AN ABSTRACT OF THE DISSERTATION OF

Mauricio Andres Acuna for the degree of Doctor of Philosophy in Forest Engineering

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Title: Wood Properties and Use of Sensor Technology to Improve Optimal Bucking and Value Recovery of Douglas-fir.

Abstract approved:

Glen E. Murphy

There are a number of wood properties which affect the quality of forest products such as lumber and pulp. Of these, wood density is considered by some to be the single most important physical characteristic because it is an excellent predictor of strength, stiffness, hardness, and paper-making capacities. Accurately assessing density in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on density.

Mechanized harvesting machines are frequently fitted with computer technology and rudimentary sensor systems for measuring external stem dimensions. Research into technologies for measuring stem quality attributes is progressing on a number of fronts

with varying levels of success. Some of these scanning technologies could be integrated into the design of mechanized harvesting systems.

In this dissertation:

- It is shown how Douglas-fir wood density can be predicted from near infrared (NIR) spectroscopy measurements of chain saw chips, ejected as a stem is cut into logs by a mechanized harvester,
- it is provided an analysis of the potential use of NIR technology for log segregation based on wood density,
- it is presented a general methodology to estimate log prices of Douglas-fir based on the net return obtained when logs of different wood density classes are processed and converted into end products (lumber and pulp),
- it is demonstrated how wood density could be included in optimal bucking procedures, and
- it is analyzed the effect of market requirements for density on log yields, total volume and revenue from a representative sample of Douglas-fir stems.

New sensor technologies are likely to lead to measurement, segregation and supply of a wider range of wood properties for forest product markets.

Wood Properties and Use of Sensor Technology to Improve Optimal Bucking and Value Recovery of Douglas-Fir

by
Mauricio A. Acuna

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APPROVED:

Major Professor, representing Forest Engineering

Head of the Department of Forest Engineering

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Mauricio Andres Acuna, Author

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I would also like to acknowledge the assistance of Dr. Stephen Kelley who was working for the National Renewable Energy Laboratory when many of the NIR spectra used in

Chapter 2 were collected. Also, I recognize the contribution of Michael Murphy who assisted with sample preparation and measurements of wood properties.

Finally, I want to thank and dedicate this work to my wife Marlene. Without her love, patience, and support it would have been impossible to finish successfully this academic program. Part of this Ph.D. belongs to her. Along with her, I want to dedicate this piece of work to my future daughter Angelina who is about to be born in the next weeks. Certainly they are the two treasures that I love most in this life and who have inspired me during these years. Also, I want to thank my parents, because despite the distance they always gave me their support and love. Both my education and the person I am are fruit of their sacrifice and the values I received from them.

CONTRIBUTION OF AUTHORS

I would like to recognize the contribution of Dr. Glen Murphy on all the papers contained in this dissertation.

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WOOD PROPERTIES AND USE OF SENSOR TECHNOLOGY TO IMPROVE OPTIMAL BUCKING AND VALUE RECOVERY OF DOUGLAS-FIR

CHAPTER 1

INTRODUCTION

Douglas-fir (*Psudotsuga menziesii* (Mirb.) Franco) is of considerable economic importance, especially for the forest products industries of the United States, Canada, New Zealand, and some areas of Europe. It is expected that international and U.S. wood product markets, especially high-quality structural lumber markets, will continue demanding Douglas-fir logs. Many timber production regions are facing competitive and complex market scenarios. Buyers demand and suppliers offer, logs that have been cut for very specific end-uses. Hence, niche markets and not mass markets are gradually becoming the norm. In addition, where at one time tree dimensions and external quality characteristics (such as branch size, sweep, and scarring) may have been sufficient to specify a log-sort, consideration is now being given to specifying such wood properties as density, stiffness, spiral grain, and extractives content. Therefore, to satisfy the requirements of the different users and to ensure that maximum value and quality are obtained from the raw material, trees must be cut and sorted into a variety of products. Understanding of the sources of variability of properties that affect those products will allow industry to match wood to markets.

Worldwide there is a trend towards increased mechanization of forest harvesting operations. This has come about for a number of reasons; to reduce the impacts of smaller trees on productivity and costs, to improve worker safety, to reduce environmental impacts and to overcome the difficulties some regions face in attracting labor to work in their forests. Mechanization provides opportunities to: reduce the variability in product performance by sorting for niche uses, capture and store detailed descriptions of many stems within each stand, reduce the variability in decision-making about which are the best markets to supply from each tree, and optimally control the bucking of logs at harvesting time. Thus, by optimally matching wood quality to markets, gains such as improved product uniformity, productivity and profitability could be attained along the seedling to customer supply chain.

There are a number of wood properties which affect the quality of final products. Of these, wood density is considered by some to be the single most important physical characteristic because it is an excellent predictor of strength, stiffness, hardness, and paper-making capacities. Accurately assessing density in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on density. Variables such as stand age and height within a tree have been used in the past as substitutes for accurate measurements of density.

Mechanized harvesting machines are frequently fitted with computer technology and rudimentary sensor systems for measuring external stem dimensions – usually diameters over bark along the stem and stem length. Research into technologies for measuring stem quality attributes is progressing on a number of fronts with varying levels of success; e.g. acoustics, optical and laser scanning, x-ray, microwave, ultrasound and near infrared (NIR) spectroscopy. Some of these scanning technologies could be integrated into the design of mechanized harvesting systems. Measuring wood properties of logs in real time should lead to improved log allocation decisions early in the supply chain, improved value recovery for the forest owner, and optimal matching of wood to markets.

This dissertation is a comprehensive study of internal wood properties and sensor technology to improve optimal bucking and value recovery in Douglas-fir. It has been written in a manuscript format and is made up of four distinct manuscripts. While each manuscript may stand alone, it has been written using a logical sequence that allows the reader to get a broad understanding of the effect of internal properties (mainly wood density) and advanced sensor technologies (mainly near infrared [NIR] spectroscopy) on value recovery. Figure 1.1 presents a general scheme of the dissertation chapters.

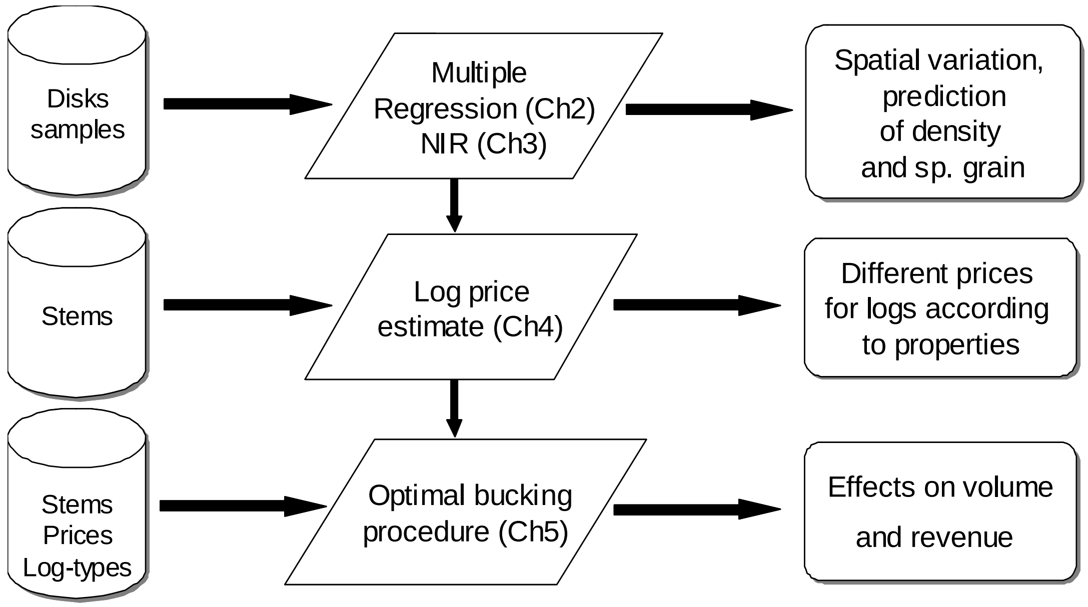

Figure 1.1 - General scheme of the dissertation chapters.

Chapter 2 summarizes the results of an investigation into modeling the effects of variation in site and within tree spatial characteristics - in particular, elevation, aspect, and height within trees - on Douglas-fir wood density and spiral grain from a range of sites in western Oregon. The goal was to determine if these wood properties could be accurately predicted based on spatial characteristics.

Chapter 3 provides an analysis of the potential use of NIR technology by mechanized harvesting equipment (e.g. harvesters) for log segregation based on wood density. It describes a study of a non-destructive testing method, NIR spectroscopy, and multivariate analysis (partial least squares and principal component analysis), and their potential to accurately predict Douglas-fir wood density based on three types of samples – green chain saw chips, dry rough chain saw chips, and dry ground chain saw chips.

Chapter 4 presents a general methodology to estimate log prices of Douglas-fir based on the net return obtained when logs of different wood density classes are processed and converted into end products (lumber and pulp). For lumber, a number of different grades and their prices are used to estimate the price that markets would be willing to pay for logs. For pulp logs, their price is estimated from the net product value per metric ton which considers pulp selling price and non-wood and fixed cost.

Chapter 5 looks at how an internal wood property, such as basic density, could be included in optimal bucking procedures. A new bucking algorithm is described. The algorithm is used to analyze the effect of density on the volume by log-type, total volume and revenue from 100 Douglas-fir stems. The study uses hypothetical scenarios with different market requirements with regard to density of the products in order to see the potential impact of this variable in the decision-making and on the economics of the operations.

