed that measurements on two and three metres length on the same side were also in general faster than speed calculated side to side. These results were subject to limitations due to the assumed travel path and therefore the speeds calculated are not necessarily actual speeds of wave propagation.

5.5 Discussion

This chapter showed that timber quality assessment based on the use of portable acoustic tools offered different grades of reliability depending on the method used (resonance or TOF), and the level of segregation.

The TOF measurements on clears and MOE_C were strongly and linearly related (R^2=0.88), similar to the resonance method applied in structural pieces (R^2=0.90). Using resonance measurements, Raymond et al. (2007) found in clears of radiata pine a strong relationship between MOE_{dyn} and MOE_C (R^2=0.98), and Moore et al. (2009b) in structural pieces of Sitka spruce (R^2=0.88).

The similar performance of the acoustics in clears and structural pieces, even though the presence of knots, suggest that acoustic velocity did not say much about the presence of knots, and their effect may not be important for calculating MOE_{sta}. For MOR prediction, MOE_{dyn} in clears explained 57% of variation of MOR, and $MOE_{dyn,MTG}$ 43% in structural pieces. A linear regression using $MOE_{dyn,MTG}$ as predictor variable determined that the additive effect of species and knots were significant, which increased the prediction of MOR up to 59%.

TOF applied to clears can place transducers at both ends, so it is easier for the wave to travel in the longitudinal direction. This way, the small clear resembles a rod and the wave can be considered planar. Due to the relatively small size, and the lack of defects, it can be considered that the front wave covers the whole section of the clear. That is not the case in standing trees.

A comparison between $TOF1_{ave}$ applied in trees and resonance in logs, where the wave propagation is also planar, gave a moderate relationship (R^2 = 0.50). The same comparison on Sitka spruce found a relationship of R^2 = 0.60 (Moore et al., 2009b), and Grabianowski et al. (2006) reported for 8-11 years old radiata pine trees correlations of R^2 = 0.92. Using a distance of 1.3-1.4 m Chauhan and Walker (2006) found a strong relationships between TOF_{ave} and resonance in logs for radiata pine of 8, 16 and 25 years old (R^2 = 0.89, 0.91 and 0.75, respectively), with bigger differences between speeds in the older and larger trees.

Overall, the $MOE_{dyn,log}$ offered better estimations of wood stiffness than MOE_{dyn} using $TOF1_{ave}$, which in general provided higher values of MOE_{dyn}. At a log level, the relationship of $MOE_{dyn,log}$ with the mean MOE_{PB} resulted moderate (R^2 =0.52), slightly stronger than the R^2 =0.47 observed for Sitka spruce in Moore et al. (2009b). At a tree level, there was a weak relationship between the MOE_{dyn} using $TOF1_{ave}$ and the mean MOE_{PB} cut from the tree (R^2 = 0.33). Even though, $TOF1_{ave}$ discerned the lower MOE_{dyn} of western red cedar compared to the other species.

Ranking per site and species the MOE values calculated it was not possible to conclude a common pattern between approaches. Whereas in western hemlock and western red cedar $MOE_{dyn,log}$ ranked like MOE_{PB}, in noble fir $TOF1_{ave}$ worked better. None of the methods however ranked Norway spruce correctly. At a plot and site level the linear relationships were stronger than a tree level. Results in Table 5-7 offered a better correlation between $MOE_{dyn,TOF1}$ and MOE_{PB} including all the trees in the plots than analysing only the trees from which the timber was processed. By measuring more trees more variation between trees is captured, so the lower correlation of $MOE_{dyn,109}$ and MOE_{PB} it is likely a consequence of the sampling, and by destructively testing more trees the correlation had been better.

For the 12 stands studied in the present chapter (three sites per species), results indicated a strong correlation per site of the mean MOE_{PB} with the $MOE_{dyn,log}$ (R^2 = 0.66), and weak-moderate with $MOE_{dyn,109}$ (R^2 = 0.38). Also over 12 sites, a study by Moore et al. (2013) obtained slightly better relationship with $MOE_{dyn,TOF1}$ (R^2 = 0.83) than with $MOE_{dyn,log}$ (R^2 = 0.80). Thereby, acoustic measurements at tree or log level may not identify correctly individuals on the basis of the wood quality, but they can be of help at a plot, and particularly site level, for comparison of timber quality between stands. Yet, the acoustic measurements may fail to catch the timber capabilities of a site. The south and north sites of noble fir registered high MOE_{dyn} using $TOF1_{ave}$ compared to the low MOE_{PB} measured in the laboratory, and similarly using $MOE_{dyn,log}$ in the south site. Noble fir presented some decolouration signs, although it was not possible to determine the reason or quantified as it was not an aim of the study. The southern stand of noble fir had the lowest density of the 12 sites studied, and it was the youngest stand. It can be hypothesized that the assumption of 1000 kg/m^3 resulted in a false impression of high stiffness.

To explain the higher values of the TOF measurements, and the weaker relationship of the measurements on standing trees with sawn timber compared to those on logs some studies concluded that the TOF methods measure the time delay of a wave moving in the outer part of the tree. The mentioned study by Grabianowski (2006) compared TOF measurements on logs and green boards, and obtained a higher correlation with the outerwood timber (r = 0.94) than with the piece cut from the corewood (r = 0.86). This made to conclude that *TOF tools measure the outerwood properties of stems.* The trees were 8-11 years old, and the unknown diameter may have had an influence in the results. The same idea of TOF relating better to the outerwood was supported by a study using scanned radial strips with SilviScan (Hong et al., 2015), but the bigger proportion of outerwood on the entire section could have had an influence. In addition, SilviScan estimates MOE from microfibril angle and density.

In most of the studies the distance measured using TOF was around 1 metre, and the trees assessed younger than in the current study. Placing the probes on opposite side of the trunk, Dickson et al. (2004) reported a correlation between the mean MOE_{sta} of boards and the standing tree measurements of R^2= 0.06, and with logs of R^2= 0.16. This coefficients are too weak, and can be seen as no relationship exists. The relationship improved when dealing separately with sapwood (R^2= 0.24 and R^2= 0.53) and heartwood (R^2= 0.13 and R^2= 0.37). The study concluded that the stronger correlation of the acoustic measurements with sapwood was due to the wave being biased towards the stiffer outerwood, although the authors admitted that *"The probes [...] were only 1 m apart [...]. In a short large log, it will take relatively longer for a sound wave to radiate in the radial dimension [...] thus not allowing a true velocity to be measured"*.

This chapter examined alternative approaches to improve the segregation of trees based on the MOE. The starting hypothesis to explain the weaker relationship of acoustic measurements on standing trees with stiffness of sawn timber was the short distance travelled by the wave, not covering the variation of properties within the trunk (Searles, 2012), and influenced by the ratio diameter/length (Zhang et al., 2011). The results indicated a better relationship in a tree between the $MOE_{dyn,TOFx}$ and the mean MOE_{PB} than with the outermost specimen on the side acoustically tested, stronger as the stress wave induced travelled longer. The best relationship was found for TOF3 (R^2 = 0.58), slightly stronger than using $MOE_{dyn,log}$ (R^2 = 0.52). This would suggest that the wave does not move directly between the transducers in the outer part of the tree.

It is possible that after the wave travelling 3 metres, it started to become in a plane wave, occupying the whole section in the tree and accounting better for the variability within the trunk. Even though, increasing the distance to at least 2 metres allowed the stress wave induced to traverse a more representative proportion of the stem section, adding useful segregation potential. The results were thus consistent with recent studies which indicate that a stress wave it is not confined to travelling through the sapwood in the outer part alone, but as

Searles (2012) explains: "*when the excitation is initiated, the stress wave starts propagating both up toward the top probe and outward across the tree's cross section*. The use of TOF1 offered less accurate predictions, and it was more useful to discern the lower quality timber at a site level, represented in this study by western red cedar.

Increasing the distance also improved the relationship with the mechanical properties measured in clears (R^2 = 0.52 using TOF3). The better relationship may be explained because the clears were obtained just above the top probe measuring TOF3, and in addition the wave after travelling 3 metres may become planar, covering the whole section of the stem. The relationship of MOR with MOE_{dyn} also improved as the distance of TOF was longer (R^2 = 0.38 using TOF3). The poor relationship of $MOE_{dyn,TOF1}$ with MOE_{sta} and MOR in clears (R^2 = 0.16 and R^2 = 0.14) can be explained by the different height of the stem studied, roughly three meters apart. Mora et al. (2009) acoustically assessed young loblolly pine trees of relatively small dbh using $TOF1_N$ speed, and obtained clears from just above the section acoustically tested, obtaining a strong relationship with MOE_C (R^2 = 0.65). In addition, only a radial section was processed into clears weighting to replicate a bark-to-bark pattern, which is not representative of the entire section, particularly on trees with big dbh. A study on Scots pine (Auty and Achim, 2008) tested clears obtained from a log previously assessed using $TOF1_N$ speed. The study weighted the MOE_{sta} of clears to replicate the whole section, and found a moderate relationship (R^2 = 0.53) with acoustic velocity. Similarly, the study found a stronger relationship between $TOF1_N$ speed and weighted MOR (R^2 = 0.59).

According to the results, TOF tools do not only measure the outerwood properties of stems, and stiffness prediction would be importantly influenced by the distance measured. Measuring TOF over distances of two or three metres offered more reliable results of the stiffness in a tree than the commonly used one metre, most likely due to a change in the wave propagation. This becomes more important in larger trees. Further investigation could investigate Poisson's ratio from TOF3 measurements using established equations and apply that to trees assessed with TOF1.

5.6 Conclusions

This chapter has demonstrated the usefulness of portable acoustic tools for prediction of wood quality. In sawn timber they determined stiffness very reliably, and in combination with knot indexes gave a good prediction of strength. However acoustic measurements lack the capability of describing the variation of wood properties within a tree or log.

Resonance measurements in logs provided good estimation of average stiffness. Current acoustic tools applied to standing trees over one metre distance must be used with care. If the aim is to segregate individual trees of commercial size for timber production a distance of at least two metres must be measured. This allows to improve the prediction of wood quality.

This study also support the hypothesis that a stress wave travelling in a tree initially behaves as dilatational, changing with distance to a plane wave. This implies that the wave does not travel directly between the two probes, but likely up and across the tree’s trunk.

Chapter 6. Tree architecture and merchantability

6.1 Introduction

Estimation of standing tree volume has been always a major concern for growers. Measurements on standing and felled trees can describe the tree architecture and determine the timber volume. In G.B., wood volume is assessed to a top minimum diameter of 7 cm over bark. Depending on the top minimum diameter timber will be destined to different end products. An upper diameter of 14 cm over bark is the minimum size used for sawlogs, and 7 cm for pulpwood and biomass.

Taper describes the tree shape as the decrease in stem diameter with increasing height up the stem. By calculating diameters at a certain height, taper functions allow estimations of the volume in a tree, and between any specified heights. It is common to obtain the merchantable volume equations for different end products relating diameters and heights. As well as volume, it is of primary importance to assess stem straightness because it determines the length of the sawnwood available, but it also has an effect on mechanical properties as the lack of straightness increases deviations in the grain angle (Macdonald and Hubert, 2002).

Another two indicators of the tree architecture are slenderness, defined by the height and dbh of the stem, and crown ratio, defined by the relationship between crown depth and total tree height. These indicators could relate to timber quality. Growth responses are driven by the crown structure, which is defined by branchiness characteristics, which in turn cause the presence of knots in sawnwood, having ultimately an influence on the wood properties.

The objective of this chapter is to investigate the architecture of noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. Taper functions had not been yet developed for these four species in G.B. In addition, straightness, slenderness, crown and particularly branching characteristics are described. These results helped to understand better the potential merchantability for sawn timber of the four species investigated, and will help forest management decisions for timber production.

6.1.1 Objectives

Specifically, the aims of this chapter for the four species studied are:

1. To investigate the stem architecture and model taper functions for each species.

   To assess the straightness, and determine the tree diameter at any height, making possible calculation of the merchantable volume.

2. To explore the relationship of crown ratio (CR) and slenderness with the mechanical properties.

   To evaluate the use of CR and slenderness as indicators of bending stiffness and bending strength.

3. To examine the branching characteristics.

   To quantity the variation due to species, plots, trees and height within trees, and model the frequency, size and angle of insertion of branches.

6.2 Literature review

Previous chapters have been mostly concerned with wood quality for structural purposes. When timber production is pursued, knowledge on the quantity of timber available from a forest plays a key role for sustainable management.

Knowledge on the relationship tree height-dbh is of primary importance for foresters, because ultimately these allow to predict wood volume. The relationship can also indicate the site index, and be used to compare stands because within a species it is expected that on a good site quality the height and dbh will be higher than in a lower quality site.

The relationship varies over time, typically height and dbh increasing with age, and so does volume. For the mostly practised thinning from below, it is usually assumed that in an even-aged stand, the tallest trees are not affected by the thinning. The *mean total height of the 100 trees of largest dbh per hectare* is called top height (Matthews and Mackie, 2006). For a 0.01 ha sample plot the tree of largest dbh is referred to as top height sample tree (Forestry

Commission, 2016). The potential productivity of an even-aged forest plantation in British forestry is based upon the estimation of the Yield Class (YC), which is determined from the top or dominant height in relation to age (Matthews and Mackie, 2006).

As well as productivity, it is essential to know the sawn wood recovery that can be diverted for structural timber. Stem straightness is an important attribute that determines the length of the sawnwood available per tree. In G.B. is assessed on the bottom six meters of the tree, and it was identified for the industry as the most important factor for quality of spruce logs (Methley, 1998).

Sawlogs can be obtained over 14 cm diameter over bark. In order to estimate the sawlog volume it is recommended to construct taper functions or tree profile models. "*Taper is the term used to describe the decrease in stem diameter with increasing height up the stem*" (Clutter et al., 1983), and as Kozak (2004) states: *taper equations provide estimates of: […] (ii) total stem volume; (iii) merchantable volume and merchantable height to any top diameter and from any stump height*. Continuous technological changes in sawmills, in the merchantability standards and the requirements from the industry adapted to new end-uses products, suggest the need of models capable of adapting to varying merchantable limits. These models are flexible for the different shape in which trees develop, as opposed to the more traditional Smalian's or Huber's formulae. Taper functions have only been studied in G.B. for Sitka spruce and Scots pine (Fonweban et al., 2011)

Another two characteristics of the tree architecture are slenderness and crown ratio (CR). Slenderness is the relationship between the tree height and dbh. Studies on radiata pine found a very good relationship between slenderness and stiffness (Lasserre et al., 2009), relating increases in slenderness with increases in stiffness to minimise the risk of stem buckling (Watt et al., 2006). Other study on Sitka spruce stated that slenderness is more accurate than standing tree velocity for stiffness estimation (Searles, 2012).

Crowns play an essential role in the development of trees, they *are an important link between stand dynamics and physiological processes* (Weiskittel et al., 2010). The crown development can be a measure of inter-tree competition, and therefore be an indicator of wood quality (Mäkinen and Hein, 2006). Moore *et al* (2013) found a significant negative association of CR with mechanical properties, and suggested the use of the CR as a simple approach for wood quality segregation on Sitka spruce. A shorter crown is associated with a higher mechanical performance compared to a deep crown. The association is considered by some authors as a way of controlling the transition between juvenile and mature wood (Lachenbruch et al., 2011).

The CR depends on the light availability, competition and shade-tolerance of species. A deep living crown implies a longer retention of branches, which among other factors is a consequence of a reduced competition (Macdonald and Hubert, 2002), due to either initial spacing or following silvicultural practices which derives in thicker branches and a bigger taper. Likewise, higher stand densities increase the height of the lowest living branch and lowest living whorl (Mäkinen and Hein, 2006). This chapter is interested in the branch characteristics because they are the cause of the presence of knots, having an influence on the wood properties but also on the log sorting and processing (Holland and Reynolds, 2005). Even though knots may not always be a primary cause of downgrade on some species like Sitka spruce (Methley, 1998), they may be on species with larger branches when grading structural timber in the intended use. A deeper study in the branchiness of these four species will help to understand their influence in timber quality, particularly knot size.

Branchiness has been studied in G.B. for Sitka spruce (Achim et al., 2006), Scots pine (Auty, 2011) and Douglas fir (Drewett, 2015), but there is not any study in G.B. analysing the branching characteristics for the four species here studied, that in addition have different growth patterns. Whereas noble fir and Norway spruce form distinct growth units, identified with whorls and interwhorls, western red cedar and western hemlock lack of them. This different growth pattern was addressed before in a study of the crown of five conifer species (Weiskittel et al., 2010) dividing the crown length in 0.5 m sections.

The aim of this chapter is to investigate the external stem characteristics of the four species studied. Relationships between heights and dbh are examined, and the stem profile characterised based in some known taper functions so that the sawlog volume can be estimated. Straightness, CR and slenderness are examined in relation with wood quality. Finally, the branching characteristics are described. The number of trees investigated per species is low, and the analysis aimed to give an overview of the branchiness to help to understand the growth of the species in G.B. and the influence in wood quality. Outcomes of this chapter may help in the development of decision supporting systems where stem volume and wood quality are included to maximise the production considering wood quality.

6.3 Material and methods

6.3.1 Material and methods

The general description regarding data collection used in this chapter were fully described in Chapter 2 Material and methods. A summary is provided below.

- Three even-aged single species planted forests from different latitudes.
- The age of the stands was different, as well as possibly the initial spacing, based on the common practise at the time of planting (Table 2-2).
- Trees felled in the northern site were used for branchiness assessment, with the exception of the extra tree of western hemlock.
- There was no record of the silvicultural practices applied, but it was observed that the four stands had been thinned.

Table 6-1 includes a list of those abbreviations used throughout this chapter.

Table 6-1. Nomenclature and abbreviations used in Chapter 6.

Variable	Definition
CR	Crown ratio (crown length/tree length)
BD	Diameter branch
BDM	Maximum branch diameter
BRA	Branch angle
Dtop	Distance from the stem apex to base of a metre section
HT	Tree height
Section	Section of the trunk of one metre length used for modelling branches
NBR	Number of branches in a metre
YC	Yield class

6.3.1.1 Standing tree measurements

A total of 631 trees were measured within the studied plots for dbh, height and straightness as described in Chapter 2. Straightness assessment was based in a scoring system that evaluates the viability of the lower six metres stem to produce sawlogs (Table 6-2 and Figure 6-1).

Table 6-2. Straightness scoring system

Score	Number and length of straight log lengths counted in butt 6 m
1	No straight lengths ≥ 2 m
2	One straight length ≥ 2 m but <3 m
3	Two straight lengths ≥ 2 m but <3 m
4	One straight length ≥ 3 m but <4 m
5	One straight length ≥ 2 m but <3 m and 1 straight length ≥ 3 m but <4 m
6	One straight length ≥ 4 m but <5 m
7	One straight length ≥ 5 m

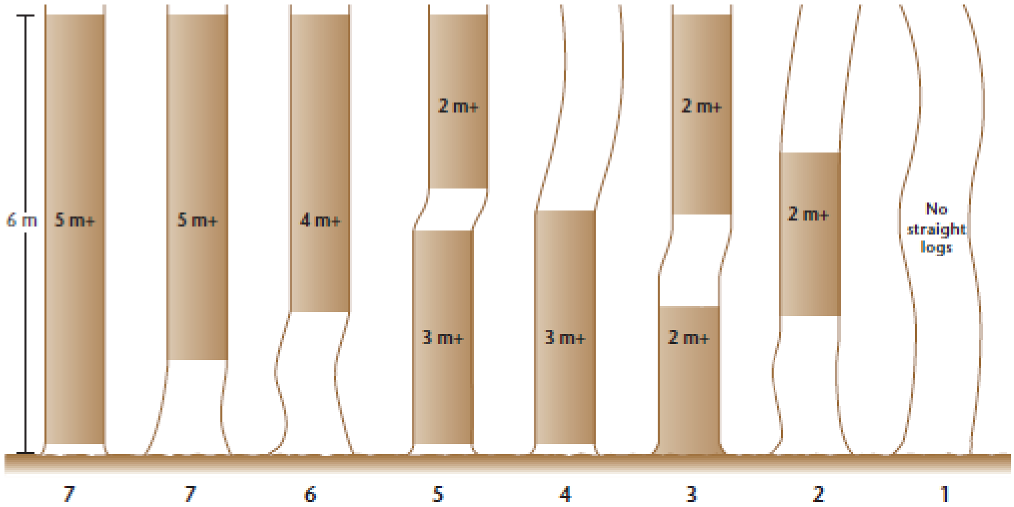


Figure 6-1. Straightness scoring system (MacDonald et al., 2000; Methley, 1998)

The straightness is a categorical variable so the median was calculated ranking the values as for ordinal variables.

6.3.1.2 Taper measurements and merchantability

Nine trees per species and site, except ten western hemlock in the north, were used for taper. After debranching the felled trees, diameters were measured over bark at 1-m intervals from 1 metre height up to tree top (Figure 6-2). Two diameters, the maximum and its perpendicular, were measured with callipers, and averaged to give an estimated mean diameter. The position of the measurement was slightly moved if a whorl, scar or similar was found, so avoiding alterations in the taper. Diameter tape was used if the calliper could not encircle the section. If a fork was found, the longest stem was considered the main one.

Figure 6-2. Taper measurements on noble fir.

These measurements were used to calculate the taper function. The Smalian's formula was used to calculate the volume of every 1 m section of the stem. The formula resembles the log as a cylinder of section the average of the large and small ends for the full log length (Figure 6-3). The tree top was treated as a cone.

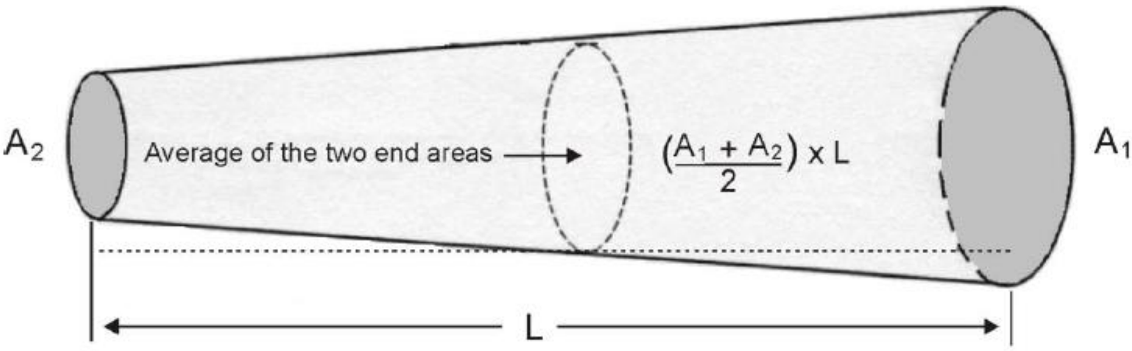


Figure 6-3. Smalian's formula. Source: Ministry of Forests, Lands and Natural Resource Operations of British Columbia.

The total volume was obtained by summing the individual sections. The merchantable volume for sawlogs was calculated up to 14 cm diameter over bark.

6.3.1.3 Crown depth

Crown depth was identified on the trees selected for felling (108 trees). For noble fir and Norway spruce it was defined as the lowest living live whorl, considering at least 75 % of whorl was alive. Figure 6-5 shows the typical whorl growth. Western red cedar and western hemlock do not grow whorls (Figure 6-6), and the crown was determined as the presence of at least four consecutive live branches. In addition, the height of the first living branch was measured.

6.3.1.4 Branchiness

Branchiness was assessed in the trees felled in Scotland (Figure 6-4) following the methodology shown in Colin and Houllier (1992), which was also adopted in G.B. for Sitka spruce (Achim et al., 2006). No signs of pruning were detected in any of the sites.

Figure 6-4. Branchiness of a Norway spruce sampling tree.

The following measurements were made on all of the branches over 5 mm diameter at the point of insertion, from the tip to the butt:

- Distance from the bottom of the tree to the branch, that is, height of the branch in the standing tree.
- Horizontal and vertical diameter of the branch at the point of insertion.
- Angle of insertion of the branch with the stem, placing a protractor at the centre of the base of the branch.