At the end of this dissertation, an analysis of the relationships and links between the results obtained in each chapter is presented, along with an integrated analysis of the findings. It also includes a summary of the dissertation and comments on the future research that should be conducted in this area.

CHAPTER 2

SITE AND WITHIN TREE VARIATION OF WOOD DENSITY AND SPIRAL GRAIN IN DOUGLAS-FIR

Mauricio Acuna and Glen Murphy

Department of Forest Engineering

Oregon State University

Corvallis, OR 97331-5706

USA

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Forest Product Society

2801 Marshall Court

Madison WI 53705-2295

USA

2.1 ABSTRACT

In many parts of the world log markets are becoming increasingly competitive and complex. Buyers are demanding, and suppliers are offering, logs that have been cut for very specific end-uses and which may be specified in terms of internal as well as external properties. Optimally matching logs to markets requires good measurements and/or predictions of the wood properties in each stem. This information could be used either at the planning stage or in on-board computers installed in harvesters to enhance bucking and sorting.

To assess the site and within tree variation in wood density and spiral grain in Douglas-fir stems, over 400 wood disks were collected from 17 sites in the Cascade and Coastal Ranges of Oregon. Sites were selected from a range of elevations and aspects. Trees selected at each of the sites were of a similar age (45-60 years) and average size (20-54 cm, diameter at breast height). Disks came from different vertical positions in each tree. No statistically significant relationship between wood density and either elevation or aspect was found. There was evidence of a weak negative association between wood density and the height in a tree from where the samples came. No statistically significant relationship between height, elevation or aspect was observed for spiral grain.

Keywords: wood density, spiral grain, bucking, wood markets.

2.2 INTRODUCTION

Douglas-fir (*Psudotsuga menziesii* (Mirb.) Franco) is of considerable economic importance, especially for the forest products industries of the United States, Canada, New Zealand, and some parts in Europe (Gartner *et al*. 2002). This is due to its primary uses as dimension lumber, plywood, and pulp. By optimally matching wood quality to markets, gains such as improved product uniformity and productivity and profitability could be attained along the Douglas-fir seedling to customer supply chain. Reductions in wood waste and energy consumption may also be realized. Wood quality can be defined in terms of attributes that make it valuable for a given end use. Quality attributes of significance to wood products include wood density, microfibril angle, fiber length, lignin content, ring width, knot size and distribution, grain angle and coarseness, color, etc. (Walker *et al*. 1993). It has been noted, however, that the factors controlling wood quality can be confusing and are frequently contradictory (Anon. 1965). In this paper we will focus on just two quality attributes, density and spiral grain, which can affect the economic value of Douglas-fir.

2.2.1 Density

Wood density is a simple measure of the total amount of solid wood substance in a piece of wood. It provides an excellent means of predicting end-use characteristics of wood such as strength, stiffness, hardness, heating value, machinability, pulp yield and paper making quality (Jozsa *et al*. 1989).

Each tree species has its own characteristic average wood density and range (O'Sullivan 1976). Wood density may, or may not, vary among provenances and is very variable among trees and within individual trees of a given provenance (Yang *et al*. 2001; Zobel and Van Buijtenen 1989). Density has been shown to be a highly heritable characteristic (Cown *et al*. 1992; Zobel and Jett 1995; Hanrup *et al*. 2004); that is, the phenotypic variation between individuals is largely due to genetic differences as opposed to environmental effects.

Aspect, elevation and latitude are indicators for environmental variables such as temperature and precipitation which have been shown to have an effect on density for a number of species. Cown *et al*. (1991) reported that wood density of radiata pine (*Pinus radiata* D.Don) grown in New Zealand decreases markedly with both increasing elevation and latitude. Wilhelmsson (2001) developed density models for Norway spruce (*Picea abies* L.) and Scots pine (*Pinus sylvestris*) which included the diameter over and under bark at breast height, number of annual rings, latitude, elevation, and temperature as explanatory variables. These variables accounted for 50% of the total variation in the spruce density and 59% of the pine density. Harding and Copley (2000) demonstrated that density was linked to latitude in slash-Caribbean pine (*Pinus elliotti* Engelm. X *Pinus caribbea*) hybrids grown in Queensland. Elevation has also been shown to affect wood density in five species of pine grown in South Africa (Clarke *et al*. 2002) and in Douglas-fir grown in the Pacific Northwest (Anon. 1965).

Within individual trees, density varies from early wood to late wood within rings, from pith to bark at a given height in the stem, and from stump to tip (Gartner *et al*. 2002; Jozsa *et al*. 1989; Kennedy 1995). Jozsa and Kellogg (1986) examined the density pattern from pith to bark at several sampling heights in Douglas-fir. Their results indicated relatively low density juvenile wood in Douglas-fir for the first 15-20 years of growth. Then a rapid increase was evident to about age 30, followed by a stable or slightly increasing density trend. This trend has also been reported by other researchers (Megraw 1986a; Gartner *et al*. 2002). For a tree of a given age, density usually decreases with height in the stem (e.g. as reported for radiata pine by Donaldson *et al*. 1995) but may be constant or even increase (e.g. as reported for spruce species by Ward 1975). Silvicultural management (e.g. pruning and spacing) has been shown to affect density in some cases (Polge 1969; Megraw 1986a, 1986b; DiLucca 1989) but not in others (Wahlgren *et al*. 1968).

The distribution of Douglas-fir tree relative density from Canada, USA, Europe and New Zealand tends to be bell shaped with a mean between 0.40 and 0.50. Density for individual trees in the Western (Coastal) USA ranges between 0.33 and 0.57 (Anon 1965).

In 1959, Knigge (1962), cited in Anon. (1965), selected five trees from each of 51 second growth (< 100 years old) Douglas-fir stands situated between the Canadian border and northern California and from the Coast Range to the western slopes of the

Cascades. In general, specific gravity increased with age, improved with site class, increased with average growing season temperature and decreased with increasing growing season precipitation and increasing elevation. However, only 34% of the variation between individual trees could be accounted for; age, ring width and site class having the greatest impacts on density.

In the early 1960's a much larger survey of wood density was carried out in the western USA for nine "high priority" species, including Douglas-fir (Anon 1965). Over 9000 Douglas-fir trees were sampled. A sub-sample of 1402 trees from the western Cascade Ranges was chosen for more detailed analysis. Trees came from elevations ranging between 0 and 2400 m, from latitudes spanning 650 km, and from ages between 5 and 250+ years. For trees between 35 and 149 years old, only two variables were significantly related to increment core specific gravity at diameter breast height, elevation and latitude. Both of these negatively affected specific gravity, but together they only accounted for 10% of the variation in density between individual trees. The authors noted that elevation and latitude were indicators of precipitation and temperature, two of the factors that Knigge (1962) found to influence density. The authors recommended that other factors, such as aspect, site index, and topography class, should be investigated.

2.2.2 Spiral grain

In a standing tree which has straight-grained wood the fibers will be oriented parallel to the long axis of the stem. With little exception, fiber arrangement is at some angle, however small, to the stem axis rather than precisely parallel to it. At times this deviation is large, resulting in an obvious spiraling grain pattern. From a utilization standpoint, spiral grain is important in view of its detrimental effects on the strength, seasoning and machining properties of wood (Noskowiak 1963; Forest Products Laboratory 1999). Lumber sawn from such logs is characterized by slope of grain which causes low strength and stiffness as well as a tendency to twist as it dries. Excessive spiral grain (about 35 degrees) can severely impact log quality (Jozsa and Middleton 2004). Noskowiak (1963) observed grain angles as high as 40 degrees in foxtail pine (*Pinus balfouriana* Grev. and Balf.).

Noskowiak (1963) reviewed the literature on spiral grain in trees. He noted that spiral grain is a normal phenomenon in the life span of trees and to a large extent is genetically controlled. In conifer trees there appears to be a general radial pattern. Young trees start out spiraling to the left. As the tree gets older, the magnitude of the slope gradually decreases to zero. Then the tree begins spiraling to the right, the magnitude of the spiral increasing with age (Northcott 1957; Noskowiak 1963). The magnitude of the grain deviation, and the age at which there is a change from left spiral to straight grained, and from straight grained to right spiral varies widely.

Tessier du Cros *et al*. (1980) found that the individual tree variation in spiral grain found in beech (*Fagus sylvatica*) was very large. Harris (1989) has argued that although spiral grain is largely controlled by heritability, its manifestation is partly dependent on the environment. He demonstrates this with the example of seed from trees of good form producing trees with spiral grain when grown in a different environment. Walker *et al*. (1993) note that, while there is considerable evidence that environmental extremes favor the development of spiral grain, this has not been formally established. Noskowiak (1963) cites conflicting evidence that aspect (Smythies 1915 [yes], Rault and Marsh 1952 [no]), elevation (Kindseth [no date] [yes], Wellner 1955 [no]), and soil type (Champion 1925 [yes], Troup 1921 [no]) affect the magnitude of spiral grain.

There is also conflicting evidence as to the effect of height in the tree on spiral grain angle. Northcott (1957) cites studies where spiral grain angle decreased with height for red alder (*Alnus rubra* Bong.), was not affected by height for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and increased with height for both ponderosa pine (*Pinus ponderosa* P. & C. Lawson) and *Araucaria cunninhamii*.

Silviculture can also affect spiral grain. Polge (1969) reported that pruning radiata pine resulted in a reduction in spiral grain. On the other hand, Harris (1989) notes that economic pressures to reduce rotation ages have resulted “in a relatively higher proportion of the stem than formerly, consisting of young wood with significant spirality".

Northcott (1957) measured the spiral grain on 140 pieces of Douglas-fir from trees up to 500 years old. For cambial ages less than 100 years old the spiral grain was generally less than 4 degrees. However, some specimens ranged from 16 degrees left spiral to 19 degrees right spiral. Differences were noted between localities, individual trees and both radially and vertically within individual trees.

Optimally matching logs to markets requires good measurements and predictions of the external and internal properties of the wood in each stem (Clarke *et al*. 2002, Wilhelmsson 2001). If wood properties, such as density and spiral grain, can be predicted with a reasonable degree of accuracy for individual trees and logs, measurements of these properties will not be required in the forest or log yard. In 2003 a series of studies were undertaken to determine (a) if wood properties could be accurately predicted based on spatial characteristics, and (b) if wood properties could be successfully measured using near infrared (NIR) technology on chainsaw wood chips gathered at time of harvest.

This paper summarizes the results of the investigation into modeling the effects of site characteristics - in particular, elevation, aspect, and height within trees - on Douglas-fir wood density and spiral grain from a range of sites in western Oregon. The results of the NIR study will be reported in a later paper.

2.3 MATERIAL AND METHODS

2.3.1 Sites and trees selected

In mid-2003, 119 trees were felled at 17 forest sites located in the Coast Range and the Cascade Range of Oregon. The latitude and longitude of the sites ranged from 44^{o} 13' to 45^{o} 36' and from 122^{o} 00' to 123^{o} 35', respectively. The sites were chosen to cover a range of elevations (217 to 996 m) and aspects. Approximately 7 trees were felled at each site and these were selected to cover the range of diameters present. All stands contained second growth Douglas-fir and were of similar age class (45-60 years). The characteristics of each site under study are shown in Table 2.1.

Table 2.1 - Characteristics of the sites under study

Site	*Elevation of the site (m)*	*Aspect**	*DBH Range of trees selected (cm)***	*Site Location Latitude/Longitude*
1	396	ENE to WNW	24.5 - 39.1 (32.0)	44° 35.796’ / 123° 38.014’
2	217	ENE to WNW	26.0 - 44.2 (35.3)	44° 36.786’ / 123° 39.631’
3	453	ESE to WSW	23.1 - 42.6 (34.0)	45° 01.059’ / 122° 30.064’
4	294	ENE to WNW	24.7 - 36.5 (30.5)	44° 39.963’ / 122° 44.964’
5	642	WSW to WNW	26.3 - 41.8 (35.6)	45° 23.929’ / 122° 00.951’
6	681	ENE to WNW	22.4 - 41.9 (32.2)	45° 24.018’ / 122° 02.784’
7	996	ENE to WNW	20.2 - 36.6 (29.2)	44° 32.476’ / 122° 32.400’
8	870	ENE to ESE	27.4 - 43.0 (36.7)	45° 31.030’ / 123° 23.908’
9	546	ENE to WNW	34.1 - 54.0 (47.1)	45° 36.018’ / 123° 23.512’
10	864	WSW to WNW	26.3 - 34.4 (31.0)	45° 33.749’ / 123° 26.638’
11	864	ESE to WSW	24.0 - 42.2 (34.4)	45° 16.754’ / 123° 36.079’
12	360	ESE to WSW	28.5 - 43.1 (34.4)	45° 17.475’ / 123° 34.935’
13	600	ESE to WSW	27.1 - 41.8 (33.6)	44° 15.796’ / 123° 35.014’
14	705	ESE to WSW	24.0 - 38.9 (32.9)	44° 14.416’ / 122° 12.935’
15	705	ESE to WSW	21.8 - 38.8 (30.6)	44° 13.193’ / 122° 14.804’
16	375	ENE to WNW	26.1 - 34.8 (30.2)	44° 43.996’ / 122° 25.857’
17	510	ENE to WNW	23.8 - 41.0 (31.5)	44° 47.123’ / 123° 28.449’

*ENE: East-Northeast, WNW: West-Northwest, ESE: East-Southeast, WSW: West-Southwest. ** Average dbh in parenthesis.

After felling, disks approximately 100 mm thick were cut at regular intervals up each stem: at 0, 5, 10, and 20 meters above the base of the tree. The disks were labeled, placed in large bags, and stored in a cold room until they were ready to be used for the wood density determination. Close to 400 disks were collected.

2.3.2 Wood density

Two wood samples (about 5 cm wide) were randomly cut from each disk at about 4-5 cm from the outer edge and immediately placed in a cold store with an identification tag. The samples were later dried in an oven at 103 degrees C until their weight stabilized (24 to 72 hours). The volume of each of the samples was then measured using a water displacement method. Relative wood density (specific gravity) was then calculated as the ratio dry wood weight to dry volume (Hughes 1967). Data on the pith to bark density of each disk was not obtained.

2.3.3 Spiral grain angle

Each disk was cut in half and a radial line marked perpendicular to the pith. Two rings (spirals) on each side of the pith were selected; one approximately 6 cm from the outer edge and the other 5 cm from the pith. At each of the selected rings a line perpendicular to the radial line was drawn. The deviation between this perpendicular line and the direction of the spiral was taken with a protractor to obtain the spiral grain angle (for more details see Hannrup et al, 2002). An average spiral grain angle was calculated for each disk.

Two measurements of over bark diameter were made along the longest and shortest axes and averaged. In addition, measurements were made of the average diameter without bark, and the average diameter of the heart wood (recognized by a color change in the disk); these were not used in the analyses for this paper.

2.3.4 Data analysis

Statistical analysis of the data was undertaken following a stepwise multiple regression analysis methodology proposed by Ramsey and Schafer (2003). Briefly, it included graphical analysis of the data to determine if transformations were needed, examination of the correlation matrix, fitting of the model, exploration of the residuals, checking to see if the variable added at each step was significant, and improvement of the final model. The statistical software S+ ® v. 6.0 was used for the analysis. A p-value of 0.05 was used to determine if an explanatory variable was significant and should be included in the model.

Three models were explored, one for spiral grain and two for the density. One of the density models assumed that no prior information was known about density lower down in the tree. The other assumed that a density measurement for the base of the tree was available. The potential explanatory variables included HEIGHT, the height along the tree where the disks were collected from (0 m , 5 m, 10 m or 20 m above the base), AVOB, the average diameter of each disk including the bark (mm), ASPECT, the aspect of the trees where the sample came from (1 for ENE to WNW, 2 for ENE to

ESE, 3 for ESE to WSW, and 4 for WSW to WNW), and ELEV, the elevation of the site where the samples were selected from, and DENSITY_0, the density at 0 meters above the base.

2.4 RESULTS AND DISCUSSION

2.4.1 Density

Relative density for all samples had a mean value of 0.404 gr/cm^3 with a standard deviation of 0.041. The mean, 0.45 gr/cm^3 is lower than is usually quoted for Douglas-fir. A higher value would have been reported if the relative density had been weighted by the square of the diameter at which the sample was taken, an indicator of the volume at that point in the tree.

Examination of the scatter plots indicated that the regression assumptions of normality and specially the homogeneous variance and linearity were not met for the response variable DENSITY and the explanatory variables ELEV and AVOB. Log transformations of these variables were made before fitting the model. Variables HEIGHT and ASPECT were not transformed because they were nominal ones and because of their pattern observed in the scatter plots.

Potential outliers in the data were tested using Cook's distances and found to not be influential. Therefore, all data points were used in developing the regression models.

The matrix of correlations among variables is presented in Table 2.2. The log transformed DENSITY (*ldensity*) response variable had mild correlations with HEIGHT (-0.508) and log transformed AVOB (*lavob*) (0.423). As expected, however, there was a strong correlation between *lavob* and HEIGHT (-0.847).

Table 2.2 - Matrix of correlations among the variables considered in the study

	Height	Aspect	Lavob	lavspgr	Lelev	ldensity
Height	1.000					
Aspect	0.034	1.000				
lavob	-0.847	-0.024	1.000			
lavspgr	-0.087	0.105	0.110	1.000		
lelev	-0.043	0.409	-0.008	0.069	1.000	
ldensity	-0.508	0.036	0.423	0.140	0.009	1.000

When a regression model was fitted using HEIGHT, ASPECT, *lavob*, and *lelev* as the explanatory variables and *ldensity* as the response variable, only HEIGHT was significant ($p = 0.000$).

Not finding elevation as a significant explanatory variable for Douglas-fir density runs counter to the results of the surveys by Knigge (1962) and Anon (1965). However, the later survey, in particular, found that only accounted for 6% of the variation in density even though the survey covered an elevational range that was three times that of this study. A drop in density of 0.01 was found for each 300 m increase in elevation. Not finding aspect as a significant explanatory variable for density just adds to the already conflicting literature on this topic. We recognize that the samples collected from different aspects did not constitute a balanced design. This makes drawing conclusions on the effect of aspect on density difficult.

The simple regression model with HEIGHT as the explanatory variable accounted for only 25.9% of the variance in *ldensity*. A very simple model (not log-transformed) was fitted and considered the definitive one. The results of this fit are presented in Table 2.3 and shown in the equation below. A box plot chart showing the average and range values in density obtained for the heights along the tree can be observed in Figure 2.1.

Table 2.3 - Results for the regression between DENSITY and the explanatory variable HEIGHT.