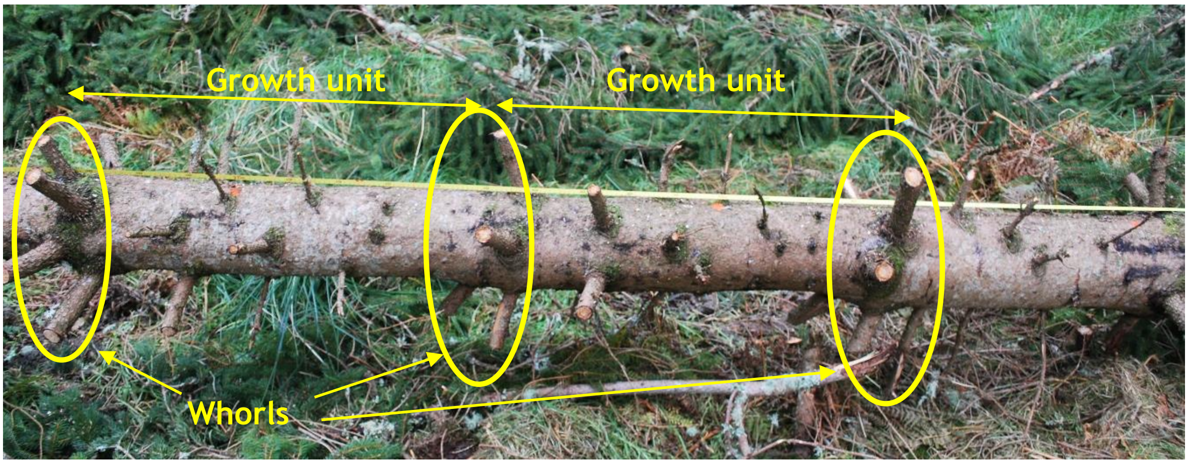


Figure 6-5. Branch distribution in a Norway spruce.

Figure 6-6. Branches in a western hemlock. Blue dots represent a metre of distance.

A total of 11042 branches were measured from 36 trees, nine per species. A summary of the main tree and branch attributes is given in Table 6-3.

Table 6-3. Mean and standard deviation (in brackets) of the trees assessed for branchiness. See Table 6-1 for abbreviations.

	Noble fir	Norway spruce	Western red cedar	Western hemlock
CR (%)	43.9 (5.7)	51.9 (8.1)	61.7 (7.4)	43.7 (12.0)
BD (cm)	20.9 (11.0)	18.3 (11.1)	24.4 (12.4)	21.0 (13.0)
BDM (cm)	32.5 (11.8)	31.8 (11.9)	35.7 (14.4)	36.1 (14.9)
BRA (°)	84 (11)	78 (12)	80 (11)	84 (17)
dbh (cm)	36.6 (5.6)	46.5 (3.8)	64.9 (8.4)	52.4 (6.2)
HT (m)	20.8 (1.2)	28.0 (1.3)	30.5 (1.6)	33.0 (2.3)
NBR	12.9 (3.9)	15.6 (6.2)	9.1 (3.4)	9.5 (4.3)

6.3.2 Statistical analysis

The taper measurements aimed to model the stem profile of the species, not considering differences by sites. The material collected for branchiness represented only an overview of the branchiness of the species, which may change under different management. The statistical analysis was carried out with the R open-source statistical programming environment (R Development Core Team, 2016). The specifics of the analysis for each of the aims are:

1. To investigate the stem architecture and model taper functions for each species.

The relationship between the height and the dbh of the trees measured in the plots was examined. The software Forest Yield (Forestry Commission, 2016) was used to obtain the YC using the top height and age as inputs. The top height per site was calculated as the average height of the n thickest trees per plot, where n is the number of ares (one are is 0.01 ha) of the plot.

The distribution of straightness scores was examined, and a Chi-Square test of independence conducted to examine differences between species.

After investigating the relationship between variables, five taper functions were examined. They correspond with the five models retained for Scots pine and Sitka spruce in Northern Britain (Fonweban et al., 2011). The models were:

Model 1

$$\boldsymbol{d} = dbh \times \boldsymbol{x}^{(\alpha_0+\alpha_1 \times (z-1)) + \alpha_2 \times (\exp(\alpha_3 \times z))} \qquad [6\text{-}1]$$

where $x = (ht - h)/(ht-1.3)$;
$z = h/ht$: relative height along the stem;
ht = total tree height (m)
h = height along tree bole (m)
dbh = diameter ar breast height (cm)

Model 2

$$\boldsymbol{d} = \beta_0 \times dbh^{\beta_1} \times {x_1}^{(\beta_2 \times z^2+\beta_3 \times \ln(z+0.001)+\beta_4\sqrt{z}+\beta_5(dbh/ht))} \qquad [6\text{-}2]$$

where $x_1 = [(1-\sqrt{z})/(1-\sqrt{p})]$;

P= point of inflection. It represents the point at which the tree shape changes from a neiloid form to a paraboloid form. It was fixed at 1.3/ht.

Model 2b

$$\boldsymbol{d} = \beta_0 \times dbh^{\beta_1} \times {x_1}^{(\beta_2 \times z^2 + \beta_3 \times \ln(z+0.001) + \beta_4 (dbh/ht))} \quad [6\text{-}3]$$

Model 3

$$\boldsymbol{d} = \varphi_4 \times dbh \times (1-z)^{k(h,\varphi)} \times (1 + \varphi_2 \times e^{(\varphi_3 \times z)}) \quad [6\text{-}4]$$

where ;

$k(h,\varphi) = \varphi_0 + \varphi_1(1\text{-}z)$;

$\varphi_0 = \varphi_{00} + \varphi_{01}(ht/\text{dbh})$

Model 3b

$$\boldsymbol{d} = \varphi_4 \times dbh \times (1-z)^{(\varphi_0 + \varphi_1 \times (1-z))} \times (1 + \varphi_2 \times e^{(\varphi_3 \times z)}) \quad [6\text{-}5]$$

The models were compared using the Akaike's information criterion (AIC). The model efficiency (R^2) was measured as the linear relationship between observed and predicted diameter, and error (RMSE). The chosen model was refitted afterwards using the nlme library in R (Pinheiro et al., 2016) for mixed-effects models. The random effects consisted of site and plot.

2. To explore the use of crown ratio (CR) and slenderness as indicators of bending stiffness and bending strength.

CR is the relationship between crown depth (m) and total tree height (m). Slenderness is the ratio between the tree height (m) and dbh (m). Pearson's correlation examined the strength of the relationships between the variables defining the CR and slenderness as well as age and the height of the first live branch and first live whorl. A single one way ANOVA analysis tested differences in the mean values of CR between species. The correlation of the mechanical properties with CR and slenderness was tested at tree and site level.

3. To examine and model the branching characteristics.

Characteristics included number of branches, mean and maximum branch diameter, and angle of insertion. Since the species investigated had different growth patterns, the trunks were equally divided into 1 m sections, starting at the ground level. A mixed model for hierarchical data structure was used to estimate the variance components (equation [2-6]) of the branch characteristics. The random effects consisted of plot, tree and section within the tree.

A paired *t*-test investigated differences between the horizontal and vertical branch diameters. The branch size was investigated as average size and biggest branch per section. A single one way ANOVA analysis examined differences between species followed by a Tukey (HSD) test with $\alpha = 0.05$. Different models used before for different species (Achim et al., 2006; Auty, 2011; Weiskittel et al., 2007) were tested, but this thesis adapted the models to the peculiarities of the growth pattern of the species studied. In order to minimise the influence of age, and more importantly avoid the influence of the larger stems, branchiness was investigated as relative height in the tree and per section of trunk.

6.4 Results

The most traditional stem variables, tree height and dbh, were strongly correlated (Table 6-4). Age showed a strong correlation with tree height, less well with dbh.

Table 6-4. Pearson's correlation (r) between variables for the 108 trees felled for taper

	Tree Height	1st live branch	1st live whorl	dbh	CR	Age
Tree Height	1					
1st live branch	0.23*	1				
1st live whorl	0.57***	0.76***	1			
Dbh	0.72*** (0.66[1])***	-0.22*	0.14^{ns}	1		
CR	-0.01^{ns}	-0.76***	-0.80***	0.32***	1	
Age	0.74***	0.22*	0.50***	0.57***	-0.09^{ns}	1
Slenderness	0.01^{ns}	0.55***	0.39***	-0.65***	-0.46***	-0.02^{ns}

[1] Correlation between variables for the 627 trees within plots. ****P*-value< 0.001; ***P*-value< 0.01; **P*-value< 0.05; ns: no significant

6.4.1 Stem architecture

6.4.1.1 Heights and diameters

The overall relationship between the height of the measured trees in the plots and dbh was moderate (R^2 = 0.44, RMSE = 3.6 m). A significant difference in the relationship was observed due to the effect of species and site (*P*<0.001). By species, the strongest relationship was in noble fir, and the lowest in western red cedar (Figure 6-7).

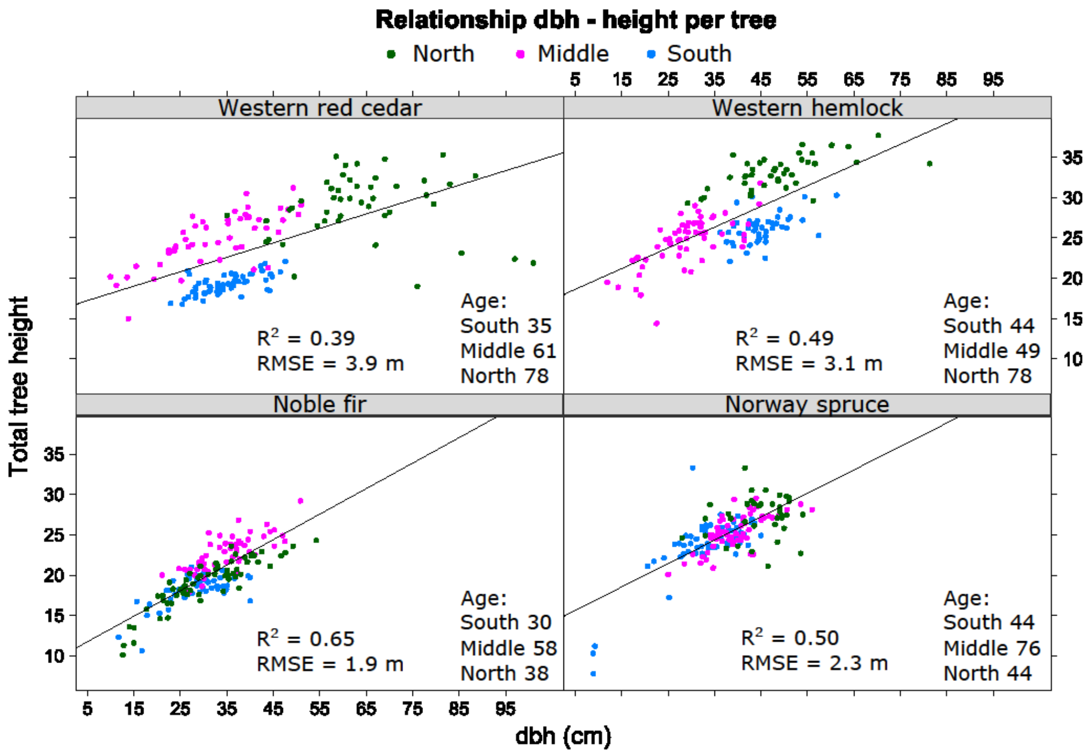


Figure 6-7. Relationship between dbh and height per tree by species.

The younger western red cedar trees in the south site reached a lower height compared to the middle site for a similar dbh. Otherwise, the relationship showed a general trend for which the larger the dbh the taller the tree, both increasing with age.

The three variables determined the productivity of the site, calculated from the top or dominant height in relation to age (YC). Figure 6-8 shows an example of the output in Forest Yield (Forestry Commission, 2016) of the YC for the stand of western red cedar in the middle site.

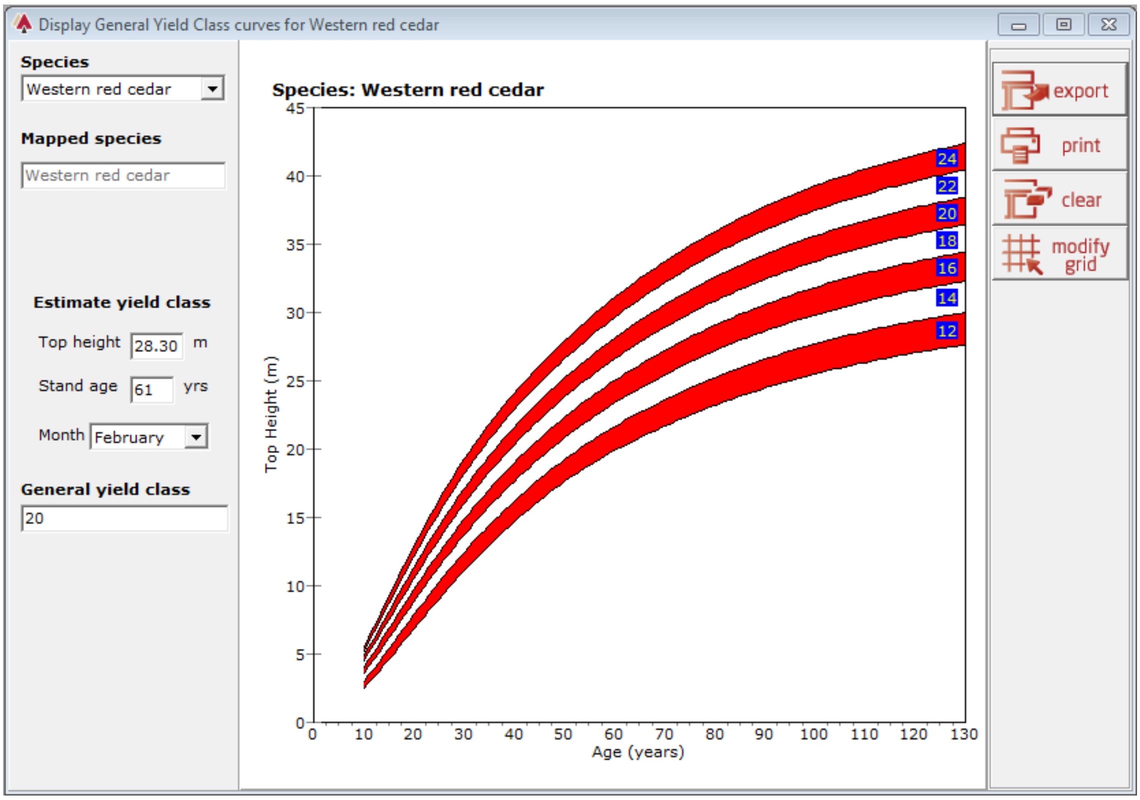


Figure 6-8. Example of YC 20 for western red cedar in the middle site.

Table 6-5 includes the age and top heights used to calculate the YC per site and species as well as other stand and tree characteristics.

Table 6-5. Stand and tree characteristics for study sites.

Species	Site	Age (years)	YC	Top Ht (m)	Density N/ha[1]	dbh (cm) Mean	dbh (cm) Sd	Ht (m) Mean	Ht (m) Sd	Volume (m^3) Mean	Volume (m^3) Sd	CR (%) Mean	Slenderness (m/m) Mean	Slenderness (m/m) Sd
		Stand level characteristics				**Tree level characteristics**								
Noble fir	S	30	22	18.5	2040	28.0	6.4	18.2	2.0	0.610	0.187	47.0	62	8
	M	58	18	24.9	442	35.1	6.5	22.8	2.2	0.120	0.303	46.5	65	5
	N	38	22	22.8	1011	30.7	9.4	19.1	3.1	0.108	0.405	43.9	58	7
Norway spruce	S	44	22	25.5	428	33.4	7.6	23.9	3.8	0.688	0.135	54.5	66	5
	M	76	14	27.1	414	39.4	5.6	25.4	2.1	0.103	0.460	42.9	62	5
	N	44	22	27.2	247	44.5	6.2	27.3	2.6	0.282	0.359	51.9	61	5
Western red cedar	S	35	22	20.4	644	34.7	5.9	19.2	1.2	0.106	0.158	65.3	55	8
	M	61	20	28.3	796	32.6	10.9	24.9	3.3	0.143	0.376	50.6	73	15
	N	78	16	27.8	314	64.0	13.9	29.0	3.9	0.170	0.732	61.7	48	5
Western hemlock	S	44	20	26.6	241	45.1	5.1	26.2	1.8	0.163	0.306	57.4	56	6
	M	49	20	27.5	995	28.8	7.3	24.6	3.0	0.969	0.352	34.0	80	12
	N	78	18	34.1	466	48.8	10.2	33.1	2.0	0.277	0.771	43.7	64	7

Sites: S, south; M, middle; N, north; Ht: Tree height; YC: yield class (m^3 ha^{-1} $year^{-1}$);[1]Stand density at the time of the data collection based in the plots measured.

6.4.1.2 Straightness

Norway spruce and western red cedar scored better than noble fir and western hemlock in terms of straightness (Figure 6-9). Data showed there are similarities in the distribution between noble fir and western hemlock, and from most of the trees, only a 2-m straight log (category 2) could be obtained. Norway spruce and western red cedar also keep some similarities, with most of the trees producing straight logs of at least 4-m length (categories 6 and 7) in the bottom six metres.

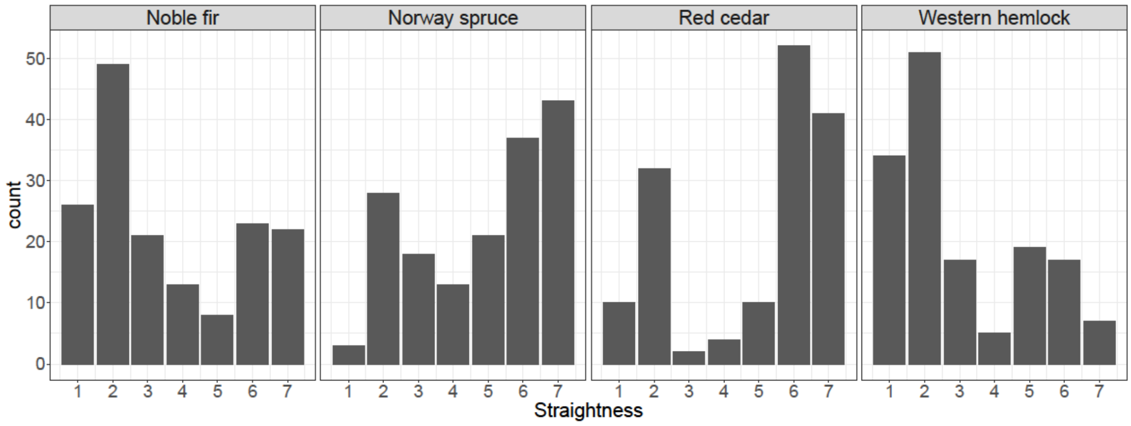


Figure 6-9. Barplot of category straightness by species.

As straightness is a categorical variable, a Chi-Square test of independence was conducted, and a significant difference between species was observed ($P < 0.001$). The distribution of straightness in percentage is shown in Table 6-6.

Table 6-6. Percentage of straightness by species

Straightness score	Noble fir (%)	Norway spruce (%)	Western red cedar (%)	Western hemlock (%)
7	13.6	26.4	27.2	4.7
6	14.2	22.7	34.4	11.3
5	4.9	12.9	6.6	12.7
4	8	8	2.6	3.3
3	13	11	1.3	11.3
2	30.2	17.2	21.2	34
1	16	1.8	6.6	22.7

Norway spruce stood out as the species scoring the best, although more than 60% western red cedar scored as category 6 or above. On the other hand, less than a third of western hemlock would achieve a minimum of three metres length required for structural-size timber.

A Chi-Squared test of independence found that there were differences between sites within species (*P*< 0.001) except for Norway spruce (*P*= 0.238). Particularly important were the differences in western hemlock with an important percentage of non-straight logs in the middle site and scoring mostly 2 in the south and 5 or above in the north (Figure 6-10).

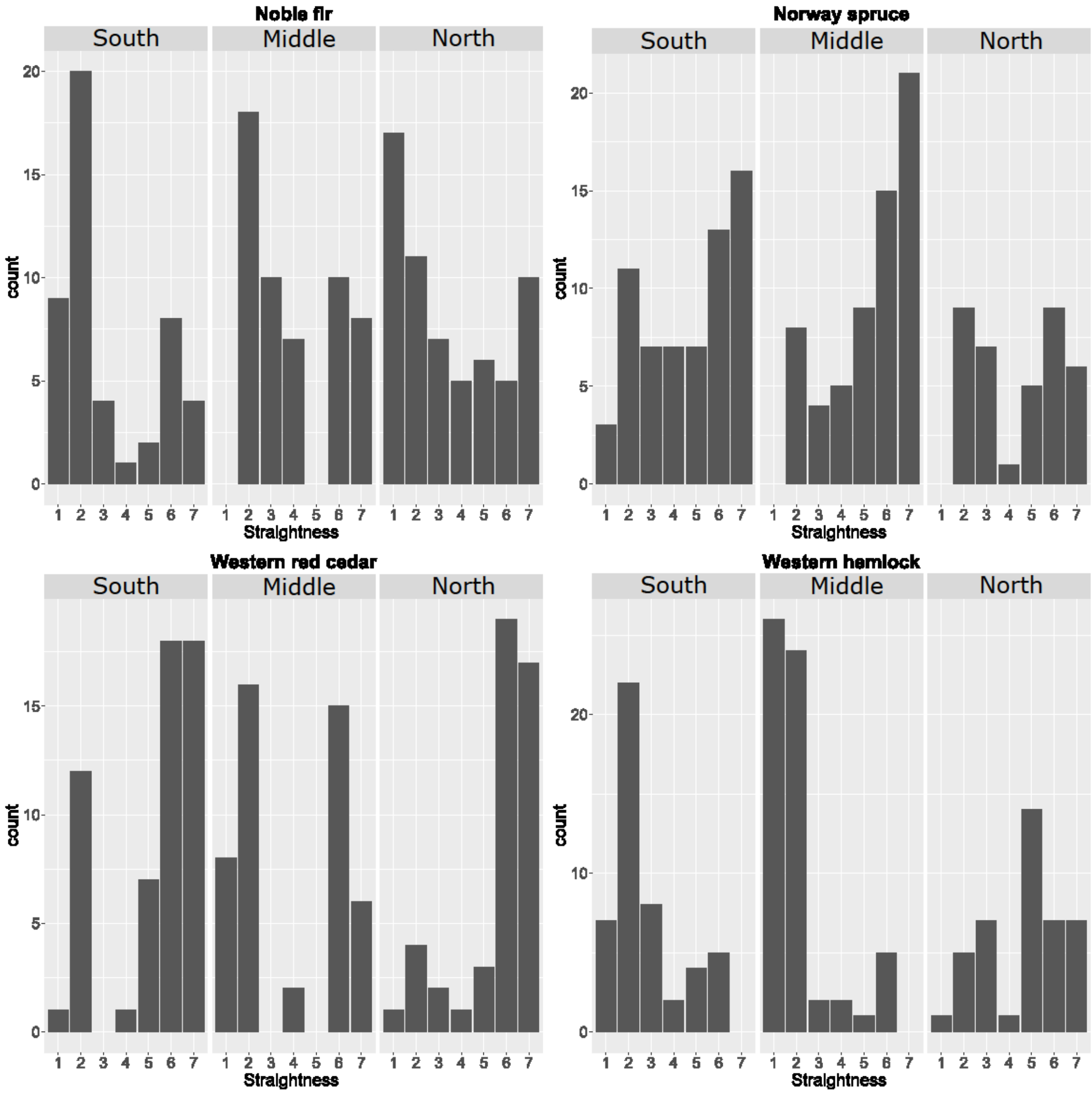


Figure 6-10. Barplot of category straightness by species and site.

6.4.1.3 Taper measurements and merchantability.

Table 6-5 reported the mean volume of the full tree length. The merchantable volume up to 14 cm diameter is given in Table 6-7. The height for sawlog production located between 65% and 79% of the total tree length. In terms of merchantable volume, this meant between 94% and 99% of the total volume. Values were similar between species.