Coefficients:	*Value*	*Standard Error*	*t value*	*Pr (>|t|)*
Intercept	0.4271	0.0027	161.0893	0.0000
Height	-0.0033	0.0003	-11.6442	0.0000

Residual standard error: 0.03533 on 390 degrees of freedom

Multiple R-squared: 0.258

F-statistic: 135.6 on 1 and 390 degrees of freedom, the p-value is 0

DENSITY = 0.427 - 0.0033*HEIGHT

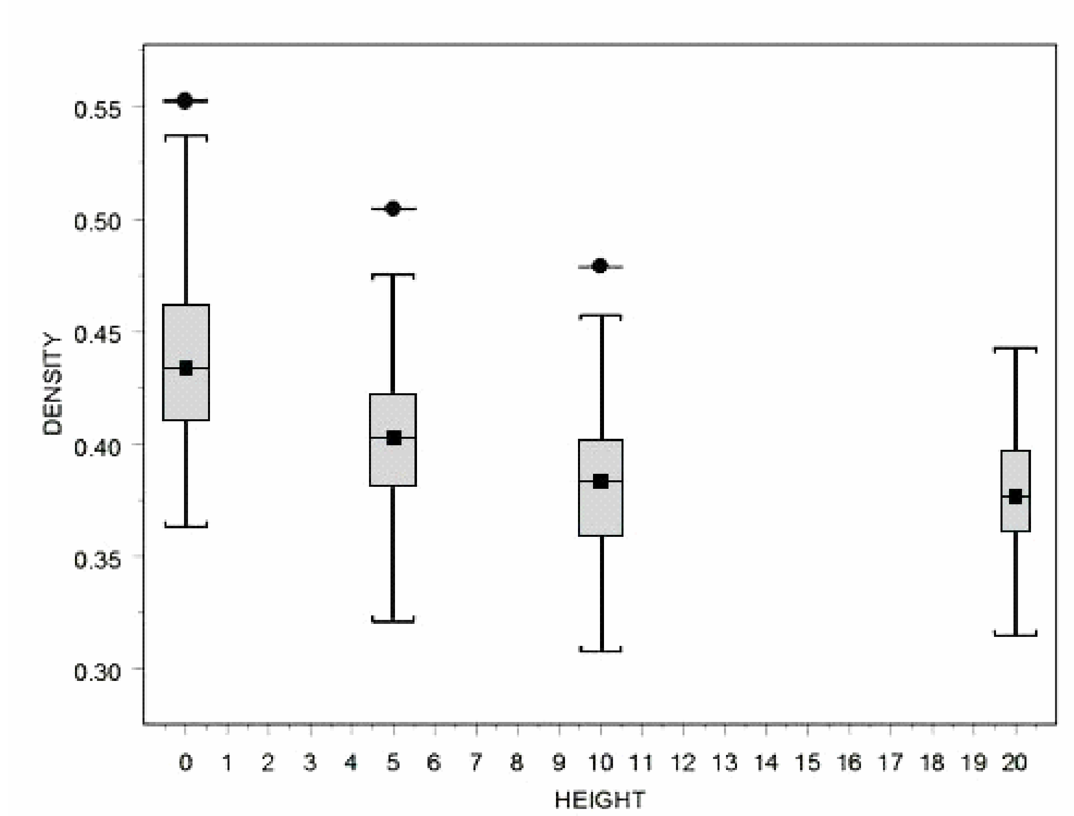

Figure 2.1 - Box-plot chart for the variables DENSITY and HEIGHT.

From Figure 2.1, it is clear that there are differences in average relative density among the four heights evaluated (0.44 gr/cm^3 at 0 meters, 0.40 gr/cm^3 at 5 meters, 0.38 gr/cm^3 at 10 meters, and 0.37 gr/cm^3 at 20 meters above the base). However it is also clear that the relative density ranges significantly for each height. The minimum and maximum values of relative density are 0.36 gr/cm^3 and 0.55 gr/cm^3 at 0 meter, 0.32 gr/cm^3 and

0.50 gr/cm^3 at 5 meters, 0.30 gr/cm^3 and 0.48 gr/cm^3 at 10 meters, and 0.31 gr/cm^3 and 0.44 gr/cm^3 at 20 meters.

The clear, albeit weak, trend of wood density decreasing from the base to the top sections of the tree has been observed in other studies of Douglas-fir (e.g. Megraw 1986a; Gartner *et al*. 2002) and for other species (e.g. for western hemlock (Jozsa *et al*. 1998) and for radiata pine (Donaldson *et al*. 1995)).

When regressions models were fitted between the basic density at 0 meters (response variables) and basic density at 5 meters and 10 meters (explanatory variables), the multiple R-squared values were 0.40 and 0.35, respectively. Although the explanatory variables are statistically significant in these models, they have limited predictive capability.

2.4.2 Spiral grain

The mean and standard deviation for spiral grain angle for the wood disks was found to be 3.1 and 2.4 degrees respectively. This is similar to the spiral grain angle shown for Douglas-fir by Northcott (1957). Regression analysis indicated that there was no statistically significant relationship between this variable and any of the explanatory variables. A model containing all four explanatory variables, HEIGHT, ASPECT, elevation and over bark diameter, accounted for less than 3% of the variation in spiral grain angle.

Finding that spiral grain angle is not affected by elevation, aspect, or height in the tree adds to the already conflicting evidence on factors affecting this wood property, although little of the evidence relates specifically to Douglas-fir.

2.5 CONCLUSIONS

The objective of this study was to determine if site and intra tree characteristics could be used to accurately predict density and spiral grain in second growth Douglas-fir stands in Oregon. Neither wood property was related to elevation or aspect. Density was weakly related to height in the tree. Having a measure of density low down in the tree would slightly improve the predictive capability for density higher up the tree.

If density and spiral grain wood properties are to be optimally matched to markets, it is likely that tools will need to be developed to measure these properties in the forest in real time for individual logs.

2.6 REFERENCES

ANONYMOUS. 1965. Western wood density survey. Report Number 1. USDA Forest Research Paper FPL-27. 58pp.

CHAMPION, H.G. 1925. Contributions towards a knowledge of twisted fibre in trees. Indian Forestry Record (Silv. Ser.) 11 (part II): 11-80.

CLARKE, C.R.; BARNES R.D.; MORRIS A.R. 2002. Effect of environment on wood density and pulping of five pine species grown in Southern Africa. Paper presented at the 2002 Technical Association of the Pulp and Paper Industry of Southern Africa Conference, Durban, October 2002. (http://tappsa.co.za/archive/APPW2002/Title/Effect_of_environment_on_wood_/effect_of_environment_on_wood_.html, Accessed February 2005).

COWN, D.J.; MCCONCHIE, D.L.; YOUNG, G.D. 1991. Radiata pine wood properties survey. New Zealand Forest Research Institute Bulletin No. 50. 50pp.

COWN, D.J.; YOUNG, G.D.; BURDON, R.D. 1992. Variation in wood characteristics of 20 year old half-sib families of Radiata pine. *New Zealand J. For. Sci*. 22(1):63-76.

DONALDSON, L.A.; EVANS, R.; COWN, D.J.; LAUSBERG, M.J. 1995. Clonal variation of wood density variables in Pinus radiata. *New Zealand J. For. Sci.* 25(2):175-188.

DILUCCA, C.M. 1989. Juvenile–mature wood transition. *In* Second growth Douglas-fir: its management and conversion for value: a report of the Douglas-fir task force. *Edited by* R.M. Kellogg. Forintek Canada Corp., Vancouver, B.C. pp. 23–38.

FOREST PRODUCTS LABORATORY. 1999. Wood handbook: wood as an engineering material. Forest Products Laboratory, Forest Products Society, Madison, Wis.

GARTNER, B.L.; NORTH, M.N.; JOHNSON, G.R.; SINGLETON. R. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. *Can. J. For. Res.* 32: 439-447.

HANNRUP B.; GRABNER, M.; KARLSSON, B.; MÜLLER, U.; ROSNER, S.; WILHELMSSON, L.; WIMMER,R. 2002. Genetic parameters for spiral-grain angle in two 19-year-old clonal Norway spruce trials. *Ann. of For. Sci.* 59 (2002) 551–556.

HANNRUP, B.; CAHALAN, C.; CHANTRE, G.; GRABNER, M.; KARLSSON, B.; LE BAYON, I.; LLYOD JONES, G.; MULLER, U.; PEREIRA, H.; RODRIGUES, J.; ROSNER, S.; ROZENBERG, P.; WILHELMSSON, L.; WIMMER, R. 2004. Genetic parameters of growth and wood quality traits in Picea abies. *Scandinavian J. For. Res.* 19(1):14-29.

HARDING, K.J.; COPLEY, T.R. 2000. Wood property variation in Queensland grown Slash X Caribbean pine hybrids. In: "Hybrid breeding and genetics of forest trees." Proceedings of QFRI/CRC-SPF Symposium, April 2000, Noosa, Queensland, Australia. (Compiled by Dungey, H.S., M.J. Dieters, and D.G. Nikles). Department of Primary Industries, Brisbane. Pages 160-167.

HARRIS, J.M. 1989. Spiral Grain and Wave Phenomena in Wood Formation. Springer-Verlag, Berlin. 214p.

HUGHES, J.F. 1967. Density as an index of wood quality with special reference to the development of rapid and efficient methods of estimating density. In: Proceedings of the Tropical Forestry Meeting by Commonwealth Forestry Institution. Oxford. pp. 1-4.

JOZSA, L.A.; KELLOGG, R.M. 1986. An exploratory study of the density and annual ring width trends in fast-growth coniferous wood in British Columbia. CFS Contract Report No. 02-80-55-017. Forintek Canada Corp., Vancouver, BC. 43 pp

JOZSA, L.A.; RICHARDS, J.; JOHNSON, S.G. 1989. Relative density. *In* Second growth Douglas-fir: its management and conversion for value: a report of the Douglas-fir task force. *Edited by* R.M. Kellogg. Forintek Canada Corp., Vancouver, B.C. pp. 5–22.

JOZSA, L.A.; MUNRO, B.D.; GORDON, J.R. 1998. Basic wood properties of second-growth Western Hemlock. Forintek Canada Corp. Special Publication No. SP-38. 51pp.

JOZSA, L.A.; MIDDLETON, G.R. 2004. Discussion of wood quality attributes and their practical implications. Web page: http://www.lumber.com/products/pro_01130.asp (Accessed June 2005).

KENNEDY, R.W. 1995. Coniferous wood quality in the future: concerns and strategies. *Wood Sci. Technol.* 29: 321–338.

KINDSETH, P. (n.d.) Solvinn og rangvinn Skog. (Abstracted in Intern. Review Agri. 19(3):310).

KNIGGE, W. 1962. Untersuchungen uber die Abhagigkeit der mittleren Rohdichte nordamerikanische Douglasienstamme von untershiedlichen Wuchsbedingungen. *Holz als Roh- und Werkstoff* 20:352-360.

MEGRAW, R.A. 1986a. Douglas-fir wood properties. *In* Proceedings, Douglas-fir: Stand Management for the Future. *Edited by* C.D.O Oliver, D.P. Hanley, and J.A. Johnson. Institute of Forest Resources, University of Washington, Seattle, Wash. Contrib. 55. pp. 81–96.

MEGRAW, R.A. 1986b. Effect of silvicultural practices on wood quality. *In* Proceedings: TAPPI R&D Conference, 29 Sept. 1986, Raleigh, N.C. Technical Association of the Pulp and Paper Industry, Atlanta, Ga. pp. 27–34.

NORTHCOTT, P.L. 1957. Is spiral grain the normal growth pattern? *For. Chron.* 33(4): 335-351.

NOSKOWIAK, A.F. 1963. Spiral grain in trees – a review. *For. Prod. J.* 13(7):266-275.

O'SULLIVAN, P. 1976. The influence of initial espacement and thinning regime upon wood density in Sitka spruce (Picea sitchcensis [Bong] Carr.). M.Agr.Sci. thesis, University College, Dublin.

POLGE, H. 1969. [Density of planting and pruning of live brnahces, or why, when and how to prune.] RFF 21 Special “Silviculture” 31:451-462.

RAMSEY, F.L.; SHAFER, D.W. 2002. The statistical sleuth: a course in methods of data analysis. Duxbury Press. Second Edition. 742 pp.

RAULT, J.P.; MARSH, E.K. 1952. The incidence and silvicultural implications of spiral grain in *Pinus longifolia* Roxb. in South Africa and its effect on converted timber. South African Forest Products Institute, Pretoria West.

SMYTHIES, E.A. 1915. Notes on the twisted fibre in chir pine. *Indian Forester* 41(3):69-75.

TESSIER DU CROS, E.; KLEINSCHMIT, J.; AZOEUF, P.; HOSLIN, R. 1980. Spiral grain in beech, variability and heredity. *Silvae Genetica* 29:5-13.

TROUP, R.S. 1921. The Silviculture of Indian Trees. Oxford Press, London. Pp 1056-61.

WAHLGREN, H.E.; BAKER, G.; MAEGLIN, R.R.; HART, A.C. 1968. Survey of specific gravity of eight Maine conifers. USDA Forest Service, Research Paper FPL-95. 11p.

WALKER, J.C.; BUTERFIELD, B.G.; LANGRISH, T.A.; HARRIS, J.M.; UPRICHARD, J.M. 1993. Primary Wood Processing. Chapman and Hall, London. 595 pp.

WARD, D. 1975. The influence of tree spacing upon tracheid length and density density in Sitka spruce (Picea sitchcensis [Bong] Carr.). M.Agr.Sci. thesis, University College, Dublin.

WELLNER, C.A. 1955. Summaries of results from studies of western larch poles. Inland Empire Research Center. Intermountain Forest Range Experiment Station. Report prepared for Cooperators, Jan. 25.

WILHEMSSON, L. 2001. Characterisation of wood properties for improved utilisation of Norway Spruce and Scots Pine. Doctor's dissertation. Department of Forest Management and Products Uppsala. Swedish University of Agricultural Sciences.

YANG, J-C.; CHIU, C-M; LIN, T-P; KUNG, F-H. 2001. No clinal variation in Cunninghamia lanceolata wood density sampled from thirteen Chinese provinces. *Taiwan J. For. Sci.* 16(2):65-80.

ZOBEL, B.J.; VAN BUIJTENEN, J.P. 1989. Wood variation, its causes and control. Springer, New York. 363 pp.

ZOBEL, B.J.; JETT, J.B. 1995. Genetics of wood production. Springer-Verlag, Berlin. 337 pp.

CHAPTER 3

USE OF NEAR INFRARED SPECTROSCOPY AND MULTIVARIATE ANALYSIS TO PREDICT WOOD DENSITY OF DOUGLAS-FIR FROM CHAIN SAW CHIPS

Mauricio Acuna and Glen Murphy

Department of Forest Engineering

Oregon State University

Corvallis, OR 97331-5706

USA

Forest Products Journal (in review)

Forest Product Society

2801 Marshall Court

Madison WI 53705-2295

USA

3.1 ABSTRACT

In many parts of the world log markets are becoming increasingly competitive and complex. Wood properties, such as stiffness, density, spiral grain, and extractives content, are now being considered by log buyers. Assessing these properties in real-time will be a challenge for log supply managers. The utility of near infrared (NIR) technology for predicting wood density in Douglas fir stems was examined. Wood disks were collected from 17 sites around Oregon. Each disk was cut with a chain saw, of similar gauge to that used on mechanized harvesters/processors, to provide saw chips. Near infrared spectra were then obtained for the chip samples. Multivariate techniques were used to correlate wood properties with the NIR spectra. The preliminary research results showed that NIR could be used to predict density. Coefficient of determinations ranged between 0.80 and 0.96 for calibration models, and between 0.56 and 0.85 for validation models. These results indicate that NIR technology could be used by mechanized harvesting equipment (e.g. harvesters) for log segregation based on wood density.

Keywords: near infrared spectroscopy, log segregation, sensors, forest harvesting

3.2 INTRODUCTION

Douglas-fir (*Psudotsuga menziesii* (Mirb.) Franco) is of considerable economic importance, especially for the forest products industries of the United States, Canada, New Zealand, and some parts of Europe (Acuna and Murphy 2006; Gartner *et al*. 2002). It is expected that international and U.S. wood product markets, especially high-quality structural lumber markets, will continue demanding Douglas-fir logs (Barbour and Kellogg 1990; McKeever 2000; Schuler and Craig 2003). In many parts of the world log markets are becoming increasingly competitive and complex. Where at one time tree dimensions and external quality characteristics (such as branch size, sweep, and scarring) may have been sufficient to specify a log-sort, consideration is now being given to specifying such wood properties as density, stiffness, spiral grain, and extractives content (Andrews 2002; So *et al*. 2002; Young 2002).

There are a number of wood properties which affect the quality of final products. Of these, wood density is considered by some to be the single most important physical characteristic because it is an excellent predictor of strength, stiffness, hardness, and paper-making capacities (Megraw 1986; Kennedy 1995). Accurately assessing density in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on density. Variables such as stand age and height within a tree have been used in the past as substitutes for accurate measurements of density.

Worldwide there is a trend towards increased mechanization of forest harvesting operations. This has come about for a number of reasons; to reduce the impacts of smaller trees on productivity and costs, to improve worker safety, to reduce environmental impacts and to overcome the difficulties some regions face in attracting labor to work in their forests. Mechanized harvesting machines are frequently fitted with computer technology and rudimentary sensor systems for measuring external stem dimensions – usually diameters over bark along the stem and stem length. Research into technologies for measuring stem quality attributes is progressing on a number of fronts with varying levels of success; e.g. acoustics, optical and laser scanning, x-ray, microwave, ultrasound and near infrared (NIR) spectroscopy (Tian 1999; So *et al.* 2002; Carter *et al.* 2004). Some of these scanning technologies could be integrated into the design of mechanized harvesting systems. Measuring wood properties of logs in real time should lead to improved log allocation decisions early in the supply chain, improved value recovery for the forest owner, and optimal matching of wood to markets.

One of the most promising technologies for material assessment is NIR spectroscopy. Its benefits and future trends were recognized by So *et al*. (2004) who commented that: "*the rapid assessment of solid wood properties using NIR spectra is a fast-growing field that has broad implications in relation to wood quality and ultimately, tree improvement…It is probable that this type of monitoring will lead to increases in efficiency and profits*".

NIR spectra only relate to wood properties up to a few millimeters of depth into the sample. Measurement of wood properties deep within a stem would require internal samples of the wood to be obtained. Chain saw chips, generated as a stem is cut up into logs by a harvester or processor, are a sample of wood through the stem. This leads to the question, “will chain saw chips, and in particular green chain saw chips, be a suitable sample for predicting wood density based on NIR measurements”?

3.3 LITERATURE REVIEW

NIR spectroscopy is a long-established and now mature technology (Dryden 2003). The NIR region was first discovered in 1800 in an attempt to measure the heat energy of solar emission beyond the red portion of the visible spectrum (Hindle 2001). However, it was not until a paper was published by Norris and Hart in 1965 (Givens *et al*. 1997), recognizing the power of multivariate analysis for extracting quantitative information from complex NIR spectra (Tigabu 2003), that many studies of NIR spectroscopy began to be reported.