Table 6-7. Merchantable volume for sawlogs by species and site.

		Age (years)	Merchantable volume (m^3)			
			Mean	sd	Mean % stem volume	Mean % height stem
Noble fir	South	30	0.58	0.20	93	67
	Middle	58	1.18	0.31	97	78
	North	38	1.05	0.41	97	75
	Overall		935	0.40	96	73
Norway spruce	South	44	1.01	0.15	95	73
	Middle	76	1.40	0.46	97	74
	North	44	1.67	0.36	98	74
	Overall		1.36	0.43	97	73
Western red cedar	South	35	0.65	0.16	94	68
	Middle	61	0.99	0.38	94	69
	North	78	2.79	0.73	99	79
	Overall		1.48	1.07	95	72
Western hemlock	South	44	1.60	0.31	98	70
	Middle	49	0.92	0.36	94	65
	North	78	2.72	0.78	98	77
	Overall		1.78	0.92	97	71

The decrease of the diameter size along the relative height of the tree is shown in Figure 6-11. The minimum diameter for sawlog varied between 62 and 84% of the tree length, with the mean around 75%.

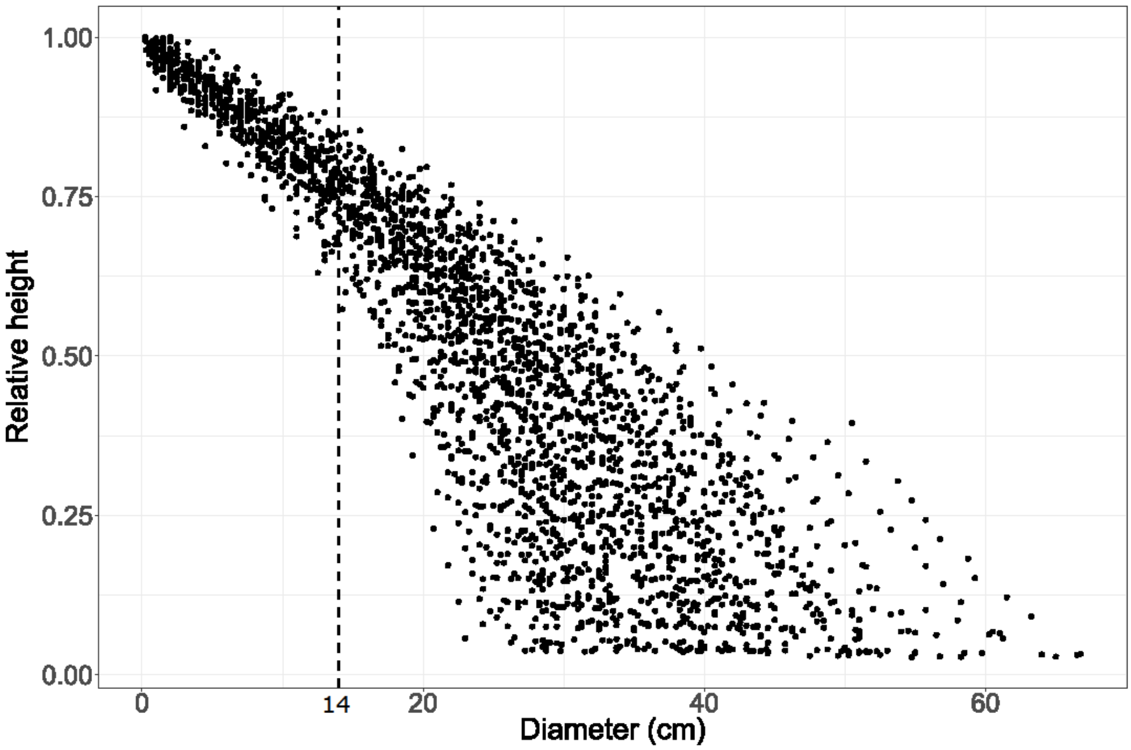


Figure 6-11. Relationship between the relative height of a point in the tree and its diameter.

Figure 6-12 shows how the diameter of trees decreased with height along the trunk. Although an overall linear relationship explained 63% of the variance, it could not be described as linear.

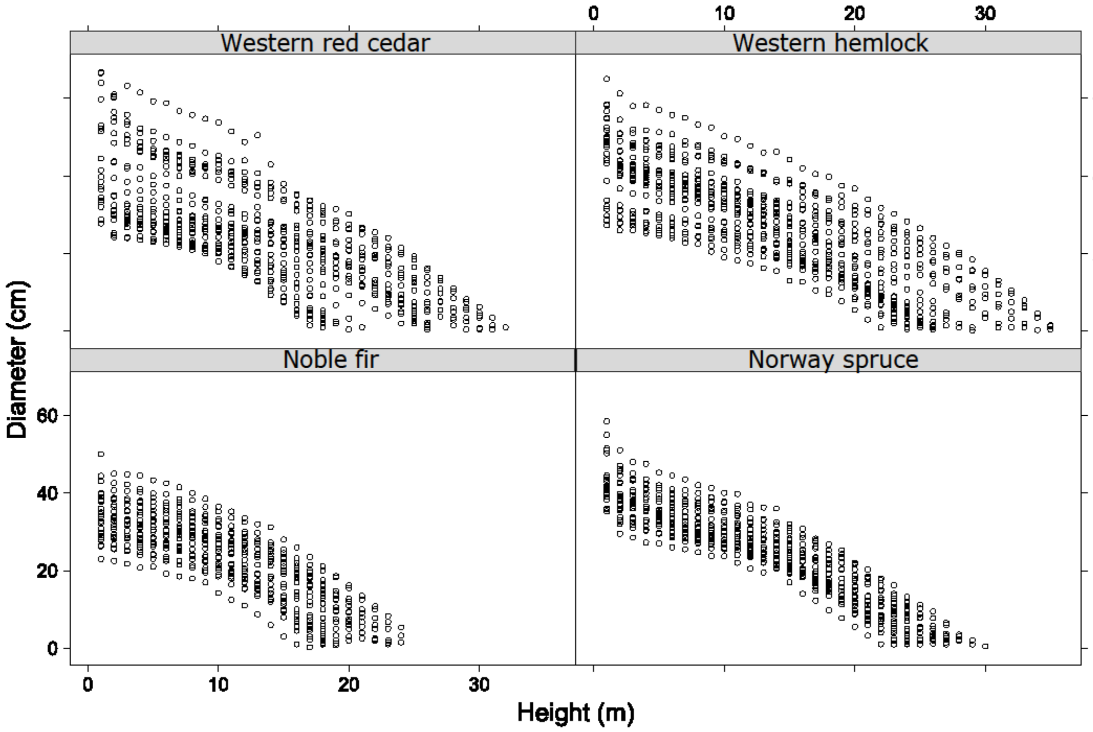


Figure 6-12. Taper profiles of the four species studied.

A further analysis, showed that the height of a point relative to the total height of the tree with the relative diameter (diameter at a certain height compared to the dbh) had a better relationship (R^2 = 0.91).

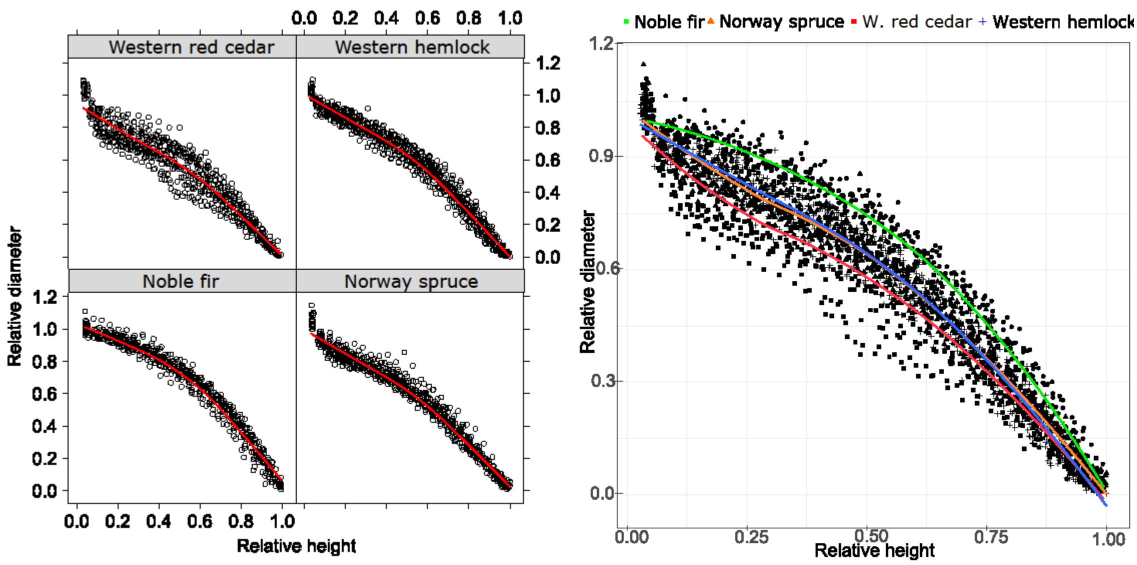


Figure 6-13. Relationship between the diameter relative to the dbh and the relative height of a point in the tree.

Figure 6-13 shows that Norway spruce and western hemlock described a similar trend, with western red cedar keeping similarities but a less pronounced curvature. Noble fir on the other hand described a wider curvature.

Table 6-8. Fit statistics for taper functions tested (NA: the model did not converge).

		Model (number of parameters)				
		1 (4)	**2** (7)	**2b** (5)	**3** (6)	**3b** (5)
Overall	R^2	0.95	0.97	0.97	0.95	0.94
	RMSE (cm)	3.00	2.39	2.41	2.79	3.07
	AIC	13615	12171	12208	13092	13774
Noble fir	R^2	NA	0.98	0.98	0.98	NA
	RMSE (cm)	NA	1.32	1.34	1.38	NA
	AIC	NA	1862	1879	1916	NA
Norway spruce	R^2	0.98	0.99	0.99	0.99	0.98
	RMSE (cm)	1.51	1.38	1.39	1.40	1.53
	AIC	2537	2406	2417	2422	2556
Western red cedar	R^2	0.96	0.97	0.97	0.97	0.95
	RMSE (cm)	2.86	2.20	2.24	2.51	2.95
	AIC	3305	2876	2898	3074	3367
Western hemlock	R^2	0.98	0.98	0.98	0.98	0.98
	RMSE (cm)	1.8	1.72	1.72	1.73	1.82
	AIC	3115	3038	3036	3045	3136

The five models tested performed well based on the “goodness-of-fit” (R^2), fitting the functions both to the overall dataset and the individual datasets for each species (Table 6-8). Model 2 and Model 2b had the highest overall R^2 and lowest RMSE for the four species, followed by Model 3. Model 1 performed slightly worse than the other models except Model 3b. Model 2b contained five parameters and required to fix the point of inflection p, which depends on the species and can be difficult to determine. Model 1 consisted of less parameters than the rest of models, and was chosen as preferred taper function.

A first attempt aimed to fit the model for the four species, but the model was not significant for noble fir. The removal of α_0 for noble fir offered a model with all the parameters significant, and with a lower AIC (1961) that the removal of α_2 (1969). The fixed model (Figure 6-14) had an R^2 = 0.98 and RMSE=1.45.

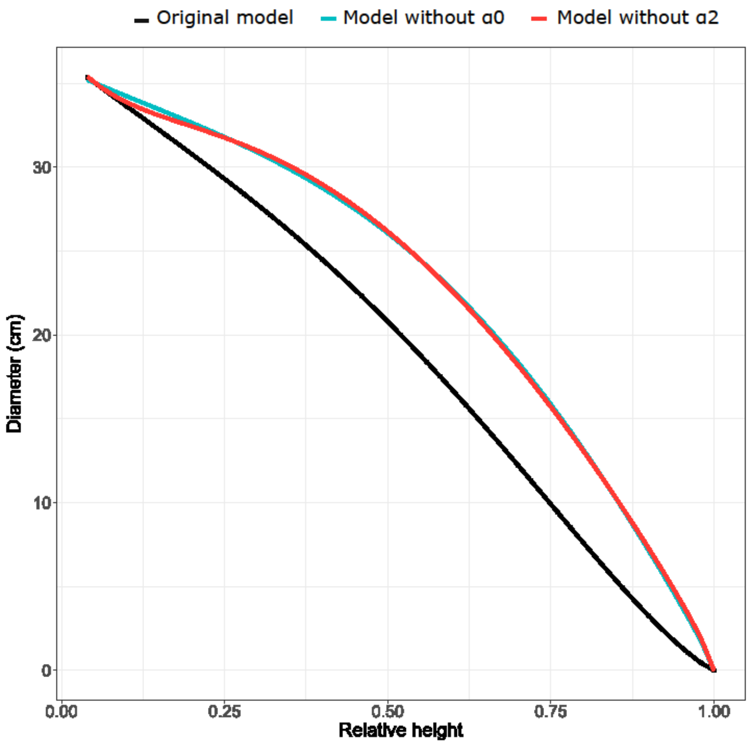


Figure 6-14. Model 1 for noble fir using the four parameters, without α_0 and without α_2.

A second stage assessed for each species the chosen model as a mixed model including sites and plots as random effects. The selected model had the form:

$$d_{ijkl} = dbh_{ijkl} \times x^{\alpha_{0,i} + (\alpha_{1,i} + A_{1,ij} + A_{1,ijk}) \times (z-1) + \alpha_{2,i} \times (\exp(\alpha_{3,i} \times z))} + \varepsilon \quad [6\text{-}6]$$

where d_{ijkl} was the diameter (cm) at the lth height along the kth tree at the jth site of the ith species. The fixed effects coefficients were α_0, α_1, α_2 and α_3 for each ith species. Parameters $A_{1,ij}$ and $A_{1,ijk}$ represented the random effects affecting α_1 at the site and plot levels, respectively. The model did not improve importantly when including random effects on α_0, α_2 and α_3. The random effects were assumed to be independent and normally distributed with mean zero and variance σ^2. The residual error was ε. Table 6-9 reports the values resulting of the selected Model 1 ([6-6]) with mixed-effects (see appendix for details). Visual inspection of residual plots did not reveal any pattern evidencing heteroscedasticity or lack of independence (see appendix Chapter 6).

Table 6-9. Parameters estimates for the selected mixed-effects model

	α_0	α_1	α_2	α_3	R^2	RMSE	AIC
Noble fir		1.67	2.16	-1.01	0.99	1.16	1759
Norway spruce	0.88	0.48	3.22	-8.28	0.99	1.36	2421
Western red cedar	0.88	0.11	6.21	-9.54	0.97	2.35	3007
Western hemlock	0.95	0.80	1.99	-5.50	0.99	1.50	2873

The Figure 6-15 shows the resulting model plot by species for a simulated tree of 35 cm dbh and 25 m height.

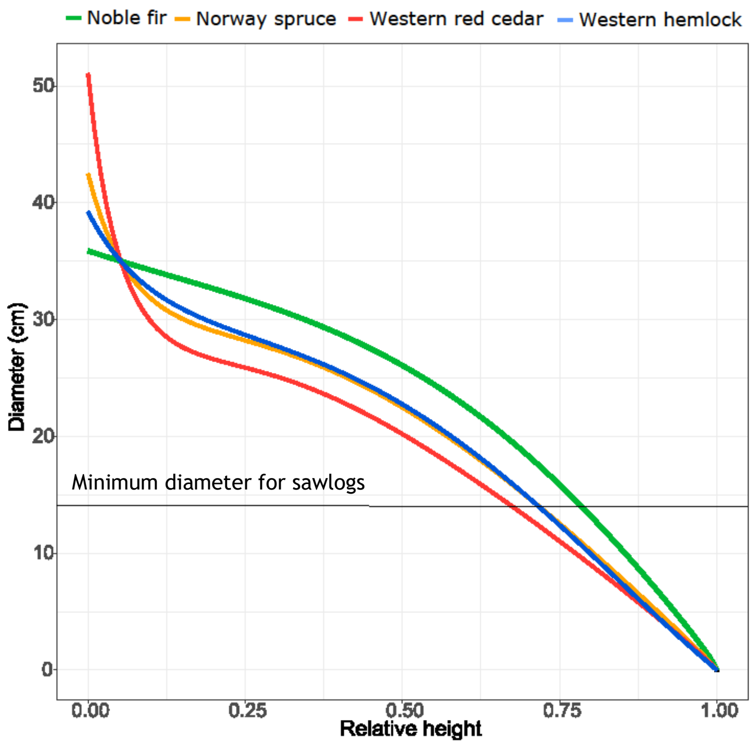


Figure 6-15. Selected model plot by species.

The figure shows that western red cedar reached the 14 cm diameter over bark at a lower height than the other species, whereas noble fir reached that higher in the stem. This means that noble fir had a longer paraboloid section on the stem and therefore more volume could be used for as sawlog. For a simulated tree of dbh 35 cm and height 25 m, the model concludes that 19.6 m of a noble fir stem could be used for sawlog conversion. A Norway spruce stem, could only be used 17.9 m, western red cedar 16.9 m and western hemlock 17.9 m.

6.4.2 Crown and slenderness characteristics

For the data here investigated, a single one way ANOVA analysis showed that the mean CR was different by species ($F_{3,104}$ = 10.1, P<0.001).

The relationship of CR with MOE is shown in Figure 6-16. At a tree level the correlation was very weak (r=-0.16), with *P-value* = 0.09. At a site level and per species, the correlation did not result statistically significant (*P*= 0.19).

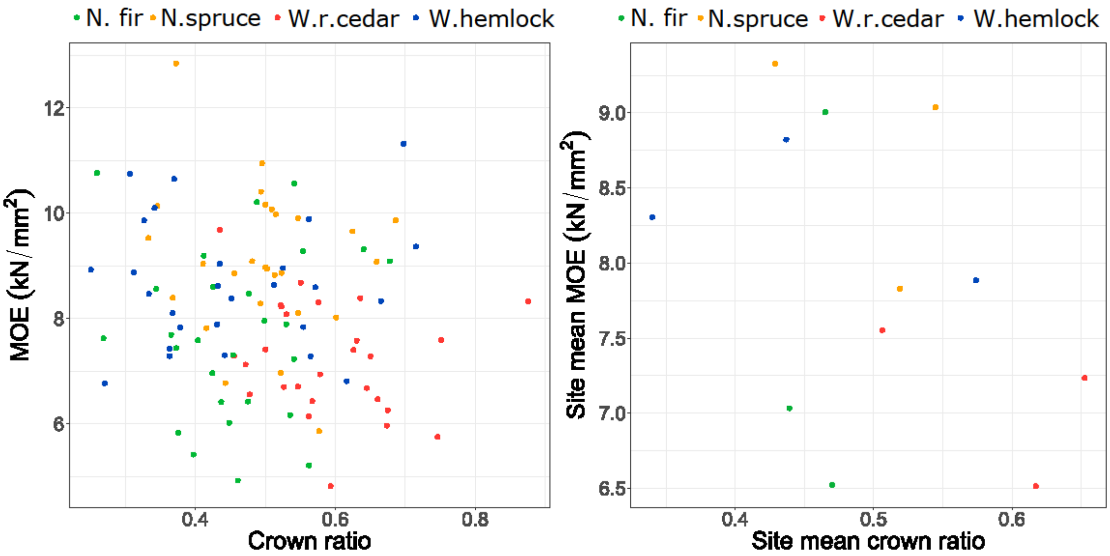


Figure 6-16. Relationship of MOE with CR per tree (left) and site (right).

The relationship of CR with MOR is shown in Figure 6-17. The correlation was not significant, neither at tree or site level (*P*= 0.8 and *P*= 0.6).

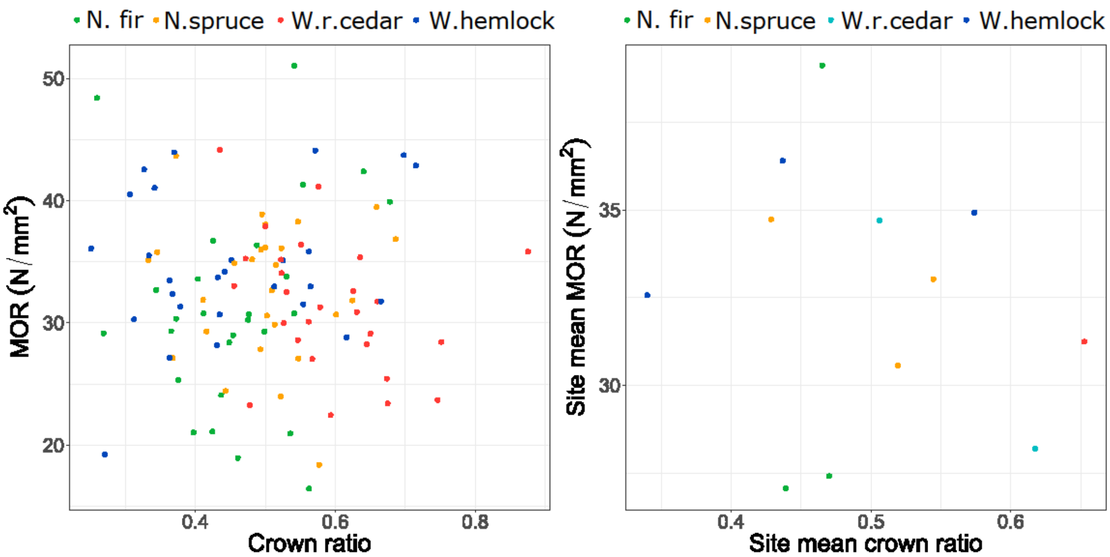


Figure 6-17. Relationship of MOR with CR per tree (left) and site (right).

The relationship of slenderness with MOE showed a more linear relationship (Figure 6-18) than CR, resulting the correlation significant at a tree level (r=0.44, *P*<0.001), but not significant at site level (r=0.45, *P*= 0.14).

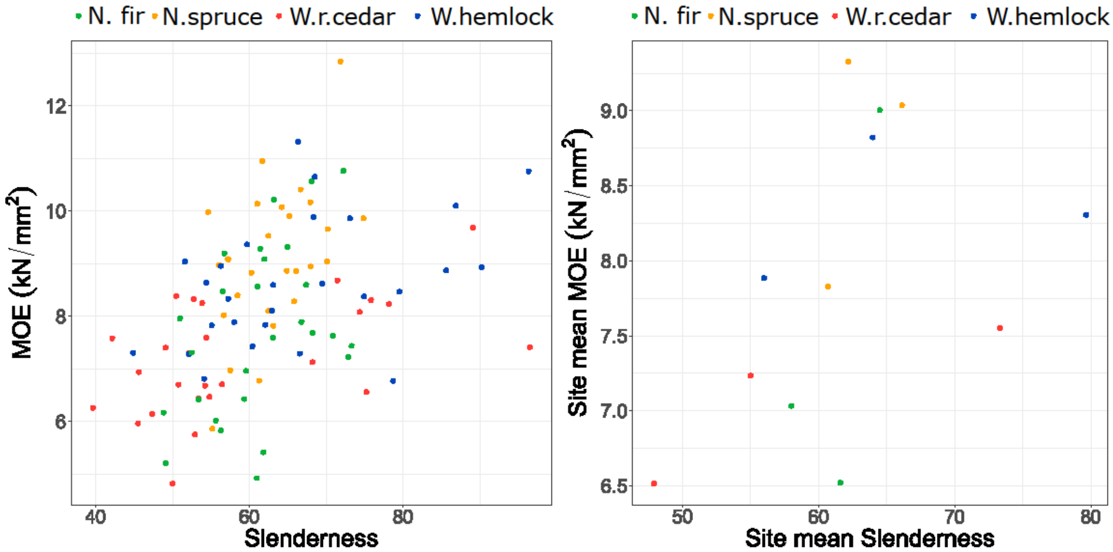


Figure 6-18. Relationship of MOE with slenderness per tree (left) and site (right).

Similarly, the relationship between slenderness and MOR (Figure 6-19) was significant at tree level (r=0.41, *P*<0.001), but it was not significant at site level (r=0.38, *P*= 0.21).