NIR spectroscopy works on the principle of electromagnetic radiation with matter, which can take several different forms (Davies 2005). When any solid material is illuminated with monochromatic radiation emitted by an NIR instrument, the incident radiation will be reflected by the outer surface (known as specular reflectance), traverse deep into the inner tissue of the sample and be reflected back (diffuse reflectance), pass all the way through the sample (transmittance), be absorbed completely (absorption), or be lost as internal refraction and scattering. If a sample absorbs none of the incident energy, total reflection occurs. In NIR spectroscopy, we are interested in the diffuse reflectance and transmittance, although the former includes the specular component (Tigabu 2003). For practical reasons, diffuse reflectance (R) is converted to absorbance according to the formula: $A = \log (1/R)$ (Workman 2001).

The NIR region extends from 780 to 2500 nm in which the spectra may be characterized by the assignment of the absorption bands to overtones and combinations of fundamental vibrations associated with C-H, O-H, and N-H bonds (So *et al*. 2004). The signals from these vibrations are similar, with resultant spectra consisting of many broad and overlapping bands. This feature of the spectra makes the interpretation of NIR spectra difficult.

Early work with NIR focused on the agricultural and food industries, and remote sensing applications. More recent work has expanded the use of NIR for applications of interest to the forest and forest products industries (Kelley *et al*. 2004b). Initial applications of NIR to forestry focused on forest health and chemical analysis of leaves and needles (McLellan *et al*. 1991; Martin and Aber 1994). These sources reported that NIR could be used to accurately estimate chemical elements of dried leaves and needles. Several different multivariate techniques (multiple linear regression (MLR), partial least squares (PLS) and principal component analysis (PCA)) were used, with very high correlations (>0.90) between NIR spectra and nitrogen content, cellulose, lignin content. Recent studies in forest science have focused on the characterization of forest tree seed quality with NIR spectroscopy and in the use of NIR spectroscopy for the detection of internal insect infestation in seed lots (Tigabu *et al*. 2004).

NIR has also been used to measure wood properties affecting a wide range of forest products. Wright *et al*. (1990) used NIR to predict cellulose content of pulps and pulp yield. Michell (1995) showed that NIR could be used to measure pulp yield, lignin content, and hot water and alkaline extractable compounds. Sefara *et al*. (2000) evaluated three different sampling methods, namely wedges, chips and sawdust and showed that good correlations ($R^2 > 0.80$) were found between NIR spectra and screened pulp yields for all three sampling methods. Terdwongworakul *et al*. (2005) used NIR with both MLR and PLS analysis procedures to develop calibration equations for total pulp yield, screened pulp yield, and content of α-cellulose, pentosans, and lignin in wood.

Many studies can be found in the literature on the prediction of physical (density, microfibril angle, tracheid length), mechanical (MOR, MOE), and chemical (glucose, lignin and extractives content) wood properties from NIR spectra for a range of softwood and hardwood species (Schimleck *et al*. 2001; Schimleck *et al*. 2002; Bailleres *et al*. 2002; Kludt 2003; Schimleck *et al*. 2003; Schimleck and Yazaki 2003; Kelley *et al*. 2004a; Kelley *et al*. 2004b; Schimleck *et al*. 2004; Via 2004; Jones *et al*.

2005). Good correlations, R^2 values ranging from 0.79 to 0.96, have been reported. NIR measurements have been made on a range of samples types, including green and dry solid wood, green and dry auger shavings, and dry powdered wood. It has also been shown that mechanical properties could be predicted using a reduced spectral range (650 nm-1500 nm) with only a small degrade in predictive ability (Kelley *et al*. 2004b).

A number of studies have dealt with the modeling of density from NIR spectra, but none with Douglas-fir. Thygesen (1994) used NIR spectra, from auger shavings and solid wood of Norway spruce (*Picea abies* (L.) Karst.), to predict basic density. Calibration models had relative errors from 3 to 8%, with R^2 values ranging from 0.71 to 0.89. Schimleck *et al*. (1999) found that the basic densities of woods from plantation-grown 8-year-old *Eucalyptus globulus* Labill. subsp. globulus (Tasmanian blue gum) ranging from 378 to 656 kg m^{-3} could be determined with an accuracy of prediction of ca. ±30 kg m^{-3}. Via *et al*. (2003) used NIR to predict the density of mature and juvenile longleaf pine (*Pinus palustris*). They found that, for density prediction, the area under the spectral curve appeared to be insensitive to mature and juvenile wood differences.

The NIR spectroscopy with its lower cost instrumentation and rapid spectra collection (with little or no sample preparation), is ideally suited for quantitative analysis (So *et al*. 2004). However, without the help of multivariate analysis, the chemical information from a NIR spectrum becomes limited. Two of the most common multivariate techniques used with NIR spectra are PLS and PCA. PLS is a technique that generalizes and combines features from PCA and multiple regression analysis. Detailed descriptions of these analysis techniques can be found in such papers as Tobias (1995), Antii (1999), Reeves and Delwiche (2003), and Abdi (2003).

3.4 STUDY OBJECTIVES

The objectives of the research reported in this paper were to determine whether NIR spectroscopy could be used to accurately predict Douglas-fir wood density based on three types of samples – green chain saw chips, dry rough chain saw chips, and dry ground chain saw chips.

3.5 METHODS

3.5.1 Sites and trees selected

In mid-2003, 119 trees were felled at 17 forest sites located in the Coast Range and the Cascade Range of Oregon. The latitude and longitude of the sites ranged from 44^{o} 13' to 45^{o} 36' and from 122^{o} 00' to 123^{o} 35', respectively. The sites were chosen to cover a range of elevations (217 to 996 m) and aspects. Approximately 7 trees were felled at each site and these were selected to cover the range of diameters present. All stands contained second growth Douglas-fir and were of similar age class (45-60 years). The characteristics of each site under study are shown in Acuna and Murphy (2006).

After felling, disks approximately 100 mm thick were cut at regular intervals along each stem: at 0, 1.4, 5, 10, 20, and 30 meters from the base of the tree. The disks were labeled, placed in large bags, and stored in a cold room until they were ready to be used for the wood density determination. Close to 500 disks were collected.

3.5.2 Sample preparation for NIR spectroscopy

From the total number of disks collected, about 150 of them were used for NIR spectra measurements. Bark was removed from the edge of each disk. Each disk was then cut with a chain saw, of similar gauge to that used on mechanized harvesters/processors, to provide saw chip samples. Chip samples were collected between 5 and 10 cm from the outer edge of each disk. Samples were divided into three groups: green (100 samples), dry rough (47 samples) and dry ground (50 samples). Chips of the green group were processed just after being collected in the field and were taken from 100 randomly selected wood disks that came from various sites and heights above the base of the tree. Chips from the two dry groups came from 50 randomly selected breast height (1.4 m) disks which had been previously oven-dried. Approximately half of the dry rough chips were then ground into fine powder with a Wiley mill. Samples from the dry ground group were cleaned and their impurities removed.

3.5.3 Near-infrared measurements

NIR measurements were spread over a period of two years and involved the use of two pieces of equipment; an ASD Field Spec and a NIRSystems 6500.

The NIR measurements for samples in the green and dry rough groups were taken with an Analytical Spectral Devices (ASD) Field Spec (product specifications in www.asdi.com) at wavelengths between 400 nm and 2500 nm using the default parameters. This device uses a fiber optic probe oriented at a right angle to the sample surface to collect the reflectance. The chip samples thickly covered the bottom of a petri dish which was placed on top of a slowly rotating turntable. The samples were illuminated with a DC lamp oriented at 30 degrees above the samples. Thirty scans were collected and averaged into a single average spectrum. Two spectra were taken from each chip sample, which were averaged to have a single spectrum for each sample. The reflectance spectra were transferred from the ASD to an Unscrambler® file and converted to absorbance spectra. The spectra collected on each sample were averaged to provide a single spectrum that was used to predict the density of the sample. The next step was to reduce the averaging spectra that were collected at 1 nm intervals, to a spectral data set at 5 nm intervals. According to Kelley *et al.* (2004a), averaging the spectral data reduces the size of the spectra matrix and significantly reduces the time required to compute the multivariate models without decreasing the quality of the models.

The NIR measurements for samples in the dry ground group were taken with a Foss NIRSystems Model 6500 at wavelengths between 400 nm and 2500 nm using the default parameters. The powder from the dry ground samples was placed in a standard static ring cup with a sample area of approximately 11 cm^2. The detectors were sited at a 45 degree angle to the incident light. Thirty-two scans were collected and averaged into a single average spectrum. The reflectance spectra were converted to absorbance spectra. The spectra, collected at 2 nm intervals on each sample, were used to predict the density of the sample.

3.5.4 Wood density measurement

Two slightly different procedures were followed for preparing samples for solid wood density measurements. The disks from which dry chip and dry ground chip samples were taken were first oven dried. Two solid wood samples (about 5 cm wide) were then randomly cut from each disk at about 4-5 cm from the outer edge. The volume of each of the samples was then measured using a water displacement method. Relative wood density (specific gravity) was then calculated as the ratio of dry wood weight to dry volume (Hughes 1967).

The alternate procedure, used with the disks from which green chip samples were taken, also involved cutting two solid wood samples 4-5 cm from the outer edge. These green solid wood samples were immediately placed in a cold store with an identification tag. The samples were later dried in an oven at 103 degrees C until their weight stabilized (24 to 72 hours). The volume and weight of each sample was then measured and relative wood density calculated. Data on the pith to bark density of each disk was not obtained.

3.5.5 Multivariate analysis of NIR spectra: Partial Least Square (PLS) analysis

The data set was divided into calibration sets for developing discriminant models and prediction sets for evaluating the classification performance of the computed models. The characteristics of the samples in each group, as well as the absorption bands used in the analysis were as follows:

- Green group: Calibration set (65 samples), Prediction set (35 samples), absorption band [502-2500], number of data points (401, every 5 nm of the spectra).
- Dry rough group: Calibration set (24 samples), Prediction set (23 samples), absorption band [355-2495], number of data points (429, every 5 nm of the spectra).
- Dry ground group: Calibration set (25 samples), Prediction set (25 samples), absorption band [400-2500], number of data points (1050, every 2 nm of the spectra).

Chemometric analysis of the spectroscopic data was made through the use of the SAS® partial least squares (PLS) software. As implemented, SAS® (version 9.1) can perform PLS regression type II only (Reeves and Delwiche 2003). While possessing several algorithms for PSLR analysis or for cross-validation and various options for determining the number of factors to use, SAS® does not possess any other spectral pretreatments routinely used in spectroscopy. A number of programs have been written using SAS® macro language to implement 1st and 2nd gap derivatives, Savitzky-Golay derivatives and smoothing, the ability to skip or average spectral data points, to correct spectra for scatter correction by either multiplicative scatter correction or standard normal variate correction with or without detrend, and finally, to mean centre all data prior to regression analysis. Despite the above and other preprocessing techniques such as orthogonal projections to latent structures, that can be used to improve the quality of the PLS models (Reeves and Delwiche 2003), very often they greatly complicate the ability to provide interpretation of the regression coefficients (Kelley *et al.* 2004a) or provide little to no improvement in predictions (Kludt 2003). Therefore, in this study no preprocessing techniques were used.

Following the recommendation given by Shao (2003), PLS regression was used to develop the calibrations with a cross validation method where every nine or ten observations were excluded. The test statistic used for the model comparison was PRESS, the predicted residual sum of squares. For the three groups analyzed, the cross-validation procedure indicated zero factors as the number to be used. Very little of the dependent variable and model effects would have been explained if this was done. For this reason, a series of analyses, using from one up to fifteen factors, was carried out. As we were primarily concerned with the prediction ability of the regression model, the number of factors that produced the highest coefficient of determination (R^2) in the prediction set was used and reported in this paper. A calibration model can have a very high coefficient of determination due to overfitting with a high number of latent variables. This can lead to a poor performance of prediction when the model is used with the prediction set.

The quality of the models in the calibration and prediction sets was measured with two common measures, R^2 and SEC (SEP for prediction set) (Martens and Naes 1991). The R^2 value is a measure of the variation of the response variable (wood density) explained by the regression model. For a heterogeneous material such as wood, R^2 values of 0.75 and above are considered good (Kelly *et al*. 2004a). Likewise, the SEC is the standard error of calibration, a measure of the prediction error expressed in the units of the original measurement (Workman 2001; Kludt 2003). This is given by the following equation:

[1] $$\mathrm{SEC} = \sqrt{\frac{\sum_{i=1}^{SC}(\hat{y}_i - y_i)^2}{(SC - n - 1)}}$$

where $\hat{y}_i$ is the value of the wood property of interest for validation of sample i estimated using the calibration, y_i is the known value of the wood property for sample i (wood density), SC is the number of samples used to develop the calibration model, and n is the number of factors used to develop the calibration model.

On the other hand, the measure of how well the calibration predicts the wood property of interest for a set of unknown samples that are different from the calibration test set is given by the standard error of prediction (SEP):

$$[2] \qquad SEP = \sqrt{\frac{\sum_{i=1}^{SP}(\hat{y}_i - y_i)^2}{(SP-1)}}$$

where $\hat{y}_i$ is the value of the wood property of interest for sample i predicted by the calibration, y_i is the known value of the wood property for sample i (wood density), and SP is the number of samples in the prediction set.

3.5.6 Multivariate analysis of NIR spectra: Principal Component Analysis (PCA)

The main purpose of this paper was to apply the PLS methodology to predict the wood density from near infrared spectra. As noted above, both PLS and PCA multivariate analysis techniques have been used to develop predictive models based on NIR spectra. Just as a way of comparing the results obtained by different multivariate procedures, PCA was applied to the same data sets (calibration and prediction) as those used for the PLS procedure.

PCA involves a mathematical procedure that transforms a set of correlated variables into a smaller number of uncorrelated variables called principal components (or latent variables), orthogonal to each other (So *et al*. 2004). However, components are chosen to explain X (explanatory variables) rather than Y (response variables), and so, nothing guarantees that the principal components, which "explain" X, are relevant for Y (Abdi 2003).

Analysis was carried out with the software S+® (version 6.1). This statistical package can be used to calculate components for a current data set (calibration set) or predict them for a new data set (prediction set). In both cases a multiple linear regression was performed between the principal components and wood density. Thus, the number of principal components reported is that which produces a similar or close coefficient of determination, R^2, in the prediction set to that obtained by PLS.

3.6 RESULTS

3.6.1 Wood density

Table 3.1 gives a statistical summary of wood density for the calibration and prediction data sets for the three sample types – green, dry rough, and dry ground chain saw chips.

Table 3.1 - Range and standard deviation (SD) of wood density (kg m^{-3}) by sample type, for calibration and prediction data sets.

Sample Type	Calibration set				Prediction set			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Green chain saw chip	315	489	399	41.7	335	509	414	43.8
Dry rough chip	371	490	433	29.8	359	509	441	40.4
Dry ground chip	381	476	436	26.5	359	499	432	40.3

The minimum density for the calibration set corresponded to the green group (315 kg m^{-3}), while the maximum density was associated to the dry rough group (490 kg m^{-3}), which is very close to that of the green group (489 kg m^{-3}). Averages densities were higher in both dry ground and dry rough groups (436 and 433 kg m^{-3}, respectively) with more than 30 units of difference with the green group (399 kg m^{-3}). A similar tendency was found in the prediction set. The minimum density in this set corresponded to the green group (335 kg m^{-3}) and the maximum density was found in both the green and the dry rough group (509 kg m^{-3}). Also, standard deviations were considerably higher in the prediction set than in the calibration set. The green samples came from heights ranging between 0 and 30 m within selected trees while the dry samples were only taken from breast height disks. Wood density tends to decrease with height in a tree, so it could be expected that the dry samples had higher average densities than the green samples.

3.6.2 Variation of NIR spectra

Peaks of absorbance for all three sample groups (green, dry rough, dry ground) were found at about 1500, 2000 and 2500 nm.

The spectral curves for the green chain saw chip group are shown in Figure 3.1. They illustrate the difference between the NIR spectra for three representative samples of low (315 kg m^{-3}), average (434 kg m^{-3}), and high (509 kg m^{-3}) densities in terms of their general absorbance.

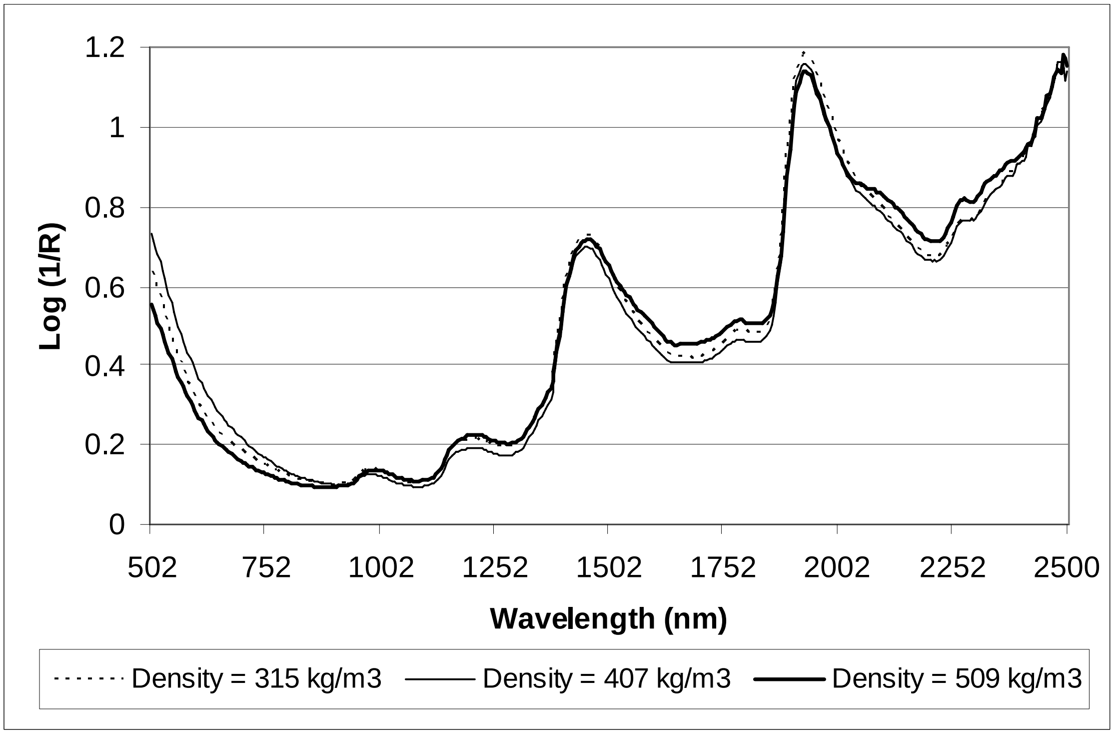

Figure 3.1 - Variation in near infrared (NIR) spectra collected from green chain saw chip samples for different values of basic density.

Figure 3.1 shows that the high-density sample has slightly less absorbance than both the low and average density samples at wavelengths below 1000 nm. For the rest of the spectral range (1000-2500 nm) the high-density sample has the highest absorbance – most notably in the 1500-1850 nm and 2000-2350 nm ranges.