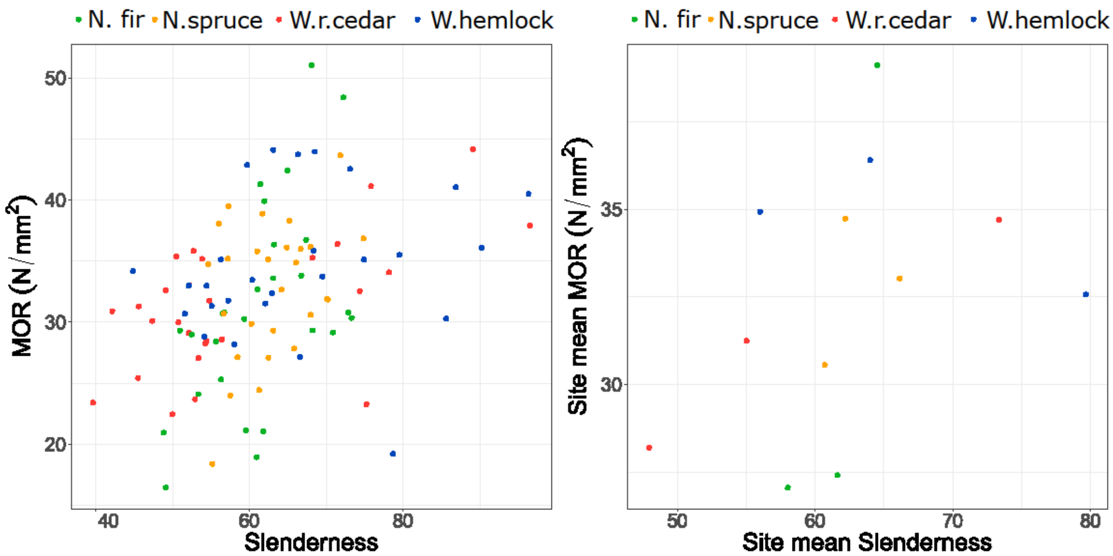


Figure 6-19. Relationship of MOR with slenderness per tree (left) and site (right).

6.4.3 Branch characteristics

The number of branches, diameter and angle of insertion were investigated. For the branch diameter, the vertical and horizontal diameters measured were averaged. An analysis of the variance components showed that the highest variance occurred within trees (Table 6-10).

Table 6-10. Percentage of total variation in branch characteristics attributable to each stratum in the experiment.

	Species	Plot	Tree	Section (Metre)	Within metre[1]
Number of branches					
Overall	29.2%	0.01%	8.7%	61.5%	0.5%
Noble fir		3.7%	6.6%	78.2%	11.5%
Norway spruce		0.01%	13.4%	86.4%	0.3%
Western red cedar		0.01%	10.1%	89.6%	0.3%
Western hemlock		0.01%	13.8%	85.8%	0.3%
Max BD per metre					
Overall	0.7%	2.6%	6.9%	89.8%	
Noble fir		6.1%	13.6%	80.3%	
Norway spruce		0.5%	0.7%	98.8%	
Western red cedar		6.1%	9.8%	84.1%	
Western hemlock		0.01%	4.7%	95.3%	
Mean BD per metre					
Overall	7.2%	1.4%	5.8%	85.6%	
Noble fir		7.3%	15.6%	77.1%	
Norway spruce		0.01%	3.5%	96.5%	
Western red cedar		2.8%	1.5%	95.7%	
Western hemlock		0.01%	5.8%	94.2%	
Angle of insertion					
Overall	3.2%	0.01%	6.5%	28.9%	61.4%
Noble fir		0.5%	4.3%	26.3%	68.9%
Norway spruce		0.01%	7.0%	33.6%	59.3%
Western red cedar		0.01%	1.8%	37.7%	60.5%
Western hemlock		0.01%	9.2%	29.1%	61.7%

[1] Within metre could only be assessed for number of branches and angle of insertion.

Overall, most of the variation occurred in trees. Whereas the number and diameter of branches varied mostly with height, the angle of insertion varied mostly within sections, which was the last hierarchical stratum assessed. These results highlighted the importance of the height variation in the modelling of branchiness.

The next sections moved on to discuss these differences, describing the within tree variation, with the due limitations due to the small number of trees per species.

6.4.3.1 Number of branches

A total of 11042 branches were measured. The trees of noble fir were considerably shorter than the rest of species and so results were investigated per individual metre (section) in the tree. Norway spruce had more branches (3756) than the other three species. Noble fir did not have as many branches (2363) although it was 6 years younger and shorter than Norway spruce. Western red cedar and western hemlock, both much older and higher than Norway spruce (branch counts of 2256 and 2667 respectively).

The histograms in Figure 6-20 show that Norway spruce had a larger number of branches per metre, mostly between 11 and 20 branches, but up to 28 branches in a metre. Noble fir mostly had between 10 and 16 branches per metre and western red cedar and western hemlock between 7 and 10 branches.

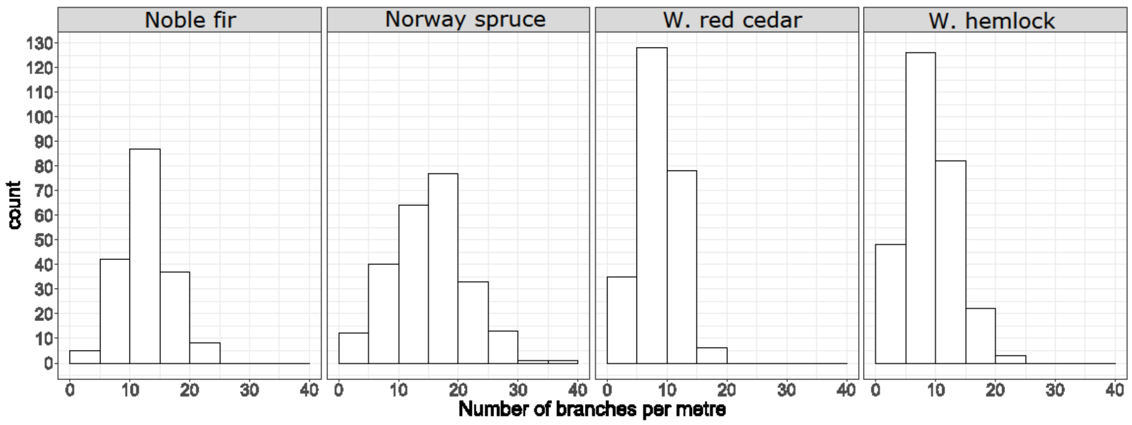


Figure 6-20. Histogram showing the number of branches per metre. The lower limit is included, and the upper limit is excluded.

In general, the number of branches increased with height, although in noble fir the number of branches was very similar along the stem. Figure 6-21 shows the density of branches per metre along the stem.

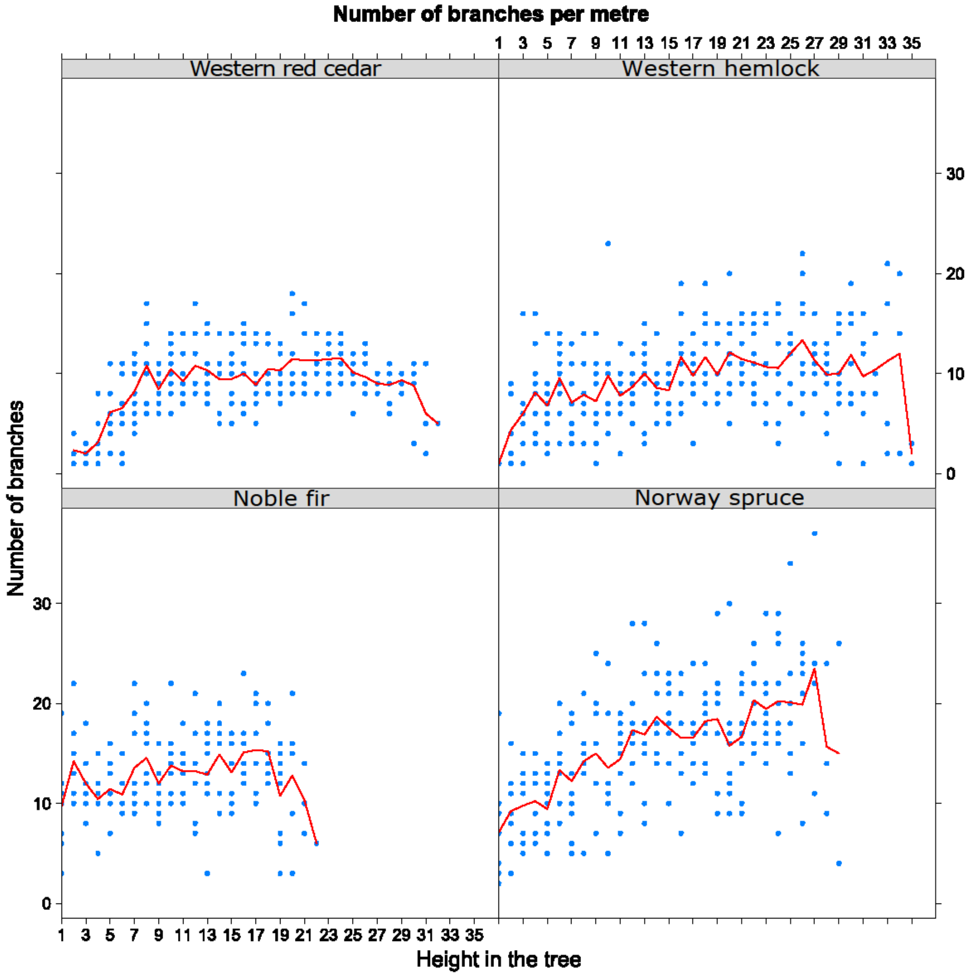


Figure 6-21. Distribution of the number of branches with height. In red the mean values.

In line with Figure 6-20, Norway spruce had more branches in each metre along the stem than the other three species, with a more pronounced increment with height than the other species. Western red cedar and western hemlock showed a steep rise in the lower part of the stem, becoming more steady afterwards. The increase in the lower part of the stem may be masked by the self-pruning dynamic in the trees due to the dynamics of the trees and the stands.

A linear model with the one-metre Section as predictor variable, and the interaction of species as categorical variable explained 40% of the variance. Including the random effect tree on the intercept of the model explained 50% of the total variation, increasing to 55% when the model was also fitted with the random effect of the one-metre Section on the slope. For the number of branches (NBR), the equation [6-7] gave the best fit for a linear model:

$$NBR_{ijklm} = \alpha_{0,i} + A_{0,ij} + (\alpha_{1,i} + A_{1,ijk}) \times Section + \varepsilon \qquad [6\text{-}7]$$

where $\alpha_{0,i}$ and $\alpha_{1,i}$ were the parameters for intercept and slope depending on the ith species and the interaction with Section. The parameters $A_{0,ij}$ and $A_{1,ij}$ were the random effect of the jth tree on the intercept and the kth metre on the slope respectively. The residual error was indicated by ε. The random effects and residual errors were assumed to be independent and normally distributed.

As non-linear functions, the following models were tested:

- $ln(NBR) = \alpha_0 + \alpha_1 ln(Section) + \alpha_2 dbh$ [6-8]

  based in Auty (2011). In addition, the NBR was also calculated without the natural logarithm (ln) transformation

  $$NBR_{ijklm} = \alpha_{0,i} + A_{0,ij} + (\alpha_{1,i} + A_{1,ijk}) \times Section + \varepsilon \quad [6\text{-}9]$$

- $NBR = \alpha_0 \times \mathrm{Section}^{\alpha_1} \times \mathrm{e}^{-\alpha_{2\times \mathrm{Dtop}}}$ [6-10]

  based in Achim et al. (2006), where Dtop is the distance from the bottom of the metre section to the top of the tree.

The models used the one-metre Section on which the tree was divided as predictor variable as oppose to the growth unit used in the original models. Due to the different trends observed in Figure 6-21 the models were fitted individually by species. The linear model [6-7] explained more variation than the rest of functions tested (Table 6-11), followed by model [6-8] with the mentioned modifications

Table 6-11. Comparison of the assessment model fit with different random effects.

Model	Noble fir	Norway spruce	Western red cedar	Western hemlock
[6-7] Linear	22%	53%	47%	34%
[6-8]	11%	49%	41%	29%
[6-9]	16%	46%	37%	31%
[6-10]	14%	34%	27%	18%

Thereby, the linear model came up as the selected model with the parameters given in Table 6-12 (see appendix 6 for details).

Table 6-12. Fixed parameters for prediction of number of branches [6-7].

	Noble fir	Norway spruce	Western red cedar	Western hemlock
Intercept	11.71	9.44	6.58	6.75
Slope	0.11	0.44	0.16	0.16

The highest slope in Norway spruce reflected the higher number of branches compared to the other three species. Plots of the normalised residuals versus fitted values and the explanatory variables selected did not show any clear trend (see appendix).

6.4.3.2 Branch diameter

A paired *t-test* showed that the vertical diameter was bigger than the horizontal ($P< 0.001$) by a difference much smaller than the measurement, and the mean value of both branch diameters was used instead.

The branch diameter (BD) was bigger in western red cedar (Table 6-3). Similar mean values were found on noble fir and western hemlock, even though there was a large difference in age. Norway spruce presented the lower mean BD, although the number of branches was particularly high between 5 and 10 mm.

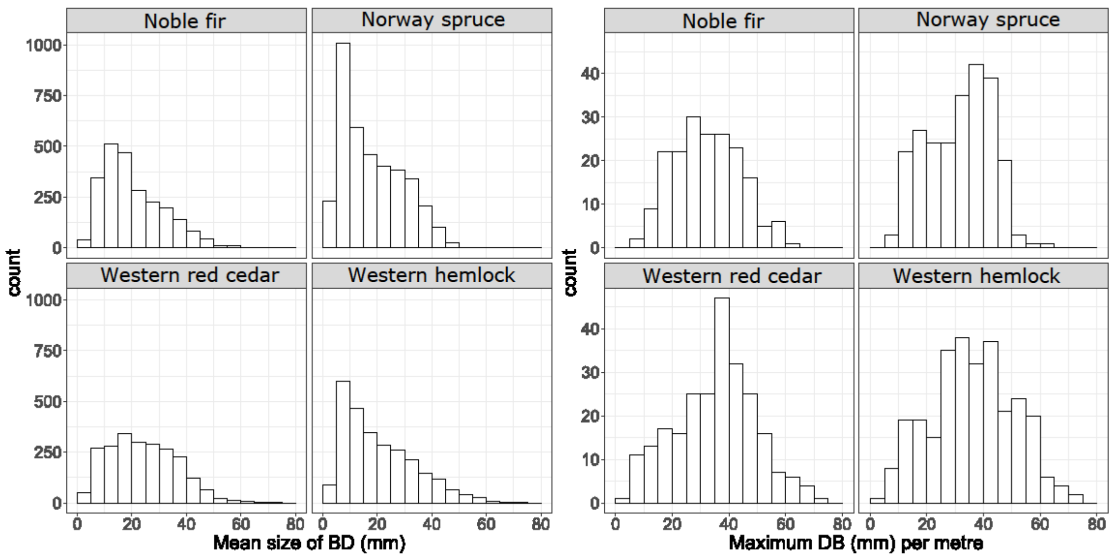


Figure 6-22. Mean (left) and maximum (right) size branch distribution by species.

The mean BD did not follow a normal distribution (Figure 6-22, left), and a Kruskal-Wallis test showed that the mean BD was different between species ($P<0.001$). The posthoc Tukey and Kramer (Nemenyi) test indicated that there were differences between all the pairs (*P*<0.001), less significant between noble fir and western hemlock (*P*<0.1) as Table 6-3 suggested.

The biggest branch per metre section followed a normal distribution. (Figure 6-22, right). A single one way ANOVA found differences between species in the means of the maximum BD. Figure 6-23 shows the posthoc Tukey (HSD) test, where the biggest branch in western red cedar and western hemlock were thicker than in noble fir and Norway spruce. No significant differences were observed between Norway spruce and noble fir or between western red cedar and western hemlock.

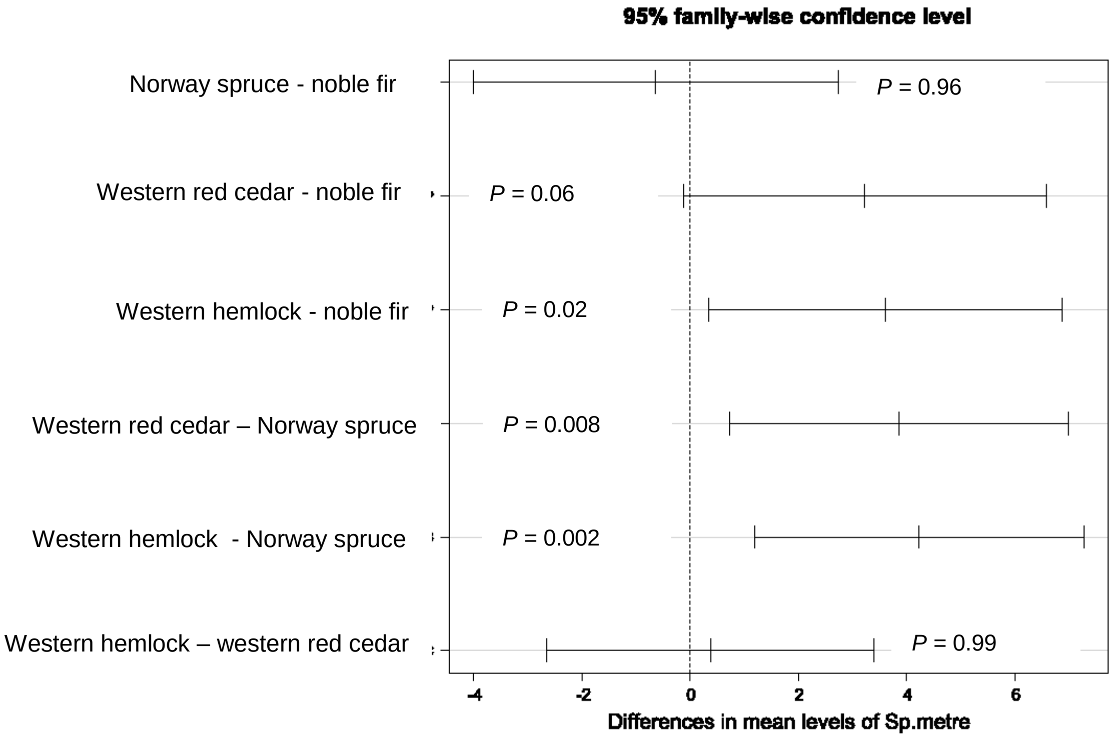


Figure 6-23. Tukey Test for the maximum branch size per metre.

The branches increased in diameter with height from the base, achieving a peak in the crown from which diameter decreased again towards the top of the tree. Figure 6-24 suggests that the biggest diameters located near the crown base although in western red cedar was higher.

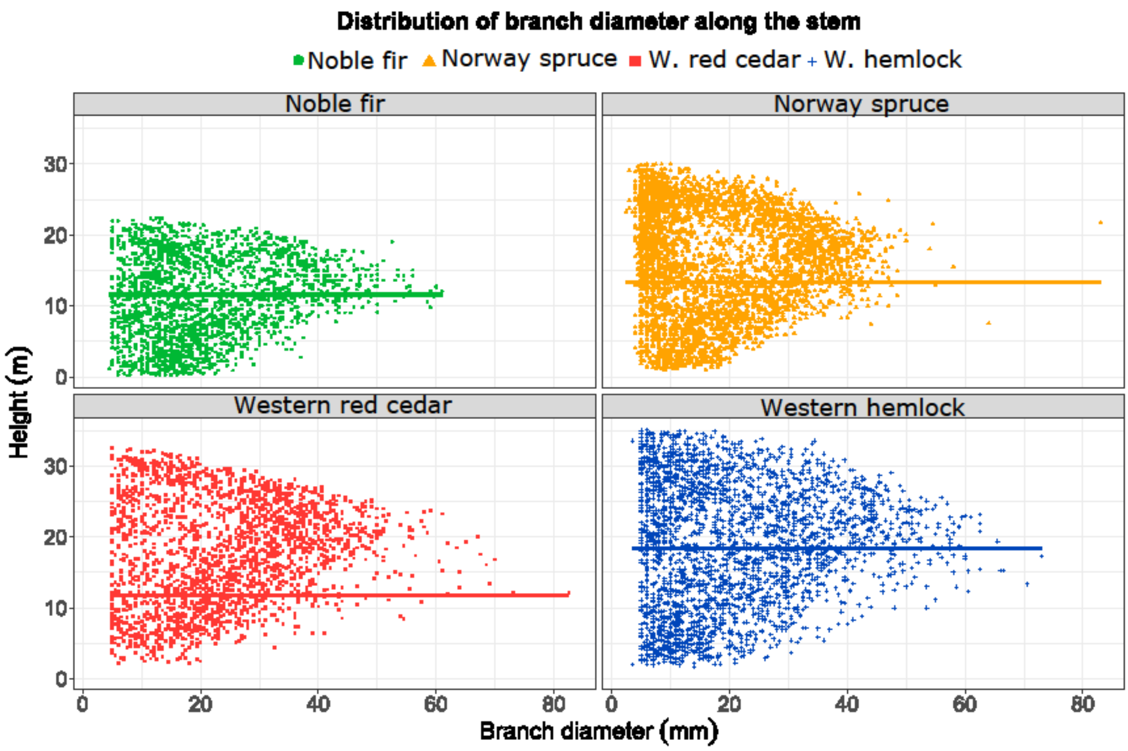


Figure 6-24. Diameter of branches along the stem. The lines indicate the mean crown base.

The location of the largest BD in the tree was calculated as relative position within the crown. The largest BD was mostly located within the crown, although there was an important variation between the four species, and in some of the trees the largest BD grew below the current crown. The largest branch per tree in noble fir occurred on average at 85% within the crown from the apex (15% above the crown base), in Norway spruce at 78%, in western red cedar at 73 % and in western hemlock at 79% (21% above the crown base). Noble fir, gathered a mean of 47% of the branches within the crown, Norway spruce 63%, western red cedar 75% and western hemlock 54%.

Examining the height of branches relative to the crown base in the tree, noble fir and Norway spruce described a more homogeneous trend, compared to western red cedar and western hemlock that showed a wider dispersion. In Figure 6-25 left, values below one indicate branches below the crown. It can also be observed the longer crown of western red cedar compared to the other three species. In relative terms of height (Figure 6-25, right), western hemlock and western red cedar had the maximum diameter branch around 65% of the tree length, with noble fir and Norway spruce slightly lower.

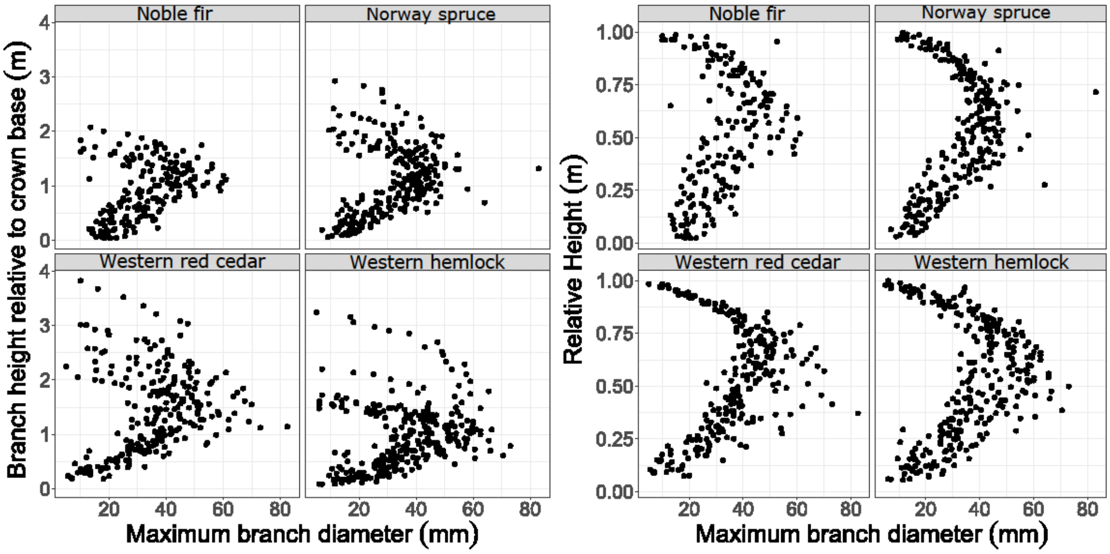


Figure 6-25. Distribution of the maximum diameter branch relative to the crown base (left) and total tree height (right).

The average branch diameter in a metre section was modelled following the function in Achim *et al.* (2006).

$$\boldsymbol{Average\ DB} = \alpha_{0,i} + \alpha_{1,i} \times (1 - h_a) \times e^{-(\alpha_{2,i} + A_{2,i,k}) \times h_a} + \varepsilon \qquad [6\text{-}11]$$

where h_a is the ratio between the distance from the apex of the tree to the bottom of the corresponding metre relative to the total tree height (Dtop/HT). Thereby, h_a in the first metre is 1, as the distance from the apex to the bottom correspond with the whole tree length. The fixed model explained 55% of the total variance. Adding species as fixed effect the model only converged with metre as random effect, which explained 64% of the variance. Parameter $A_{2,ik}$ represented the random effect affecting α_2 at the section level for the *i*th species. Table 6-13 reports the values of the parameters resulting of the selected model [6-11].

Table 6-13. Parameters estimates for the selected mixed-effects Model average BD.

	Fixed effects			
	α_0	α_1	α_2	Var. Residual
Noble fir	6.3	7.64	-3.06	5.10
Norway spruce	1.09	10.15	-2.8	3.47
Western red cedar	-1.79	11.51	-3.26	4.34
Western hemlock	-0.75	12.04	-2.93	4.98

The mean absolute error of the model was 3.5 mm, and the mean percentage error 18.9%.

The four species achieved the diameter peak at approximately the same relative height, roughly at 65% of the relative height. The Figure 6-26 shows the resulting model plot by species.

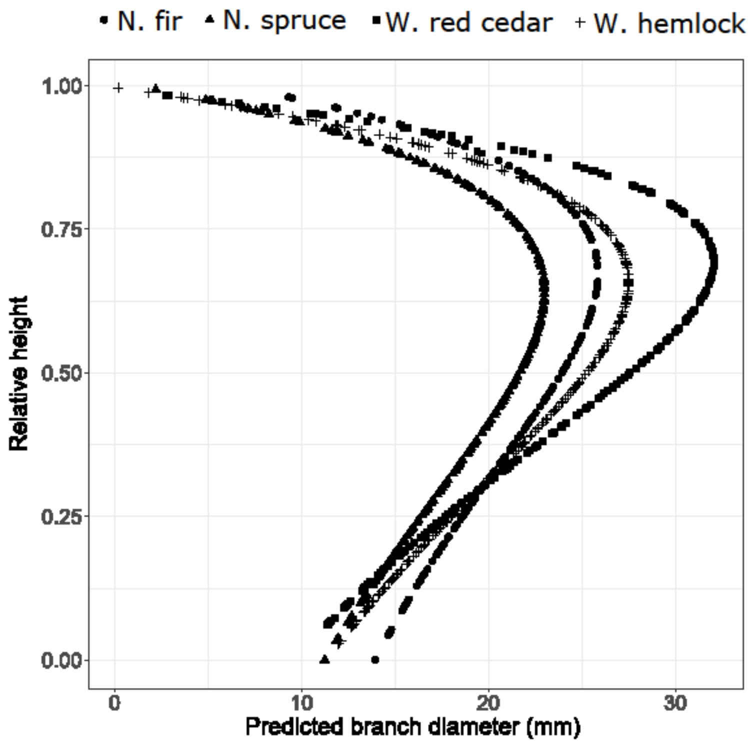


Figure 6-26. Predicted mean BD per metre for a relative height.

Plots of the normalised residuals versus fitted values and the explanatory variable metre in the trunk showed no clear trends.

6.4.3.3 Branch angle

The construction of the model used 10995 branches, with insertion angles between 15° and 130° to discard ramicorn branches or unusual growth.

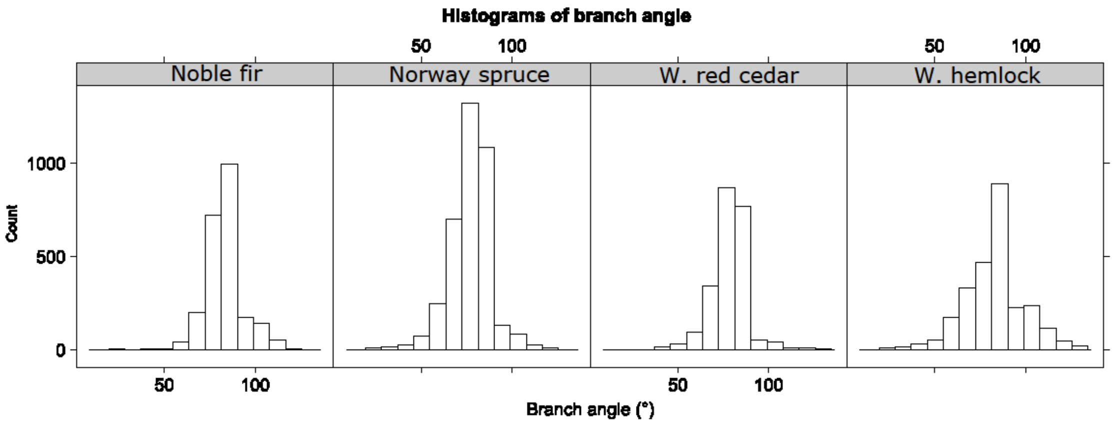


Figure 6-27. Frequency histogram of the insertion angle in the stem.

Figure 6-27 indicated that angles were mostly between 70 and 100 degrees. There were more acute branches in noble fir and western hemlock, gathering the later more branches than the rest of species with branches of more than 100 degrees. The mean values per species were 78° in Norway spruce, 80° in western red cedar and 84° in noble fir and western hemlock.

The Figure 6-28 shows that in general the branches adopted a more acute angle towards the top of the tree, showing in general a trend from the bottom upwards. In the four species, a wide range of angles was found at roughly 75% of the relative height, with a higher presence of acute branches than in the rest of the stem. Western hemlock counted with more obtuse angles of insertion than the others species, slightly more towards the top of the tree. Obtuse angles appeared mostly near the apex in noble fir, whereas in Norway spruce avoided the lower part with no clear pattern along the stem. Western red cedar did not show a clear trend for angles higher than 100°.

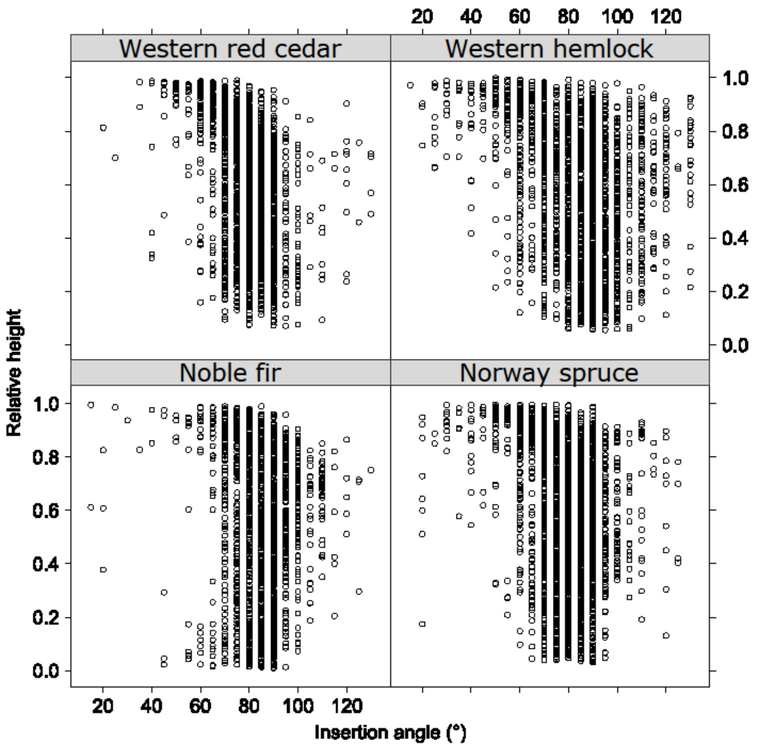


Figure 6-28. Angle of insertion of branches along the tree.

Pearson correlation between variables were explored, but that test is a measure of the strength of the linear relationship and no single variable correlated strongly with the branch angle that could be used as main predictor for modelling. Distance from stem apex has been previously used in branch angle models, but here the correlation was weak (r=0.28), nevertheless the highest.

Different non-linear functions were tested to model the angle of insertion. They corresponded to previously functions fitted to Scots pine (Auty, 2011), Sitka spruce (Achim et al., 2006) and Douglas fir (Weiskittel et al., 2007). In order to adapt the models to the study, modifications were introduced. As before, variables related to the base of the growth unit were substituted for the one metre Section. Weiskittel *et al.* (2007) included site index as variable, which was not included in the model investigated, and a fixed parameter was used instead.

The three models explained very little of the variance using only fixed effects (17%, 18% and 23% respectively). The inclusion of species as fixed effects explained 45%, 45% and 34%. The model used in Weiskittel et al. (2007) was discarded first for offering the lowest goodness-of-fit and for its complexity compared to the other two models. The model used in Auty (2011) had four parameters, and it was not significant for western red cedar and western hemlock. On the contrary, the model used in Achim et al. (2006) for Sitka spruce had three parameters, and all the parameters were significant. Table 6-14 compares the efficiency of the three models.

Table 6-14. Information criteria of the models investigated for branch angle of insertion.

Models	R^2	AIC	LogLik	MAE	ME(%)
Achim *et al* (2006)	0.45	82908	-41435	7.1	9.8
Auty (2011)	0.45	83050	-41503	7.1	9.8
Weiskittel *et al (*2007*)*	0.33	83221	-41582	7.8	10.7

The model had the form:

$$\boldsymbol{Angle} = (\alpha_{0,i} + A_{0,ij} + A_{0,ijk}) \times e^{(-\alpha_{1,i}/(\alpha_{2,i} - hr))} \qquad [6\text{-}12]$$

where $A_{0,j}$ and $A_{0,jk}$ are the random effect of tree and section affecting the parameter α_0 and *hr* is the relative height of the branch on the tree. The parameters α_0, α_1, α_2 and α_3 were the fixed effects coefficients for each *i*th species. The model was weighted to allow different variances according to the levels of species. Table 6-15 reports the values resulting of the selected model.

Table 6-15. Parameters estimates for the selected mixed-effects Model branch angle.

	Fixed effects			
	α_0	α_1	α_2	Variance Residual
Noble fir	85.81	0.004	1.00	9.09
Norway spruce	83.72	0.02	1.04	9.41
Western red cedar	86.08	0.02	1.03	8.70
Western hemlock	90.12	0.02	1.03	13.07

Plots of the normalised residuals versus fitted values and the explanatory variables selected showed no obvious trends (appendix Chapter 6). Figure 6-29 shows a simulation on the insertion angles for the mean tree per species.

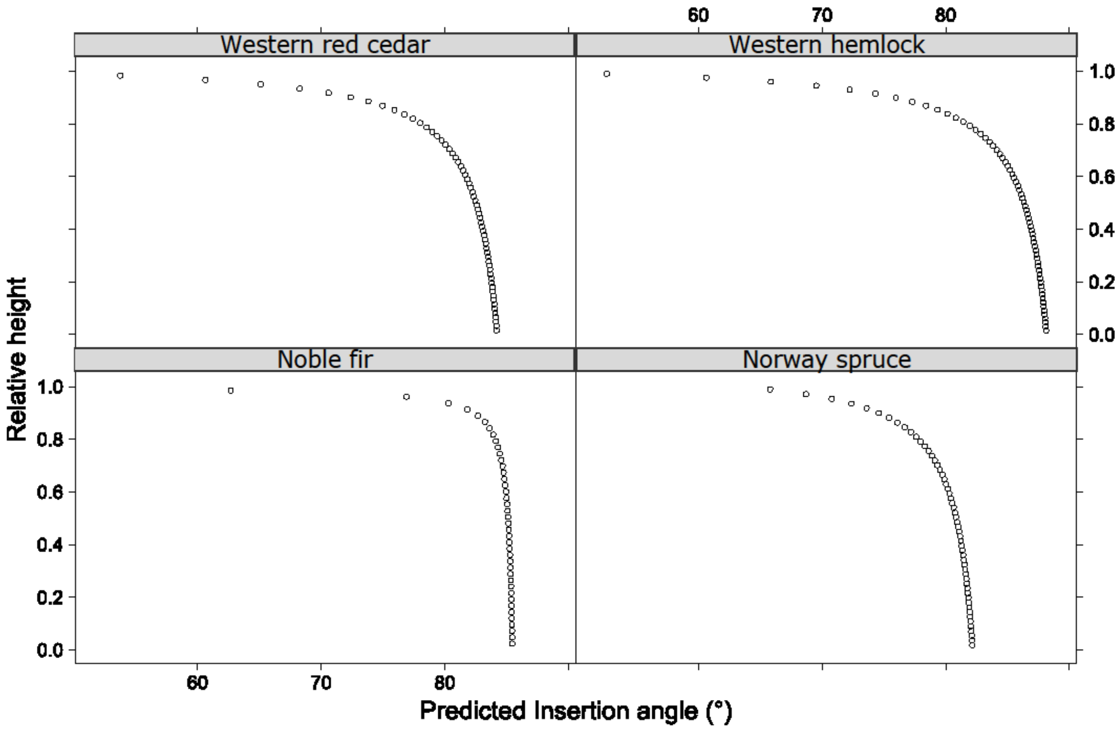


Figure 6-29. Simulated insertion angle with relative height for the mean tree per species

The model shows that the angle of insertion in noble fir barely changes along the stem, whereas in the other three species there is a progressive decrease in the insertion from about three quarters up the tree height.

6.5 Discussion

This chapter assessed the merchantability of the four species investigated considering different aspects of the tree architecture.

The relationship between height and dbh, typically employed for estimation of stand timber volume, was moderate (R^2 = 0.44), and differences with species and sites were observed. The influence of site could be due to the different age of the stands and/or the quality of the site. Therefore, the relationship height-dbh must be used on stands of similar characteristics. Attending to the YC calculated, that takes into account the age of the stand, noble fir would produce more volume than the other three species.

In order to assess what degree of wood recovery could be diverted to structural timber, straightness in the lower six metres of the stem was examined as a first approach. Differences were found between species. Norway spruce and western red cedar produced straighter logs than noble fir and western hemlock, although differences were also found between sites, except for Norway spruce.

Taper functions were built to predict the diameters at any height. For sawlogs, the British forestry industry uses an upper diameter of 14 cm over bark, which typically locates above the six metres assessed for straightness. The taper models built gathered data from three sites.

Five functions were tested, all performing well based on the “goodness-of-fit”, between 0.97 and 0.99. In terms of accuracy, the root mean square error (RMSE) in the models ranged from 1.32 to 2.95, similar to those reported in other studies (Rodríguez et al., 2015; Rojo et al., 2005), with small differences compared to the RMSE around 1 found in Sitka spruce and Scots pine in G.B. (Fonweban et al., 2011). Western red cedar showed a bigger RMSE in all the models, probably due to the buttressed and fluted trunk of some stems. Model 2 and Model 2b were found to be superior (based on AIC and residual mean squares), but they required to define the inflection point at which the tree shape changes from a neiloid form to a paraboloid form. This point varies with species (Kozak, 1988), and in this chapter was fixed at 1.3/ht as done in previous studies (Fonweban et al., 2011; Garber and Maguire, 2003).

In terms of model simplicity, and due to the small difference in “goodness-of-fit”, Model 1 was chosen as preferable. The function is a variable-form taper model, describing the stem shape with a changing exponent with relative height, and it was previously used for Norway spruce in France (Houllier et al., 1995) as well as in Sitka spruce (Fonweban et al., 2011). The model aimed to fit the four species simultaneously using a nonlinear mixed-effects model, but noble fir described a longer paraboloid profile compared to the other three species. This meant a higher proportion of the stem could be used for sawlog, in line with the higher YC suggested. As a result, a different model was built for noble fir using Model 1 without the parameter α_0. The two selected models included site and plot as random effects to account for the nested variability, which reduced the AIC and RMSE. The suggested models only required to record dbh, distance along the stem and total tree height. As well as estimate the merchantable sawlog volume, taper functions can also be used for other products with different dimensions requirements.

The taper function can be used in the absence of regional taper models, but may vary between sites, silviculture applied and genetics. These three factors have also an influence of crown development (Houllier et al., 1995), that have been used for some authors as indicators of wood quality. A wider spacing is known to influence the crown depth and wood quality (Macdonald and Hubert, 2002), associating a shorter crown with a higher mechanical performance compared to a deeper crown. For Sitka spruce in G.B., Moore *et al.* (2013) found a significant negative association between the mean value of MOE_{PB} and CR (ρ = -0.63, P<0.05) in a site. Even though there may be an effect of CR on mechanical properties as part of the stand dynamics, this was not significant in this thesis. In none of the four species, not a tree or site level, a significant trend was found. Kuprevicius *et al* (2013) specifically examined the relationship between crown dimensions and wood properties on white spruce with spacing and thinning trials, and highlighted the limitations of the relationship when the trees had a small range of crown ratios like in the present chapter.

Another external characteristic, slenderness, was found to have a strong relationship (r=0.84) with dynamic stiffness in a 11 years old crop of radiata pine with two spacing treatments (Lasserre et al., 2009). Results in this thesis found a moderate correlation with the mean MOE_{PB} per tree (r=0.44). In line with the CR, the different spacing in Lasserre's study may have had a bigger impact in the slenderness compared to likely the more similar management in the stands here investigated.

The influence of management regimes on growth (Hein et al., 2007; Hein et al., 2008b) and timber quality (Houllier et al., 1995) have often been study through branch characteristics. This thesis examined the number of branches, size and angle of insertion in the four species under study. The four species studied do not have the same growth pattern. Noble fir and Norway spruce grow distinct annual growth unit, whereas annual branch whorls are not distinct in western hemlock (Nigh, 1996). The case of western red cedar has been referred to as "guerrilla-like growth pattern" with new branches being formed one at a time, on alternating sides of each terminal bud (Edelstein and Ford, 2003). In order to compare the four species, it was decided to model the branches per metre of stem instead of using the growth unit as other studies typically address. This approach has limitations as it will not account for the vigour of the tree, which influence the number (Hein et al., 2008a) and size of branches.

Studies typically assess branch attributes in one species. This study quantified the differences between and within the four species. Hierarchical mixed models found that the variation between species was only important for the number of branches. Most of the variation occurred along the stems. This can be due to the different physiological processes along the tree stem and the foreseeable difference between the living crown and the rest of the stem. Nevertheless, only nine trees per species were studied, and factors like site and silviculture may also have an important influence that this study could not evaluate.

Norway spruce had a higher number of branches per metre. The pattern growing whorls may help explaining the larger number of branches. Another reason may be the shade tolerance of Norway spruce, comparable though to western red cedar or western hemlock, and more shade-tolerant than noble fir (Wilson, 2011). On the other hand, western red cedar and western hemlock produced less branches per metre than the other two species. Weiskittel et al.(2010) compared the branchiness of five conifer species, and even though two shade tolerant species (*Picea rubens* (Sarg.) and *Abies balsamea* (L.) Mill) tended to have more branches, also observed that the most shade tolerant species (*Tsuga canadensis (L.) Carr*) had the second lowest number of branches of all the species examined. He suggested that it is *more species and not shade tolerance per se that drive differences in branch density*.

In this study the number of branches generally increased with height, although the relationship varied from species to species. Previous studies found that the distance between the stem apex, and the annual height increment, were related to the number of branches (Achim et al., 2006; Colin and Houllier, 1992; Weiskittel et al., 2007).

The vigour of a tree is related with the branches development, and some studies included the tree height/dbh ratio and the annual height increment of the previous year to model the number of branches (Hein et al., 2007; Hein et al., 2008a). Due to the difficulties to measure the annual growth in the forest, the present study divided the tree lengths in one metre sections, and each one was used as independent variable in a linear model instead of the year growth. The model included the interaction of species and the random effect of tree on the intercept and the slope, and explained 55% of the total variance, higher than the 45% of the non-linear models investigated by Auty (2011). The use of the one-metre section resulted a good predictor of the number of branches at a certain height in the tree, and it was a good substitute of the more commonly used annual height increment, which can only be practical in the forest applied to species growing whorls and so subjected to the correct identification in the field of the growth units. However, the accuracy of the model may be limited for very high trees as the model lacked of an upper limit.

The number of branches was inversely related to the branch diameter, and Norway spruce and noble fir developed branches of smaller diameter. The vertical diameter was found to be bigger than the horizontal by 0.4 mm (± 0.05 mm). The accuracy of the measurements was of 1 mm, and it would be difficult to aim in the forest for a higher precision of the measurements. Branch diameter size increased from the bottom of the tree up to the base of the crown, decreasing again after. It is logical to hypothesise that older trees will grow bigger branches, at least within the crown, and while self-shading has not caused self-pruning. This was the case to a certain extent in the present study, with western red cedar and western hemlock growing bigger diameter branches.

The biggest diameter branches located near the crown base, at around 80 % of the crown length from the apex, although this varied between species. Like Weiskittel et al. (2010) explained, *the maximum branch diameter profile is not only dependent on tree and crown size, but also species shade tolerance to* *some degree*. The same author stated that *after the peak the maximum diameter generally rapidly decreases as self-shading increases and branch radial growth and longevity decreases*. Western red cedar showed a different behaviour to some extent, as it still increased in maximum diameter within the crown. Most of branches in western red cedar located within the crown, which suggests either a longer crown, more shade tolerance or more self pruning. Without comparison with other sites and silvicultural practices, it is not possible to conclude a reason.

Differences in the mean diameter branch were observed between species, less significant between noble fir and western hemlock. Interesting, both species were quite different in age (38 and 78 years old), but the influence of age could not be specifically assessed in this study due to the limited sampling. The average branch diameter in a metre section was modelled following the study in Sitka spruce in Achim *et al.* (2006). The model is an exponential function that described an increment in the diameter with height before achieving a peak near the crown base where the diameter drops in size until the stem apex. A mixed effect model was used, with species as fixed effect and metre as random effect, which explained 64% of the variance. The predicted branch diameters showed the thicker branches of western red cedar and western hemlock compared to noble fir and Norway spruce.

Whereas a horizontal branch will produce a knot with the same size as the branch, as the angle of insertion becomes smaller (steeper branch) the knot area increases. For the four species the angle increased from the apex towards the bottom. This is a typical behaviour in many conifers, where branches near the apex are more acute searching for light and branches become more planar towards the bottom, occupying more surface to reach the light penetrating the foliage. This has also been observed in Sitka spruce (Achim et al., 2006), Scots pine (Auty, 2011), Norway spruce (Colin and Houllier, 1992) or Douglas fir (Drewett, 2015; Weiskittel et al., 2007).

Noble fir and western hemlock showed more acute angles. There was no one variable strongly related to the branch angle that could be used as main predictor variable for modelling. For the data here investigated the variation of angles within sections gathered most of the total variance which may explain the weak correlations found. The model used was based in the study by Achim et al. (2006) on Sitka spruce, and explained 45% of the variation. The four species were fitted simultaneously using a mixed model with the random effect of tree and section. The model showed that noble fir and western red cedar produced almost horizontal branches, particularly in the lower part of the trunk. On the contrary, Norway spruce produced more acute branches, particularly above two thirds of the tree length.

6.6 Conclusions

More than half of the logs of Norway spruce and western red cedar produced straight logs of at least four metres long in the bottom six metres. The stem profile of noble fir described a pattern that translated in more volume available per tree for sawlogs. Norway spruce and western hemlock described an almost identical taper profile, with a lower proportion of western red cedar stems of suitable dimensions for sawlogs. Slenderness was found to relate moderately with the mechanical properties, and so it could potentially be used for sorting timber quality.

Number, size and angle of insertion of branches were also investigated. Few studies have undertaken the description of branchiness variation across a range of species with different growth pattern. Most of the variation occurred due to height in the stem, and only the number of branches was importantly influenced by species. Norway spruce presented more branches than the other three species, although the size were smaller. Western red cedar and western hemlock had a lower number of branches, but thicker mean diameter. The maximum branch diameter was typically located within the live crown. The angle of insertion showed a large variation within a metre length of the stem, and required of the relative height of the branch to be modelled.

The branch models built can be used with variables measurable from standing trees as they do not require the growth unit length as it is normally the case for modelling branchiness. Care must be taken when applying the models to plantations where the management differs notably to the conditions investigated in this study.

Chapter 7. Summary

7.1 Objectives and aims of the study

This thesis assessed the potential of noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. to produce timber with the required properties to be used for structural purposes. The two main topics were:

1. Characterisation of wood properties:
    a. Performance and variation of bending stiffness, bending strength and density
    b. Change of the three wood properties with tree age
    c. Knots' influence on wood properties; and drying distortion
    d. The use of acoustic techniques for stiffness prediction
2. Tree architecture.
    a. Taper functions for merchantability and straightness
    b. Slenderness and crown ratio as wood quality indicators
    c. Models for branch characteristics

7.2 Experimental review. Limitations

1. The wood properties of structural-size timber reported in Chapter 3 must be taken as indicative. The number of sampled trees was relatively small, and only one log per tree was cut, but the number of structural pieces was enough to obtain a representative population within that sample. Variation by growing regions can be expected, and more research is recommended. The number of available forests was limited, and some of them were younger than typical rotation lengths in G.B. It was aimed to find all four species in as close a geographic location as possible, and reduce the influence of site, but that was not always possible. Additional trees from different sites, and especially under different managements may vary the values here reported.
2. The grading yields presented (see §3.4.3) correspond to an optimum grading, and real grading yields may be considerably lower. This is due to the real

world imperfect correlation between the indicating property measured for grading and the results measured in the laboratory. The species are not yet close enough to market to justify the cost of measurement with grading machines such as the Microtec GoldeneEye 702, but this research is a step towards that.

3. The genetics and origin of the seeds used in the plantation of the forests studied are unknown, except for the southern site of noble fir. This added a variation that could not be controlled.

4. Western red cedar from the south and middle latitudes were kiln dried with a too aggressive programme for the species, resulting in pieces with different degree of collapse (see §2.4 for details). Pieces from the north site were dried with a milder programme to a higher moisture content to minimise the risk of collapse, and so twist as drying distortion was assessed at different moisture content (see §3.4.4).

5. The comparison of the performance of structural pieces in Chapter 3 and clears in Chapter 4 was somehow limited because the structural pieces were cut bark-to-bark, as opposed to pith to bark of clears. A bark-to-bark cutting pattern was simulated instead. In addition, the clears were cut from a log above the one used for production of structural pieces. Processing of clears from each structural piece would have avoid this limitation.

6. The dynamic stiffness in green logs and standing trees assumed a constant density of 1000 kg/m^3 in all the stands studied regardless the species and the age of the stand (see §5.3). The measure of green density would potentially improve the prediction of bending stiffness.

7. Straightness in the lower six metres of the stem was visually assessed by two trained operators, but due to the limitations of the human eye, and not being able to use portable scanners the results (see §6.4.1.2) should only be used for comparison within the dataset.

8. The taper models built for the four species (see §6.4.1.3) gathered data from three sites. They can be used in the absence of regional taper models, but may vary between sites, silviculture applied and genetics.

9. The study of slenderness and crown ratio for wood quality indicator (see §6.4.2) was limited due to the small variation of both factors.

10. The branch characteristics were studied and compared between species (see §6.4.5). Only nine trees per species were measured. The noble fir and Norway spruce trees were 40 and 34 years younger than the western red cedar and western hemlock. The models were produced irrespective of stand age, and in order to be more representative it would have been necessary to sample trees of a range of ages (Colin and Houllier, 1992; Mäkinen et al., 2003). A more in depth study comparing sites, age or management was not possible within the time allocated in this study.

11. Comparison of results in branches and knots must be carefully considered because branches were only measured in one site, whereas knots were measured in sawn timber from three sites. In addition, the knots were only measured in the span mechanically tested (600 mm).

12. Western red cedar and western hemlock do not grow whorls as Norway spruce and noble fir do, and therefore the identification of growth units on those was not possible in the forest. As a result, branches were modelled per one-metre section of the stem (see §6.4.5) instead of using the annual height increment, which may have influenced the results for number and diameter of branches as the vigour of the tree was not taken into account.

7.3 Key findings

After the general introduction (Chapter 1) and the material and methods (Chapter 2) common to the whole study, this thesis split in four chapters addressing different aspects of the timber as structural material (see §7.1).

1. Characterisation of wood properties:

   a. Performance for bending stiffness, bending strength and density.

   Table 7-1 summarises the mean and characteristic values of the three properties in structural-size timber.

Table 7-1. Wood properties by species for structural timber in the current thesis.

	MOE_{PB} kN/mm^2	MOR (N/mm^2)		Density (kg/m^3)	
		Mean	$f_{m,k}$	**Mean**	ρ_k
Noble fir	7.7	31.1	14.8	378	324
Norway spruce	8.6	31.1	19.1	401	345
Western red cedar	7.0	30.1	16.3	358	318
Western hemlock	8.5	34.5	18.2	444	385

Norway spruce is currently graded in G.B. in combination with Sitka spruce. It was believed Norway spruce performed better, but there was no evidence supporting that. One of the first conclusions of this thesis is that, based in the dataset studied, Norway spruce grown in G.B. has the potential to grow timber in G.B. outperforming the average performance of UK-grown Sitka spruce. The other three species were also capable of producing high yields of C16 strength class, typically required for use in construction in G.B., and were broadly comparable to UK-grown Sitka spruce. In particular, Norway spruce and western hemlock arose as a good complement to diversify the timber resource in G.B., producing high yields of C18. Overall, the low stiffness measured prevented to grade timber of the four species to higher strength classes.

Comparison between clears and structural pieces showed a lower performance of bending stiffness in clears, but a good relationship was found at a tree level likening the width of structural pieces and clears. MOR was approximately double in clears than in the pieces of timber, likely due to the presence of knots in the latter. Density was very similar in both specimen sizes.

b. Variation and relationship of wood properties.

The performance of the wood properties changed from the inner to the outerwood. Chapter 3 and Chapter 4 highlighted that within the different stratum of the experiment, most of the variation in mechanical properties occurred within a tree, in this case due to the radial variation on the mechanical properties. Previous studies (Fischer et al., 2016; Moore et al., 2008; Moore et al., 2013; Moore et al., 2009d) had concluded the same for one species without considering the a priori likely differences between species. This thesis observed that even dealing with different species, the variation of mechanical properties within trees was more important, both in pieces of structural timber (Table 3-5) and clears (Table 4-5). Interestingly, the effect of species on the mechanical properties was higher in the absence of knots and other defects. The effect of species was more important on density, roughly 40% in structural timber and clears.

The relationship of MOE and MOR was similar in structural-size timber and clears. However, important differences were found in the relationship between density and MOE in structural timber and clears (Table 7-2).

Table 7-2. Pearson's correlation (r) between variables in structural-size timber and clears.

	$Density_{384}$ - MOE				$Density_{384}$ - MOR			
	NF	**NS**	**RC**	**WH**	**NF**	**NS**	**RC**	**WH**
Structural	0.73	0.69	0.40	0.53	0.62	0.60	0.39	0.43
Clears	0.20	0.70	-0.07	0.17	0.57	0.81	0.52	0.53

Although some authors state that: *without doubt density is the most useful indicator or wood properties (Walker, 1993);* or *density is most likely the best single predictor of mechanical properties of clear, straight-grained defect-free wood* (Zink-Sharp, 2009), the data here investigated did not support this, except in Norway spruce. This can partially be explained by the different trend that the density in these species showed in the core and outerwood that is not shown in structural size timber due to the lower resolution with respect to annual growth rings.

c. Change of the three wood properties with ring number

The radial variation of the three properties were investigated in function of ring number using small clears free of defects.

Bending stiffness increased with age, and it was described as an exponential function of ring number. The model explained 85% of the variation in bending stiffness using a mixed effects model with site, plot and tree as random effects. The function was biologically meaningful, and included, as parameters, approximations to the rate of change, maximum value and, indirectly, the stiffness of the material near the pith.

Bending strength described a linear pattern for the range of years studied, and a mixed-effects model explained 76% of the variation.

Density decreased linearly for roughly the first ten rings, which can be related to the corewood, and increased afterwards. As a result of this double trend, density had an overall weak relationship with age, and it was therefore appropriate to analyse the two sections of the radial profile separately. The mixed effects models selected explained between 64% and 81% of the variation in the decreasing section, and between 67% and 90% in the increasing section.

d. Drying distortion and knots' influence on wood properties

The pieces from near the pith tend to twist more than outerwood. Overall, the four species investigated showed higher passing rates than British spruce (Searles, 2012) with Norway spruce and western hemlock similar to Douglas fir (Drewett, 2015).

The number of knots was found to decrease in number and area from pith to bark, as it was found in Sitka spruce(Moore et al., 2012). The size was found more important than the number of knots for MOR prediction. Timber of Norway spruce had more knots, but the mean diameter was smaller. Western red cedar had a smaller total knot area, with no significant difference between the other species.

e. The use of non-destructive techniques for stiffness prediction

This thesis showed that the prediction of bending stiffness in sawn timber using density as sole predictor variable may not offer good results, and the use in combination with acoustic measurements is recommended. Similarly, a study on Douglas fir (Lachenbruch et al., 2010) using specimens of 1x1x30 cm obtained from the outer part the trees found a better prediction of mechanical properties using density in combination with acoustic velocity (R^2=0.55) than using either variable alone (R^2=0.35).

Chapter 5 assessed "acoustically" the mechanical properties of wood. Bending stiffness was strongly related to dynamic stiffness in clears and in structural timber, and in combination with knot measurements gave a good prediction of bending strength.

The propagation of an acoustic wave within a tree was also studied. Traditionally, studies hold that a wave travels in a straight line between the two probes in a tree. The most common approach is to line up the transducer on one side of the tree, assuming that the wave travels in the outer part of the tree. For convenience, the distance measured is typically one metre. This thesis explored alternative methods measuring longer distances, and concluded that a stress wave induced in a standing tree propagates both in an upward and outward direction, and it is not confined to travelling through the outer part of the tree alone. Thus, longer distances related better with the bending properties of the structural pieces by virtue of being more of an average, and less biased by the wood properties in the outer part of the tree. Thus, the relationship of the mean sawn timber in trees improved from R^2=0.27 measuring a distance of one metre to R^2=0.58 measuring three metres.

2. Tree architecture.

   a. Taper functions for merchantability

Chapter 6 described the tree architecture of the species. Different functions were tested to describe the taper profile, allowing an estimation of the diameter at any height in the trees. The four species were modelled using an exponent function and non-linear mixed-effects techniques. Noble fir described a different stem profile to the other three species that translated in more volume available per tree for the same dbh and height. The rest of species were modelled using the same function previously used on British Sitka spruce. Norway spruce and western hemlock followed an almost identical profile, whereas a lower proportion of western red cedar stems was of suitable dimensions for sawlogs.

   b. Slenderness and crown ratio as wood quality indicators

The crown and slenderness characteristics were examined as a potential approach to segregate trees based on mechanical properties, but only slenderness was found significant in this dataset.

c. Models for branch characteristics

The number of branches, size and angle of insertion were investigated. Only the number of branches was importantly influenced by species. Most of the variation occurred due to height in the stem, increasing the number of branches with height. Branch diameter size increased from the bottom of the tree up to the base of the crown (further up in western red cedar). The number of branches was inversely related to the branch diameter, and Norway spruce and noble fir developed in this order more branches, but with smaller diameter. Western red cedar and western hemlock presented less branches but with bigger diameters. The angle of insertion increased from the apex towards the bottom in the four species.

7.4 Implications and recommendations for future work based on the research findings

1. According to the results of this thesis, future interventions should probably prioritise the plantations of noble fir, Norway spruce and western hemlock where the conditions are suitable.

    1.1. Noble fir: it is a promising species for timber production. It may require longer rotation lengths than Sitka spruce to achieve the same timber quality, but it produces more wood in proportion to height, and potentially it will grow more sawlogs.

    1.2. Norway spruce: overall, the most promising species for timber production of the four species. It outperformed the average structural properties of UK-grown Sitka spruce, with lower twist distortion, small knots and straight in the lower six meters.

    1.3. Western red cedar: it produced timber with lower performance, and described a stem profile that translated in less volume available per tree for the same dbh and height compared to the other three species. Overall, it would be commercially less viable than the other three species for structural purposes.

    1.1. Western hemlock: it is a species that could be graded together with British spruce under new settings. The wood properties were comparable, and twist had a relatively low incidence. The stem described a profile similar to Sitka and Norway spruce, but the lack of straightness in the lower six metres of the stem might be a handicap for the sawmills.

2. Further research is required in order to investigate the performance of the four species in different growing regions within the UK, and to produce grading machine settings and/or visual grading assignments. These could be addressed at the same time. For machine grading, the current version EN 140181-2 requires at least 450 pieces to be tested for each species / species combination, but with these lesser known species a larger programme is advisable. This need not be full destructive testing: a larger number of specimens could be graded, and the ≥450 pieces for destructive testing selected in such a way to resemble the larger sample. Variation in timber properties according to site could probably be done largely by non-destructive measurements at board level as this thesis has established the essential relationships, which could be checked by selective destructive testing. It may be possible to combine these species, with each other, or with spruce for certain grading machines, but this cannot be assessed without the larger testing programme and in the specific context of a grading machine type. A shorter route could be obtained via visual grading, although for this to be properly representative it would still require more testing. Norway spruce can already be graded in combination with Sitka spruce and probably would not make sense to create grading settings, or visual grading assignments, for it on its own for Great Britain.

3. Stiffness is likely to be the limiting property for timber grading of the four species. Therefore, this is the property that growers should focus on for timber production. Density, *per se*, was not as important, and it should not be the focus of wood quality improvement at the expense of stiffness.

4. Grading machines based on measurement of MOE_{dyn} appeared as potentially capable of grading the four species together for C16 or higher, but under conservative settings if western red cedar was also graded (Fig 3.12). Since Sitka spruce is already graded in combination with Norway spruce this suggests the possibility of noble fir, western hemlock and western red cedar being an additional minor component of the well established “British spruce” species combination.

5. Some grading machines use knots in combination with density. The use of these two variables must be used with care as this thesis found that the association may not be extrapolated to combine species. For example, an indicating property based on density would bring limitations to the grading of western hemlock with the other species because density was high in relation to stiffness in comparison to the other species.

6. The empirical models built for bending stiffness, bending strength and density should be validated, and ensure that the models do not vary geographically.

7. Acoustic measurements in standing trees related better with bending properties measuring longer distances than the typical one metre. Thus, when assessing standing trees in new sites it is recommended the “time-of-flight” covers at least two meters. This is especially relevant in mature stands, with relatively big diameters, and if the aim is the segregation of high stiffness timber.

8. The sometimes poor correlation between density and stiffness has a confounding influence when it comes to predicting stiffness from time-of-flight acoustic measurements on standing trees and resonance measurements on logs. Research could investigate if the use of an increment borer or resistance drill could be used to estimate density and improve this measurement. This research would be applicable generally, and not just to the species in this study.

9. The usually acoustic time-of-flight measurement used on standing trees is confounded by radial differences in both stiffness and density. Research into the taking of acoustic measurements on increment cores could be carried out to see how effective this can be for assessing radial trends, determining the boundary between corewood and outer wood, and predicting properties of sawn timber. Part of this study would be solving some practical problems in actually making the measurement. This research would be applicable generally, and not just to the species in this study.

10. More research is necessary in order to know how wood properties, branchiness and taper may change depending on the silvicultural regimes applied and the environment. In order to describe the species under the

different scenarios, it will be important to obtain more than one sawlog per tree. This will also allow to assess the effect on the wood properties of the observed increment of the size of branches along the stem. It will be interesting to know how the "time-of-flight" measured in standing trees over a length of two and three metres relates to the wood properties of the upper sawlogs.

11. Validation of the taper models developed for the dataset.
12. There is an important potential for the use of these species under continuous cover forestry, but it will necessary to understand the impact of different scenarios on the timber properties.
13. Future work could address the right choice of seeds and clones for the different growing regions in G.B., and depending on the aim of the management.
14. The lack of straightness will limit the use of any tree for production of sawlogs. This thesis assessed the straightness visually, but it will be beneficial for the forest industry to use terrestrial laser scanning technology for a more accurate measurement.

7.5 Concluding remarks

This thesis has shown that there is the potential to use noble fir, Norway spruce, western red cedar and western hemlock grown in G.B. to produce high yields of structural timber.

The thesis has also shown that the use of acoustic tools to assess stiffness of wood in standing trees offered more reliable results measuring distances of two and three metres rather than the commonly used one metre.

List of Standards used

BS EN 408:2010+A1:2012. Timber structures - structural timber and glued laminated timber - Determination of some physical and mechanical properties European Committee for Standardization, Brussels, p 38.

BS EN 13183-1:2002. Moisture content of a piece of sawn timber - Part 1:Determination by oven dry method. European Committee for Standardisation, Brussels, p 5.

BS 373 (1957). Methods of testing small clear specimens of timber, 373:1957. British Standard Institution. BS, p. 31.

BS EN 338:2016. Structural timber - Strength classes. European Committee for Standardisation, Brussels, p. 11.

BS EN 384:2016. Structural timber-Determination characteristic values of mechanical properties and density. European Committee for Standardization, Brussels., p. 19.

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Appendix Chapter 3.

Variation in wood properties with radial position (structural-size pieces)

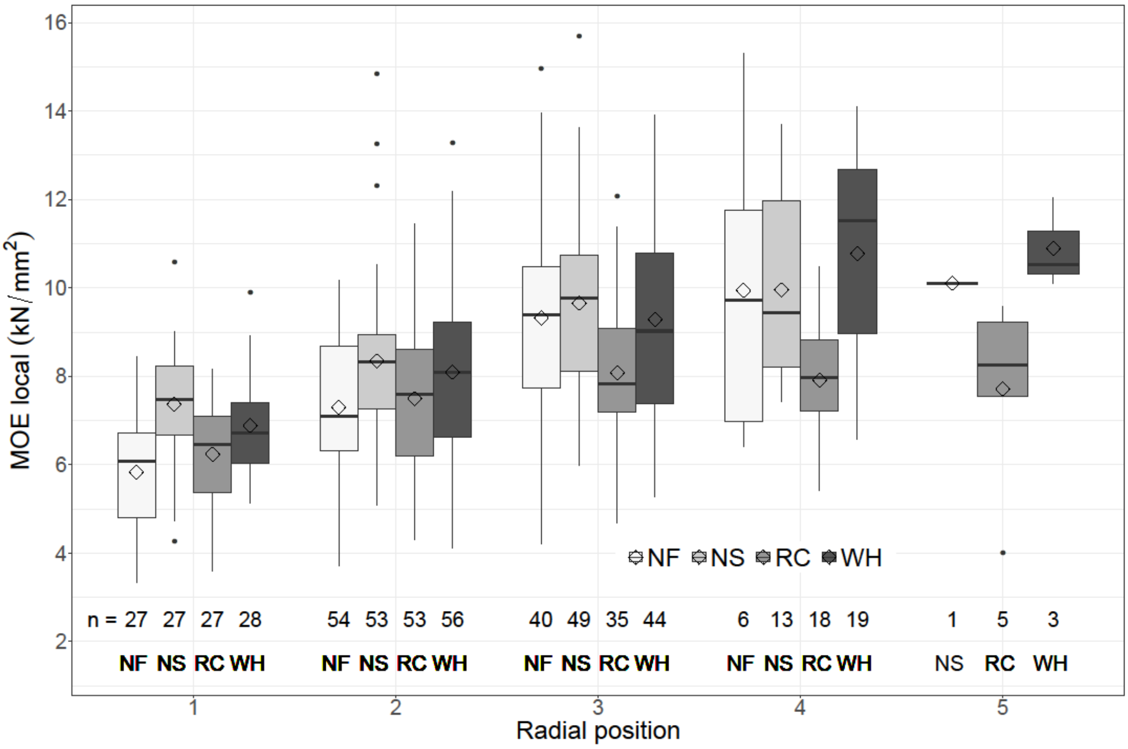

Figure A-1. Range of MOE local in structural-size timber for radial position and species.

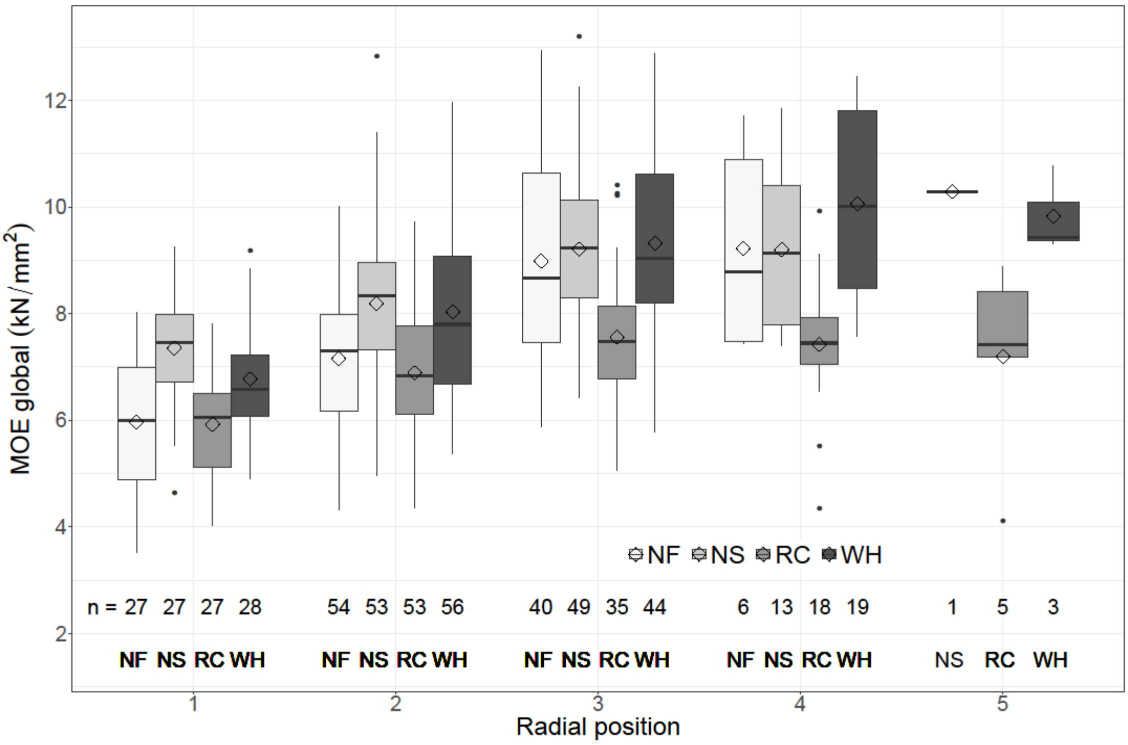

Figure A-2. Range of MOE global in structural-size timber for radial position and species.

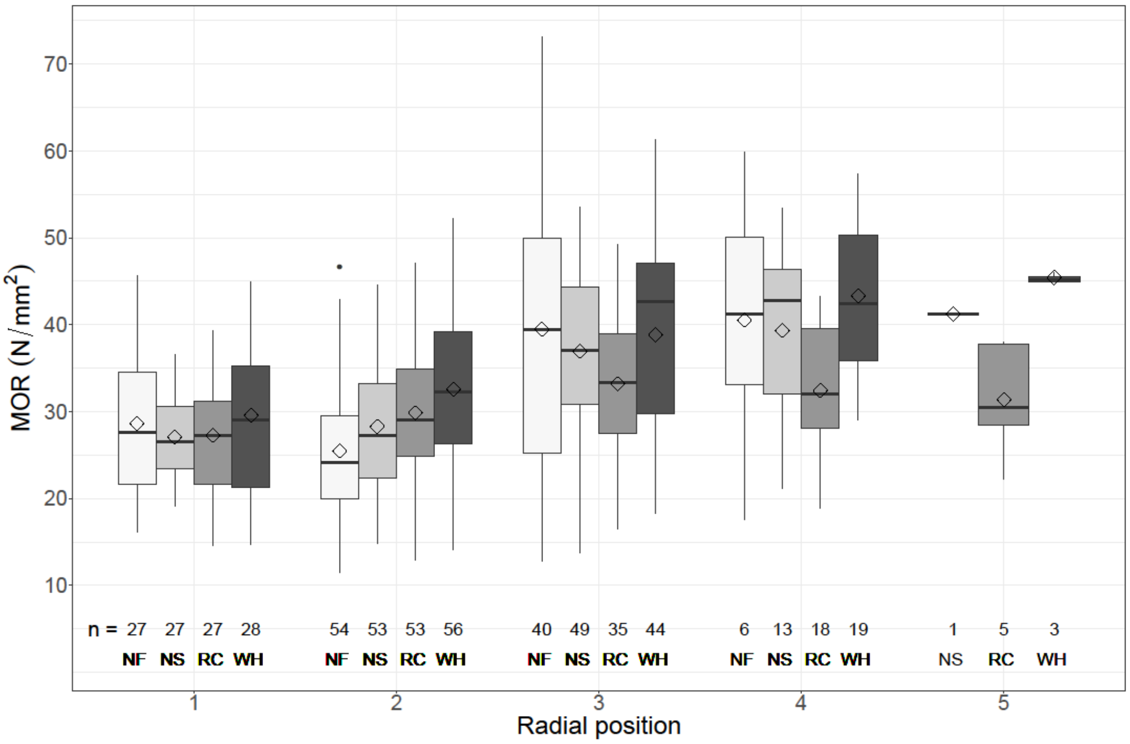

Figure A-3. Range of MOR in structural-size timber for radial position and species.

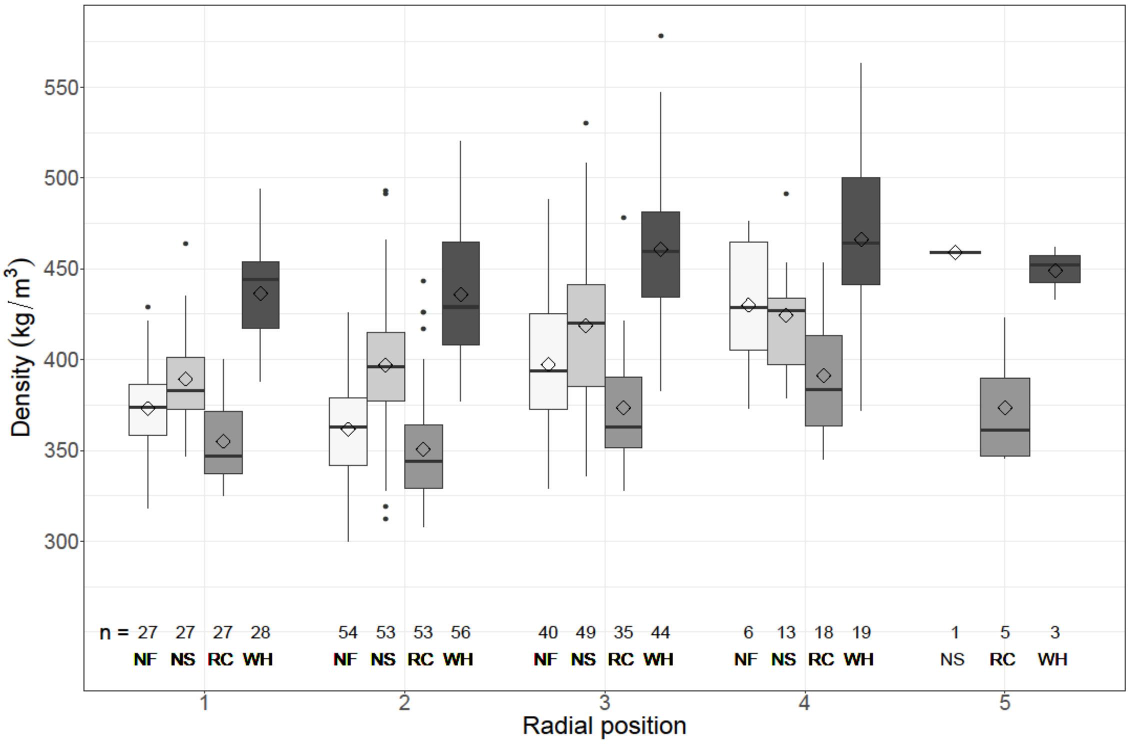

Figure A-4. Range of $Density_{384}$ in structural-size timber for radial position and species.

Characteristic values and yields for each strength class.

Noble fir

		Achieved			Required				% of required		
	n	$E_{0,mean}$ kN/mm²	$f_{m,k}$ N/mm²	ρ_k kg/m³	$E_{0,mean}$ x 0.95 kN/mm²	$f_{m,k}$ / k_v N/mm²	ρ_k kg/m³	n %	$E_{0,mean}$ %	$f_{m,k}$ %	ρ_k %
C14	126	7.71	14.77	323.7	6.65	14	290.0	100.0%	116.0%	105.5%	111.6%
C16	120	7.90	16.11	333.4	7.60	16	310.0	96.0%	104.0%	100.7%	107.5%
C18	97	8.55	22.12	355.6	8.55	18	320.0	77.8%	100.1%	122.9%	111.1%
C20	79	9.03	24.68	368.2	9.03	20	330.0	63.5%	100.1%	123.4%	111.6%
C22	64	9.52	28.45	375.4	9.50	22	340.0	51.6%	100.2%	129.3%	110.4%
C24	40	10.49	36.70	394.6	10.45	24	350.0	32.5%	100.4%	152.9%	112.7%
C27	31	10.96	39.67	402.4	10.93	27	370.0	25.4%	100.3%	146.9%	108.7%

Norway spruce

		Achieved			Required				% of required		
	n	$E_{0,mean}$ kN/mm²	$f_{m,k}$ N/mm²	ρ_k kg/m³	$E_{0,mean}$ x 0.95 kN/mm²	$f_{m,k}$ / k_v N/mm²	ρ_k kg/m³	n %	$E_{0,mean}$ %	$f_{m,k}$ %	ρ_k %
C14	128	8.55	19.13	345.5	6.65	14	290.0	100.0%	128.6%	136.7%	119.1%
C16	128	8.55	19.13	345.5	7.60	16	310.0	100.0%	112.5%	119.6%	111.5%
C18	128	8.55	19.13	345.5	8.55	18	320.0	100.0%	100.0%	106.3%	108.0%
C20	107	9.04	22.67	374.5	9.03	20	330.0	83.6%	100.2%	113.4%	113.5%
C22	84	9.52	27.09	388.1	9.50	22	340.0	65.6%	100.2%	123.1%	114.1%
C24	47	10.45	34.25	413.7	10.45	24	350.0	36.7%	100.0%	142.7%	118.2%
C27	33	10.95	37.05	423.6	10.93	27	370.0	25.8%	100.2%	137.2%	114.5%

western red cedar

		Achieved			Required				% of required		
	n	$E_{0,mean}$ kN/mm²	$f_{m,k}$ N/mm²	ρ_k kg/m³	$E_{0,mean}$ x 0.95 kN/mm²	$f_{m,k}$ / k_v N/mm²	ρ_k kg/m³	n %	$E_{0,mean}$ %	$f_{m,k}$ %	ρ_k %
C14	115	7.44	16.33	318.0	6.65	14	290.0	100.0%	111.9%	116.6%	109.6%
C16	109	7.61	20.04	324.8	7.60	16	310.0	94.8%	100.1%	125.3%	104.8%
C18	70	8.56	28.50	345.4	8.55	18	320.0	60.9%	100.2%	158.4%	107.9%
C20	51	9.04	31.26	357.6	9.03	20	330.0	44.3%	100.1%	156.3%	108.4%
C22	37	9.51	34.40	367.6	9.50	22	340.0	32.2%	100.1%	156.3%	108.1%
C24											
C27											

Western hemlock

		Achieved			Required				% of required		
	n	$E_{0,mean}$ kN/mm²	$f_{m,k}$ N/mm²	ρ_k kg/m³	$E_{0,mean}$ x 0.95 kN/mm²	$f_{m,k}$ / k_v N/mm²	ρ_k kg/m³	n %	$E_{0,mean}$ %	$f_{m,k}$ %	ρ_k %
C14	138	8.33	18.20	385.4	6.65	14	290.0	100.0%	125.3%	130.0%	132.9%
C16	138	8.33	18.20	385.4	7.60	16	310.0	100.0%	109.6%	113.7%	124.3%
C18	129	8.57	21.11	395.1	8.55	18	320.0	93.5%	100.2%	117.3%	123.5%
C20	109	9.04	26.82	415.6	9.03	20	330.0	79.0%	100.1%	134.1%	125.9%
C22	91	9.50	30.59	427.7	9.50	22	340.0	65.9%	100.0%	139.0%	125.8%
C24	57	10.45	36.99	455.5	10.45	24	350.0	41.3%	100.0%	154.1%	130.1%
C27	44	10.95	41.60	463.7	10.93	27	370.0	31.9%	100.2%	154.1%	125.3%

Note 1: $E_{0,\ mean}$ refers to MOE local

Note 2: The target mean MOE includes the 0.95 factor from EN384

Figure A-5. Characteristic values by species for the most common strength classes.

Appendix Chapter 4.

Models outputs and residuals plots

MOE model. Equation [4-2]

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: MOE40 ~ a1/(-exp(a2 * Age40)) + a3
 Data: clears40
       AIC      BIC    logLik
  2032.649 2122.402 -997.3247

Random effects:
 Formula: a3 ~ 1 | Site40
        a3.(Intercept)
StdDev:     0.06057278

 Formula: a3 ~ 1 | Plot40 %in% Site40
        a3.(Intercept)
StdDev:      0.1102131

 Formula: a3 ~ 1 | Tree40 %in% Plot40 %in% Site40
        a3.(Intercept)  Residual
StdDev:      0.6319274 0.6260485

Variance function:
 Structure: Different standard deviations per stratum
 Formula: ~1 | Sp40
 Parameter estimates:
       NF        NS        RC        WH
1.0000000 1.3294197 0.9438583 1.2331399
Fixed effects: a1 + a2 + a3 ~ Sp40
                   Value Std.Error  DF   t-value p-value
a1.(Intercept)  6.552969 0.2530000 712 25.901063  0.0000
a1.Sp40NS      -0.847411 0.8274872 712 -1.024078  0.3061
a1.Sp40RC      -2.351122 0.3060960 712 -7.680995  0.0000
a1.Sp40WH      -1.161485 0.3407279 712 -3.408834  0.0007
a2.(Intercept)  0.068103 0.0075425 712  9.029221  0.0000
a2.Sp40NS      -0.031978 0.0124696 712 -2.564501  0.0105
a2.Sp40RC       0.015697 0.0129052 712  1.216345  0.2243
a2.Sp40WH       0.005298 0.0130658 712  0.405502  0.6852
a3.(Intercept)  9.146452 0.3343718 712 27.354133  0.0000
a3.Sp40NS       1.681354 0.9499621 712  1.769917  0.0772
a3.Sp40RC      -1.403747 0.3913186 712 -3.587224  0.0004
a3.Sp40WH       0.333992 0.4400242 712  0.759030  0.4481
```

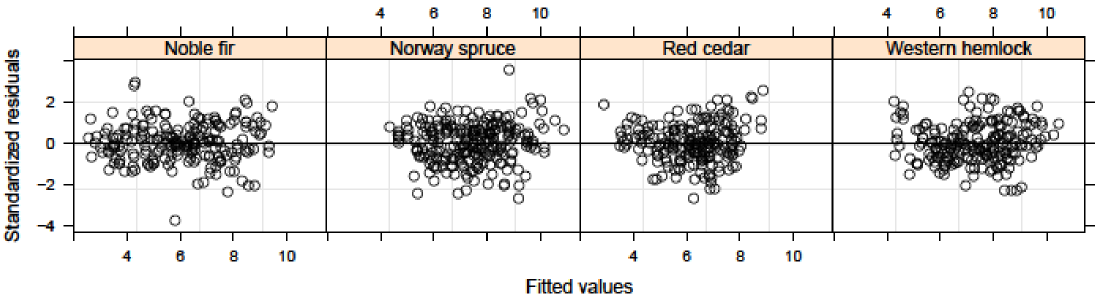

Figure B-1. Residuals vs fitted for the selected MOE model.

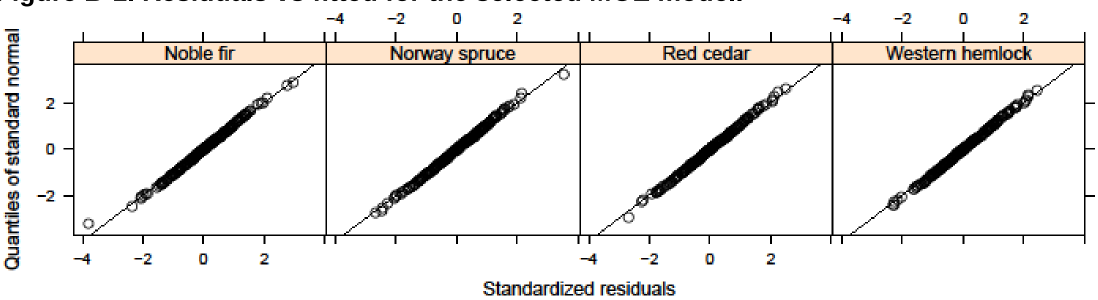

Figure B-2. Q-Q distribution for the selected MOE model.

MOR model. Equation [4-3]

```
Linear mixed model fit by maximum likelihood  ['lmerMod']
Formula:
MOR40 ~ Age40 * Sp40 + (1 + Age40 | Site40/Plot40/Tree40)
   Data: clears40

     AIC      BIC   logLik deviance df.resid
  5812.4   5897.4  -2888.2   5776.4      814

Scaled residuals:
    Min      1Q  Median      3Q     Max
-3.9423 -0.5543 -0.0340  0.5588  4.2670

Random effects:
 Groups                 Name        Variance  Std.Dev. Corr
 Tree40:(Plot40:Site40) (Intercept) 20.700237 4.54975
                        Age40        0.039970 0.19993  -0.03
 Plot40:Site40          (Intercept)  0.805481 0.89749
                        Age40        0.005526 0.07434  -1.00
 Site40                 (Intercept)  0.016107 0.12691
                        Age40        0.003783 0.06150  -1.00
 Residual                           45.546206 6.74879
Number of obs: 832, groups:
Tree40:(Plot40:Site40), 109; Plot40:Site40, 9; Site40, 3

Fixed effects:
             Estimate Std. Error t value
(Intercept)  44.59531    1.28183   34.79
Age40         0.66817    0.08423    7.93
Sp40NS        5.37174    1.73133    3.10
Sp40RC        5.53270    1.77905    3.11
Sp40WH       16.57740    1.76161    9.41
Age40:Sp40NS  0.08941    0.09290    0.96
Age40:Sp40RC -0.32638    0.09608   -3.40
Age40:Sp40WH -0.18752    0.09443   -1.99
```

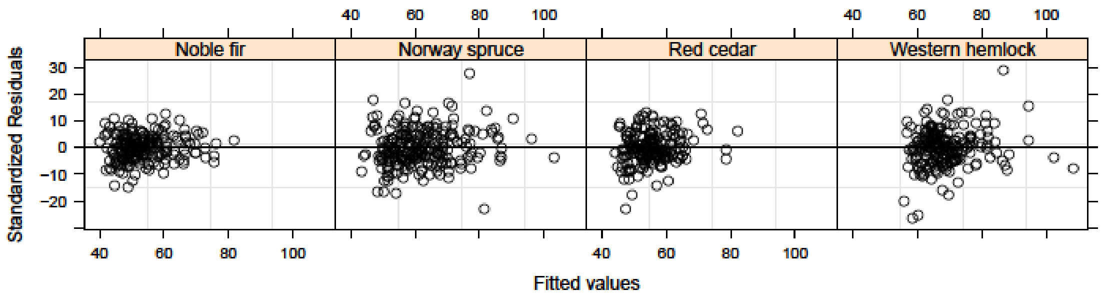

Figure B-3. Residuals vs fitted for the selected random slope MOR model.

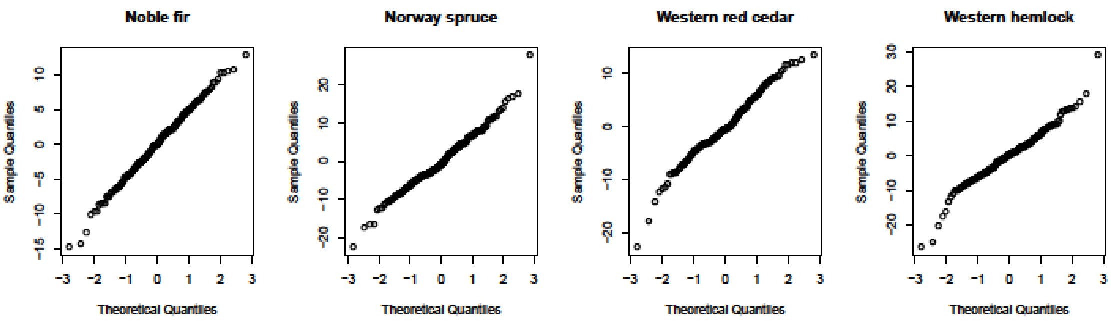

Figure B-4. Normal Q-Q distribution for the selected MOR model.

Density model. Equation [4-4]

- **Noble fir, first section**

```
Linear mixed-effects model fit by maximum likelihood
 Data: NFyoung
       AIC      BIC    logLik
  779.9966 794.2888 -383.9983

Random effects:
 Formula: ~1 | Site_NFy
        (Intercept)
StdDev:    7.909474

 Formula: ~1 | Plot_NFy %in% Site_NFy
        (Intercept)
StdDev: 0.005427696

 Formula: ~1 | Tree_NFy %in% Plot_NFy %in% Site_NFy
        (Intercept) Residual
StdDev:    16.33632 25.34716

Fixed effects: Dens_NFy ~ Age_NFy
               Value Std.Error DF   t-value p-value
(Intercept) 464.6490  8.642782 52  53.76151       0
Age_NFy     -17.9972  1.282838 52 -14.02920       0
```

- **Noble fir, second section**

```
Linear mixed model fit by maximum likelihood  ['lmerMod']
Formula: Dens_NFo ~ Age_NFo + (1 + Age_NFo | Site_NFo/Plot_NFo/Tree_NF
o)
   Data: NFold

     AIC      BIC   logLik deviance df.resid
  1093.7   1127.0   -534.8   1069.7      107

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.07142 -0.53664  0.03784  0.47716  2.16795

Random effects:
 Groups                        Name        Variance Std.Dev. Corr
 Tree_NFo:(Plot_NFo:Site_NFo) (Intercept) 858.5155 29.3004
                               Age_NFo       4.1646  2.0407  -0.92
 Plot_NFo:Site_NFo             (Intercept) 434.7607 20.8509
                               Age_NFo       0.3459  0.5881  -0.93
 Site_NFo                      (Intercept) 519.1409 22.7847
                               Age_NFo       0.8673  0.9313  -1.00
 Residual                                  235.1396 15.3343
Number of obs: 119, groups:
Tree_NFo:(Plot_NFo:Site_NFo), 27; Plot_NFo:Site_NFo, 9; Site_NFo, 3

Fixed effects:
            Estimate Std. Error t value
(Intercept) 315.4553    16.8549  18.716
Age_NFo       3.8802     0.7697   5.041
```

- **Norway spruce, first section**

```
Linear mixed model fit by maximum likelihood  ['lmerMod']
Formula: Dens_NSy ~ Age_NSy + (1 + Age_NSy | Site_NSy/Plot_NSy/Tree_NS
y)
   Data: NSyoung

     AIC      BIC   logLik deviance df.resid
   905.2    935.8   -440.6    881.2       82

Scaled residuals:
     Min       1Q   Median       3Q      Max
-1.92069 -0.44807  0.06667  0.49873  2.39991

Random effects:
 Groups                         Name        Variance  Std.Dev. Corr
 Tree_NSy:(Plot_NSy:Site_NSy) (Intercept) 3.850e-04  0.01962
                              Age_NSy     9.281e+00  3.04655 0.99
 Plot_NSy:Site_NSy            (Intercept) 1.960e+02 14.00024
                              Age_NSy     8.190e-01  0.90498 -1.00
 Site_NSy                     (Intercept) 6.276e+01  7.92186
                              Age_NSy     6.595e+00  2.56798 -1.00
 Residual                                 4.184e+02 20.45577
Number of obs: 94, groups:
Tree_NSy:(Plot_NSy:Site_NSy), 27; Plot_NSy:Site_NSy, 9; Site_NSy, 3

Fixed effects:
            Estimate Std. Error t value
(Intercept)  418.166      7.931   52.73
Age_NSy       -3.916      1.791   -2.19
```

- **Norway spruce, second section**

```
Linear mixed-effects model fit by maximum likelihood
 Data: NSold
       AIC      BIC    logLik
  1360.831 1378.481 -674.4155

Random effects:
 Formula: ~1 | Site_NSo
        (Intercept)
StdDev:     5.66578

 Formula: ~1 | Plot_NSo %in% Site_NSo
        (Intercept)
StdDev:  0.00686598

 Formula: ~1 | Tree_NSo %in% Plot_NSo %in% Site_NSo
        (Intercept) Residual
StdDev:    32.37642 23.89671

Fixed effects: Dens_NSo ~ Age_NSo
               Value Std.Error  DF  t-value p-value
(Intercept) 349.3785  9.735618 112 35.88663       0
Age_NSo       2.8775  0.278826 112 10.31989       0
```

- **Western red cedar, first section**

```
Linear mixed-effects model fit by maximum likelihood
 Data: RCyoung
       AIC      BIC    logLik
  791.7414 805.9581 -389.8707

Random effects:
 Formula: ~1 | Site_RCy
        (Intercept)
StdDev:    6.530491

 Formula: ~1 | Plot_RCy %in% Site_RCy
        (Intercept)
StdDev:  0.00186569

 Formula: ~1 | Tree_RCy %in% Plot_RCy %in% Site_RCy
        (Intercept) Residual
StdDev:    16.39824 29.99361

Fixed effects: Dens_RCy ~ Age_RCy
               Value Std.Error DF   t-value p-value
(Intercept) 458.1398  9.100655 51  50.34141       0
Age_RCy     -13.6624  1.132675 51 -12.06202       0
```

- **Western red cedar, second section**

```
Linear mixed model fit by maximum likelihood  ['lmerMod']
Formula: Dens_RCo ~ Age_RCo + (1 + Age_RCo | Site_RCo/Plot_RCo/Tree_RC
o)
   Data: RCold

     AIC      BIC   logLik deviance df.resid
  1009.1   1041.9   -492.5    985.1      102

Scaled residuals:
     Min       1Q   Median       3Q      Max
-2.46783 -0.56440  0.00037  0.50345  2.01242

Random effects:
 Groups                        Name        Variance  Std.Dev. Corr
 Tree_RCo:(Plot_RCo:Site_RCo) (Intercept) 4.229e+02 20.56494
                               Age_RCo     5.132e-01  0.71638 -0.28
 Plot_RCo:Site_RCo             (Intercept) 5.268e+01  7.25830
                               Age_RCo     6.346e-03  0.07966 -1.00
 Site_RCo                      (Intercept) 5.881e+02 24.25008
                               Age_RCo     2.364e+00  1.53746 -1.00
 Residual                                  1.466e+02 12.10861
Number of obs: 114, groups:
Tree_RCo:(Plot_RCo:Site_RCo), 27; Plot_RCo:Site_RCo, 9; Site_RCo, 3

Fixed effects:
            Estimate Std. Error t value
(Intercept) 344.1138    15.6138   22.04
Age_RCo       0.2152     0.9348    0.23
```

- **Western hemlock, first section**

```
Linear mixed-effects model fit by maximum likelihood
 Data: WHyoung
       AIC      BIC   logLik
  856.2659 870.7789 -422.133

Random effects:
 Formula: ~1 | Site_WHy
        (Intercept)
StdDev:    9.967727

 Formula: ~1 | Plot_WHy %in% Site_WHy
        (Intercept)
StdDev:    7.124197

 Formula: ~1 | Tree_WHy %in% Plot_WHy %in% Site_WHy
        (Intercept) Residual
StdDev:    17.21393 34.90577

Fixed effects: Dens_WHy ~ Age_WHy
               Value Std.Error DF  t-value p-value
(Intercept) 525.3445 11.741598 54 44.74217       0
Age_WHy     -11.5117  1.335691 54 -8.61855       0
```

- **Western hemlock, second section**

```
Linear mixed model fit by maximum likelihood  ['lmerMod']
Formula: Dens_WHo ~ Age_WHo + (1 + Age_WHo | Site_WHo/Plot_WHo/Tree_WH
o)
   Data: WHold

     AIC      BIC   logLik deviance df.resid
  1214.2   1248.0   -595.1   1190.2      111

Scaled residuals:
     Min       1Q   Median       3Q      Max
-1.79981 -0.53567 -0.06372  0.49596  2.13086

Random effects:
 Groups                         Name        Variance  Std.Dev. Corr
 Tree_WHo:(Plot_WHo:Site_WHo) (Intercept) 2.160e+03 46.4796
                                Age_WHo     1.885e+00  1.3728  -0.88
 Plot_WHo:Site_WHo              (Intercept) 4.531e+02 21.2856
                                Age_WHo     1.608e-02  0.1268  -1.00
 Site_WHo                       (Intercept) 2.657e+02 16.2994
                                Age_WHo     1.037e+00  1.0184  -1.00
 Residual                                   4.984e+02 22.3245
Number of obs: 123, groups:
Tree_WHo:(Plot_WHo:Site_WHo), 28; Plot_WHo:Site_WHo, 9; Site_WHo, 3

Fixed effects:
            Estimate Std. Error t value
(Intercept) 427.4362    16.4007  26.062
Age_WHo       0.7977     0.7108   1.122
```

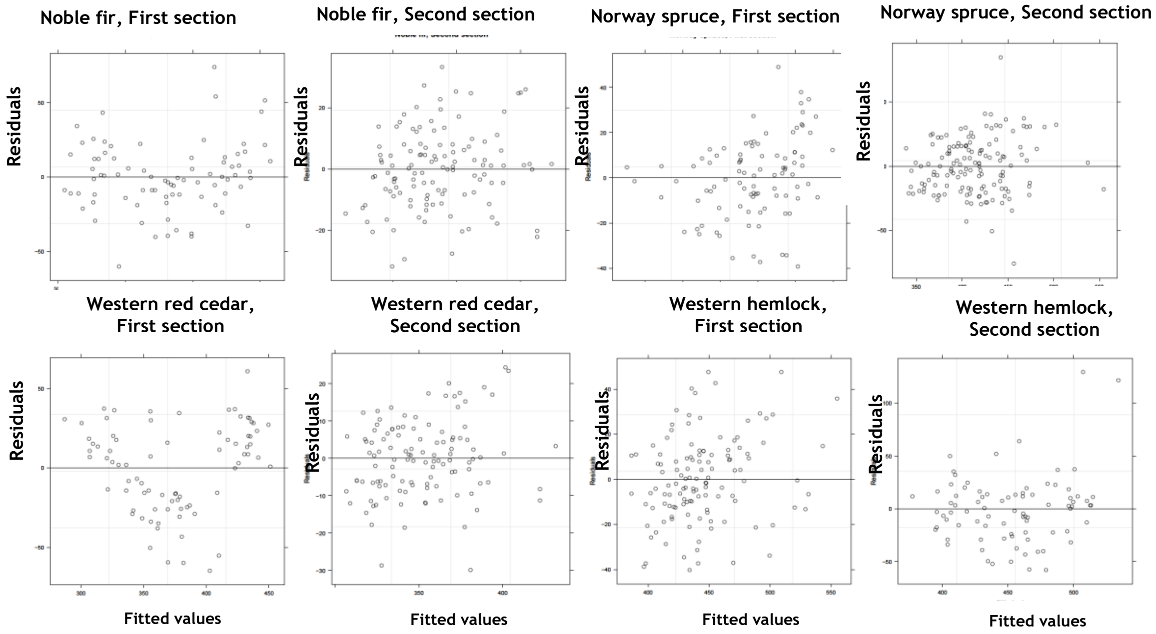

Figure B-5. Residuals vs fitted for the selected random slope MOR model.

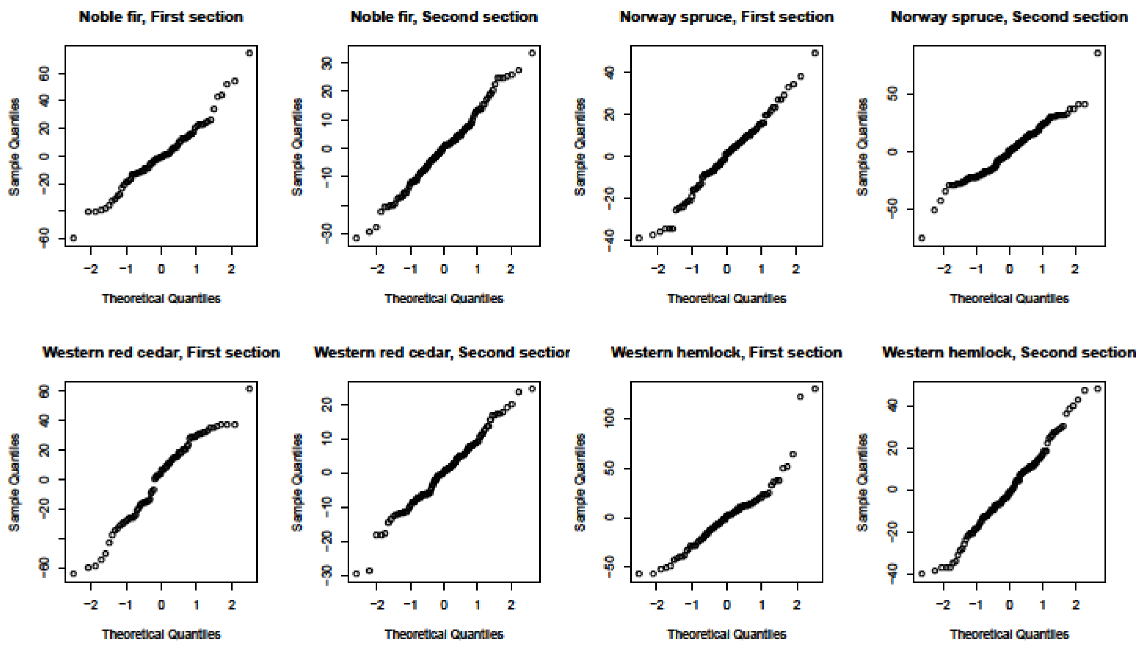

Figure B-6. Normal Q-Q distribution for the selected density models.

Appendix Chapter 6

Taper model outputs and residuals plots

6.4.1. Taper model

- **Noble fir**

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: dh.NF ~ dbh.NF * x.NF^(a1 * (z.NF - 1) + a2 * (exp(a3 * z.NF)
))
 Data: taper.NF
       AIC      BIC    logLik
  1758.575 1784.391 -873.2875

Random effects:
 Formula: a1 ~ 1 | Site.NF
              a1
StdDev: 0.122157

 Formula: a1 ~ 1 | Plot.NF %in% Site.NF
              a1 Residual
StdDev: 0.106202 1.165649

Fixed effects: a1 + a2 + a3 ~ 1
       Value  Std.Error  DF   t-value p-value
a1  1.667668 0.13919875 535  11.98048       0
a2  2.163859 0.15372187 535  14.07645       0
a3 -1.007565 0.05923857 535 -17.00859       0
```

- **Norway spruce**

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: dh.NF ~ dbh.NF * x.NF^(a0 + a1 * (z.NF - 1) + a2 * (exp(a3 *
     z.NF)))
 Data: taper.NF
      AIC      BIC    logLik
  2397.53 2429.256 -1191.765

Random effects:
 Formula: a1 ~ 1 | Site.NF
                a1
StdDev: 0.01880871

 Formula: a1 ~ 1 | Plot.NF %in% Site.NF
               a1 Residual
StdDev: 0.1157954   1.3443

Fixed effects: a0 + a1 + a2 + a3 ~ 1
       Value Std.Error  DF   t-value p-value
a0  0.886162 0.0116703 675  75.93307       0
a1  0.485286 0.0625046 675   7.76400       0
a2  3.229337 0.2792124 675  11.56588       0
a3 -8.369177 0.6079646 675 -13.76589       0
```

- **Western red cedar**

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: dh.NF ~ dbh.NF * x.NF^(a0 + a1 * (z.NF - 1) + a2 * (exp(a3 *
     z.NF)))
 Data: taper.NF
       AIC      BIC    logLik
  2956.755 2988.083 -1471.378

Random effects:
 Formula: a1 ~ 1 | Site.NF
               a1
StdDev: 0.2391087

 Formula: a1 ~ 1 | Plot.NF %in% Site.NF
               a1 Residual
StdDev: 0.2216376 2.277807

Fixed effects: a0 + a1 + a2 + a3 ~ 1
        Value Std.Error  DF   t-value p-value
a0   0.908527 0.0184854 637  49.14828  0.0000
a1   0.181913 0.1697139 637   1.07188  0.2842
a2   6.352463 0.5898410 637  10.76979  0.0000
a3 -10.041695 0.6570376 637 -15.28329  0.0000
```

- **Western hemlock**

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: dh.NF ~ dbh.NF * x.NF^(a0 + a1 * (z.NF - 1) + a2 * (exp(a3 *
     z.NF)))
 Data: taper.NF
       AIC      BIC    logLik
  2872.925 2905.468 -1429.462

Random effects:
 Formula: a0 ~ 1 | Site.NF
                a0
StdDev: 0.06422541

 Formula: a0 ~ 1 | Plot.NF %in% Site.NF
                a0 Residual
StdDev: 0.04230947 1.511149

Fixed effects: a0 + a1 + a2 + a3 ~ 1
       Value Std.Error  DF   t-value p-value
a0  0.947058 0.0415533 760 22.791404       0
a1  0.800992 0.0925168 760  8.657801       0
a2  1.990069 0.1251431 760 15.902350       0
a3 -5.502733 0.6560653 760 -8.387476       0
```

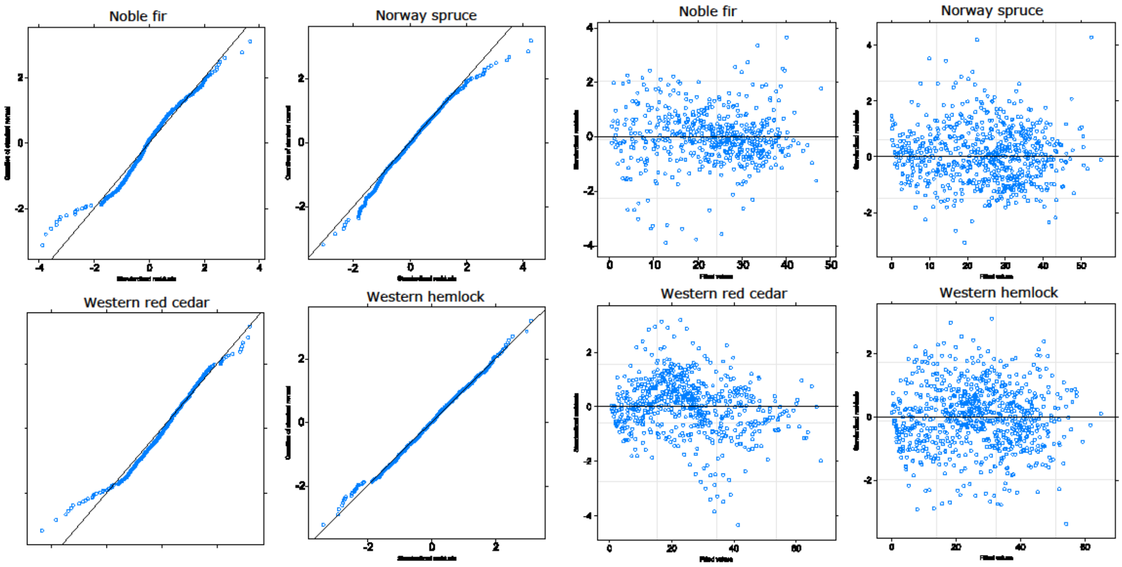

Figure C-1. Q-Q plot and Residuals vs fitted for the selected mixed-effects taper model.

Branch model outputs and residuals plots

6.4.3. Branch number per metre

```
> model1.mixed <- lme(number.br ~ number.metre * number.Sp, random = ~
 number.metre |number.Tree
)
> summary(model1.mixed)
Linear mixed-effects model fit by REML
 Data: NULL
       AIC      BIC    logLik
  5301.852 5360.002 -2638.926

Random effects:
 Formula: ~number.metre | number.Tree
 Structure: General positive-definite, Log-Cholesky parametrization
             StdDev   Corr
(Intercept)  2.420766 (Intr)
number.metre 0.145762 -0.736
Residual     3.686730

Fixed effects: number.br ~ number.metre * number.Sp
                             Value Std.Error  DF   t-value p-value
(Intercept)              11.705815 0.9889695 908 11.836377  0.0000
number.metre              0.114314 0.0683748 908  1.671879  0.0949
number.SpNS              -2.264527 1.3678772  32 -1.655505  0.1076
number.SpRC              -5.126787 1.3856347  32 -3.699956  0.0008
number.SpWH              -4.960719 1.3594966  32 -3.648938  0.0009
number.metre:number.SpNS  0.322874 0.0893810 908  3.612334  0.0003
number.metre:number.SpRC  0.048350 0.0890810 908  0.542765  0.5874
number.metre:number.SpWH  0.047180 0.0874355 908  0.539603  0.5896
```

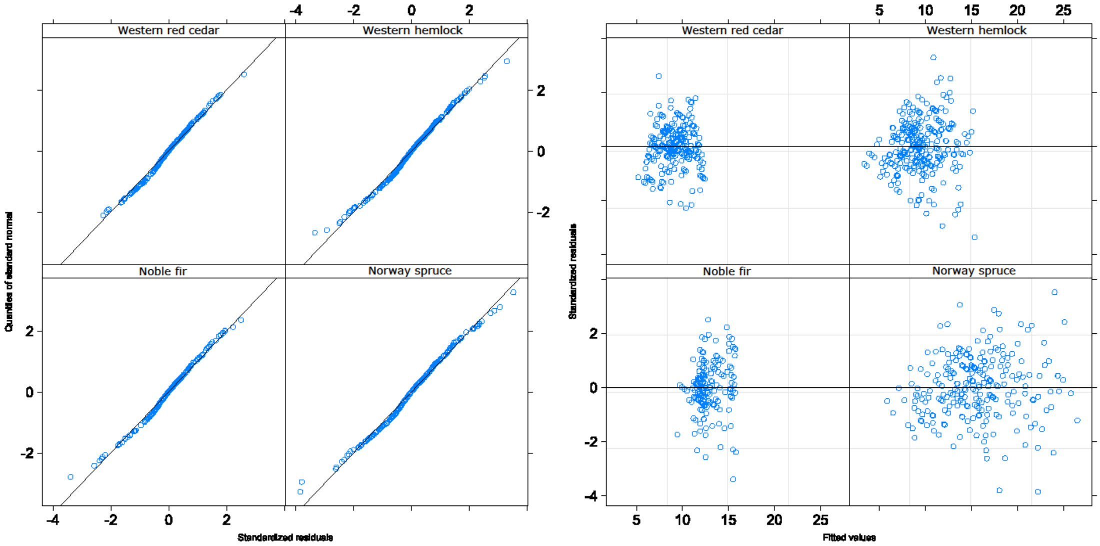

Figure C-2. Q-Q and Residuals vs fitted plots for the selected mixed-effects model for number of branches.

6.4.3 Average diameter branch: model output

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: mean_diam.metre ~ a1 + a2 * (1 - x2) * exp(-a3 * x2)
 Data: maxDB_metre
       AIC      BIC    logLik
  5593.997 5676.699 -2779.998

Random effects:
 Formula: a2 ~ 1 | Metre.metre
        a2.(Intercept) Residual
StdDev:   0.0002380572 5.101628

Variance function:
 Structure: Different standard deviations per stratum
 Formula: ~1 | Sp.metre
 Parameter estimates:
       AP        NS        WH        RC
1.0000000 0.6795166 0.9762598 0.8497699
Fixed effects: a1 + a2 + a3 ~ Sp.metre
                   Value Std.Error  DF    t-value p-value
a1.(Intercept)  6.300999 1.5053072 911   4.185856  0.0000
a1.Sp.metreNS  -5.215522 1.7674225 911  -2.950920  0.0032
a1.Sp.metreRC  -8.086069 1.8886025 911  -4.281509  0.0000
a1.Sp.metreWH  -7.052199 1.9081580 911  -3.695815  0.0002
a2.(Intercept)  7.641078 1.1420411 911   6.690720  0.0000
a2.Sp.metreNS   2.513920 1.3484697 911   1.864277  0.0626
a2.Sp.metreRC   3.868092 1.3742544 911   2.814684  0.0050
a2.Sp.metreWH   4.400819 1.4426796 911   3.050448  0.0024
a3.(Intercept) -3.057725 0.1304515 911 -23.439560  0.0000
a3.Sp.metreNS   0.259648 0.1441875 911   1.800764  0.0721
a3.Sp.metreRC  -0.202418 0.1431268 911  -1.414255  0.1576
a3.Sp.metreWH   0.130423 0.1463303 911   0.891293  0.3730
```

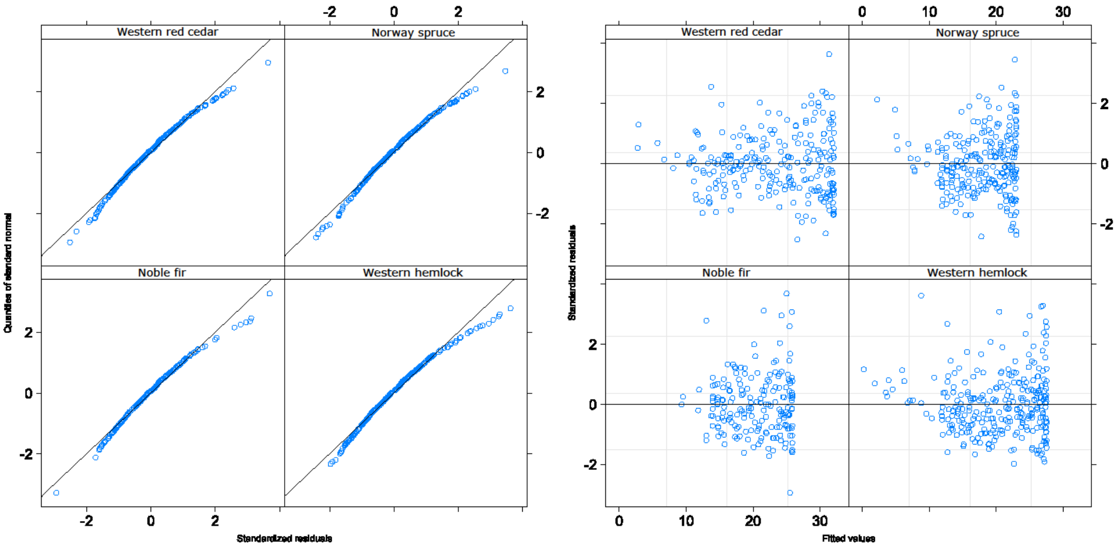

Figure C-3. Q-Q and Residuals vs fitted plots for the selected mixed-effects model for the average diameter branch.

6.4.4 Branch angle: model output

```
Nonlinear mixed-effects model fit by maximum likelihood
  Model: angle.br.angle ~ a0 * exp(-a1/(a2 - x))
 Data: angle.br
       AIC      BIC    logLik
  82909.87 83048.67 -41435.94

Random effects:
 Formula: a0 ~ 1 | angle.br.Sp
        a0.(Intercept)
StdDev:    0.002657537

 Formula: a0 ~ 1 | angle.br.Tree %in% angle.br.Sp
        a0.(Intercept)
StdDev:       3.640239

 Formula: a0 ~ 1 | angle.br.Metre %in% angle.br.Tree %in% angle.br.Sp
        a0.(Intercept) Residual
StdDev:        4.63656 9.094585

Variance function:
 Structure: Different standard deviations per stratum
 Formula: ~1 | angle.br.Sp
 Parameter estimates:
       AP        NS        RC        WH
1.0000000 1.0348964 0.9567158 1.4370734
Fixed effects: a0 + a1 + a2 ~ angle.br.Sp
                     Value Std.Error    DF  t-value p-value
a0.(Intercept)    85.77393 1.2974558 10026  66.1093  0.0000
a0.angle.br.SpNS  -2.03573 1.9038940 10026  -1.0692  0.2850
a0.angle.br.SpRC   0.24180 1.9378502 10026   0.1248  0.9007
a0.angle.br.SpWH   4.57718 1.9389333 10026   2.3607  0.0183
a1.(Intercept)     0.00398 0.0006307 10026   6.3041  0.0000
a1.angle.br.SpNS   0.01547 0.0032544 10026   4.7542  0.0000
a1.angle.br.SpRC   0.01829 0.0035978 10026   5.0824  0.0000
a1.angle.br.SpWH   0.01970 0.0032747 10026   6.0146  0.0000
a2.(Intercept)     0.99838 0.0010992 10026 908.2945  0.0000
a2.angle.br.SpNS   0.03880 0.0092066 10026   4.2139  0.0000
a2.angle.br.SpRC   0.03272 0.0090363 10026   3.6210  0.0003
a2.angle.br.SpWH   0.03586 0.0073602 10026   4.8727  0.0000
```

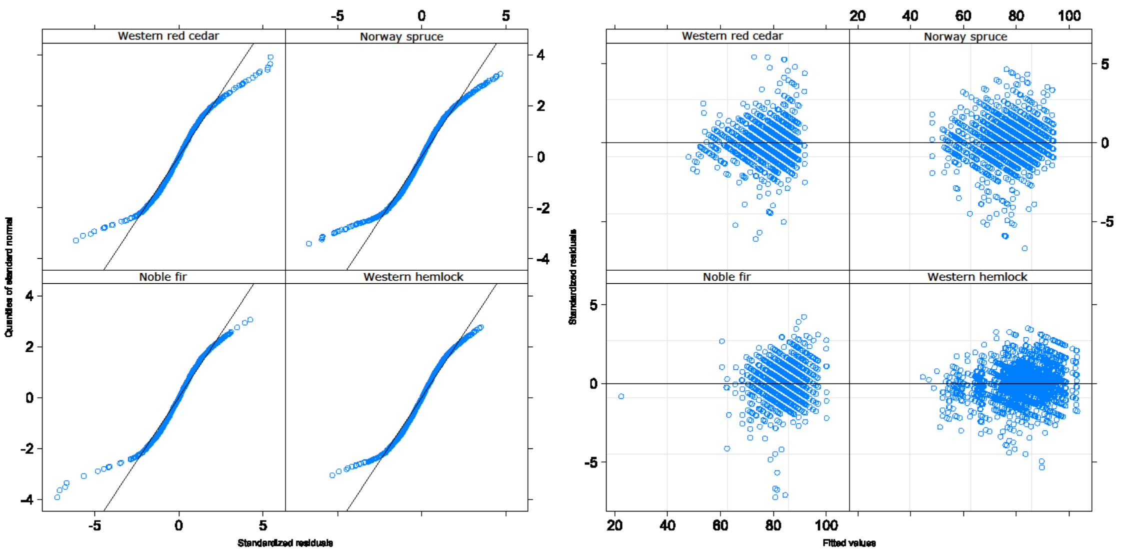

Figure C-4. Q-Q and Residuals vs fitted plots for the selected mixed-effects model for the insertion angle