The spectral curves for the dry rough group show a lower absorbance for all spectra in comparison to the green chain saw chip group. This tendency is confirmed by a previous report (Schimleck *et al*. 2003); however in their studies the difference between green and dry samples is more notable than that found here. This may be due to the characteristics of the dry rough samples used. Other differences between the spectra for the dry rough group and the green group include: a possible reversal of absorbance trends (absorbance for high density samples being higher at wavelengths below 1000 nm and lower at wavelengths above 1900 nm), and the presence of more "noise" and irregularities in the dry rough spectra.

Absorbance values for the dry ground group were intermediate between those found in the green and the dry rough groups. When compared to the other two groups (green and dry rough), there appeared to be no differences among the high, average and low density samples. On the other hand, both dry groups have similar absorbance trends. There also appeared to be no significant differences between the dry rough and dry ground groups over the 400-2500 nm spectral range.

Figure 3.2 shows the spectral curves for the three groups for their average density values. It can be seen that both dry groups had less absorbance than the green group for all the spectra. These differences increase at wavelengths above 1500 nm. This confirms the results obtained by previous studies which report higher values of absorbance as the water content of the samples increases (Thygesen 1994; Schimleck *et al*. 2003).

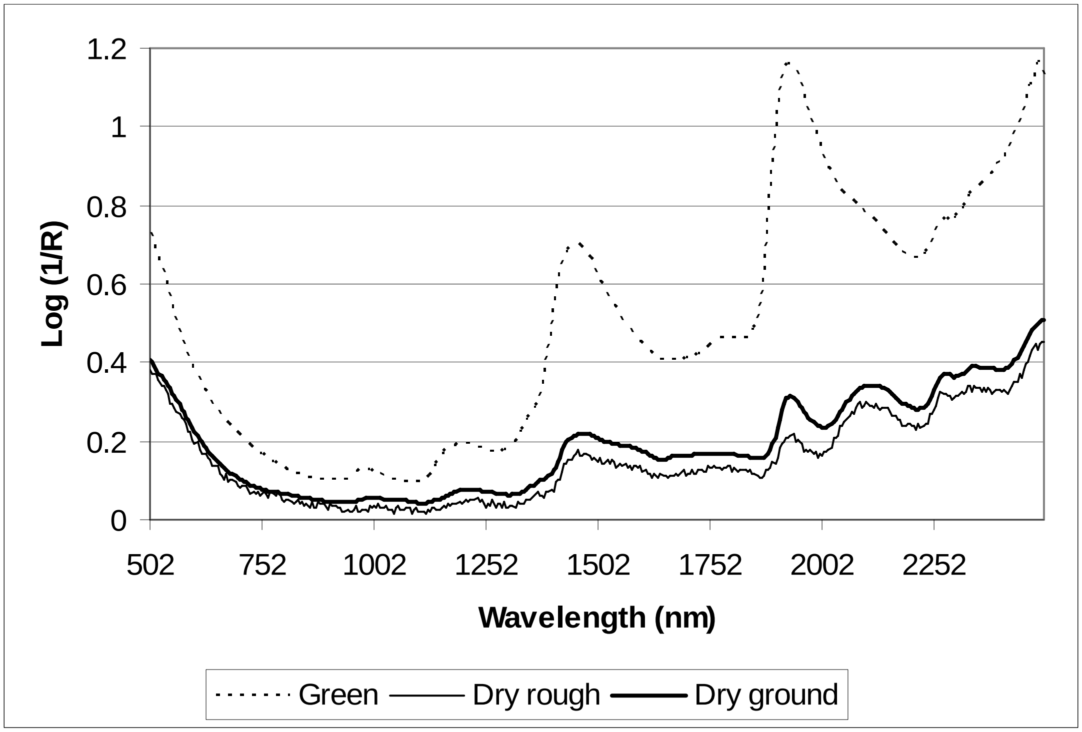

Figure 3.2 - Variation in near infrared (NIR) spectra collected from average densities for the three sample groups – green chain saw chips, dry rough chips, and dry ground chips.

3.6.3 Development and application of PLS calibrations

Summary statistics for the wood density PLS calibrations are presented in Table 3.2. The calibration developed for wood density in each group of samples gave good results, with values of R^2 ranging from 0.89 to 0.95. Wood density calibrations developed using NIR spectra obtained from the dry rough group gave better results compared with the calibrations developed using spectra obtained from the green and the dry ground groups (Figure 3.3).

Table 3.2 - Summary of calibrations with partial least squares regression and principal components regression developed for basic density using spectra collected from the samples.

Multivariate analysis procedure	Sample type	Calibration set			Prediction set	
		No. of factors	R^2	SEC	R^2	SEP
Partial least squares	Green chain saw chip	12	0.89	15.2	0.74	22.7
	Dry rough chip	3	0.95	6.9	0.56	27.4
	Dry ground chip	12	0.90	11.8	0.85	15.7
Principal component analysis	Green chain saw chip	30	0.96	23.7	0.73	31.3
	Dry rough chip	15	0.80	32.0	0.58	46.4
	Dry ground chip	20	0.91	28.5	0.83	26.8

Another interesting aspect of the calibration procedure is the difference observed in the number of factors in each group that gave the best results. While just three factors were necessary in the dry rough group to reach the best R^2 in the prediction set, twelve factors were necessary for the green and dry ground groups. Clearly, however, the R^2 in the prediction set was lower for the dry rough group than for the other two groups.

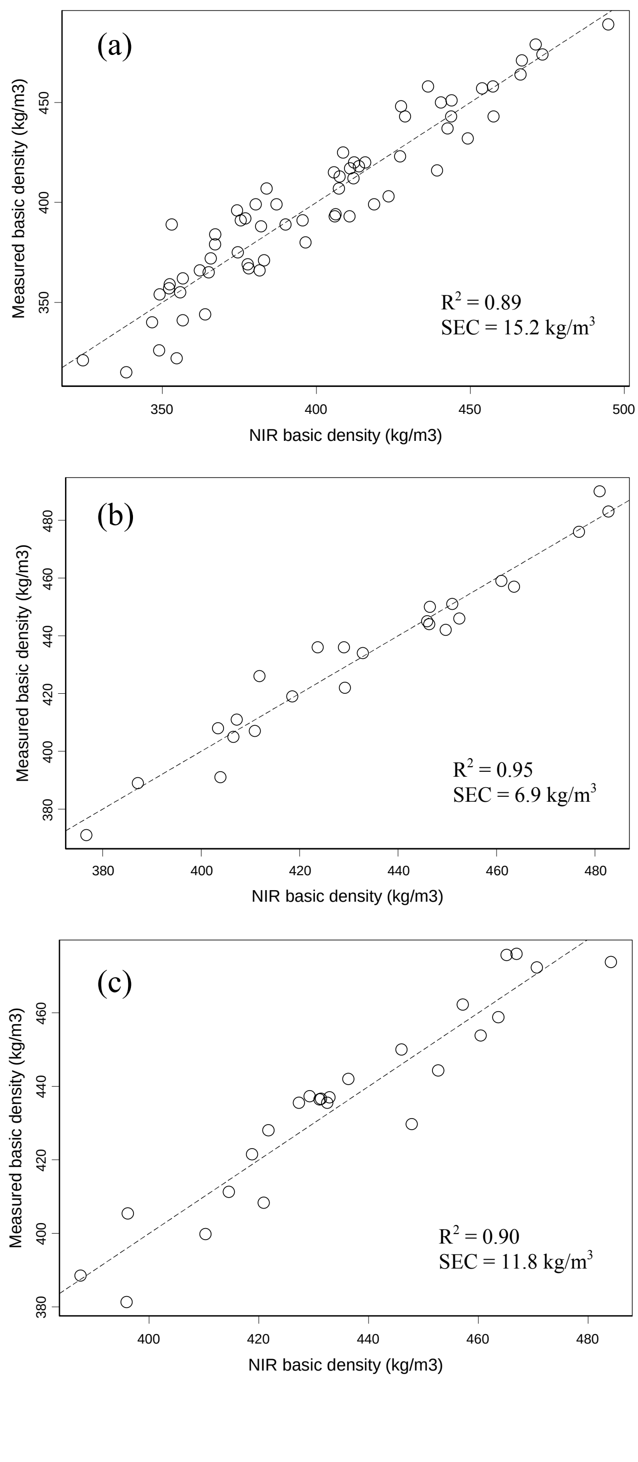

Figure 3.3 - Relationships between measured values and values predicted with near infrared (NIR) spectroscopy for (a) Green chain saw chip samples, (b) Dry rough chip samples, and (c) Dry ground chip samples. Results presented are those obtained for calibration.

The number of factors is, in general, greater than those reported in previous studies for wood density (Thygesen 1994; Schimleck *et al*. 1999); this could possibly be attributed to their use of preprocessing techniques (which were not applied here). A better understanding of the effect of number of factors is obtained by looking at Figure 3.4. In the green group, the calibration model explains only 40% of the response variable (wood density) when five factors (a common number reported in studies) are used. On the other hand, with more than ten factors the model explains a little over 80% of the wood density; however, from this point there is clear evidence of overfitting.

When calibrations were used on a separate prediction set for each sample group it was found that calibrations developed using spectra collected from the dry ground group gave the strongest prediction statistic, with a R^2 of 0.85. Conversely, the weakest relation was found in the dry rough group with a R^2 of 0.56. The regression lines between measured and NIR-predicted values for the prediction set are shown in Figure 3.5. The prediction values of R^2 for these linear regressions are shown in Table 3.2, and they represent the proportion of variation in the independent prediction set that was explained by the calibration model.

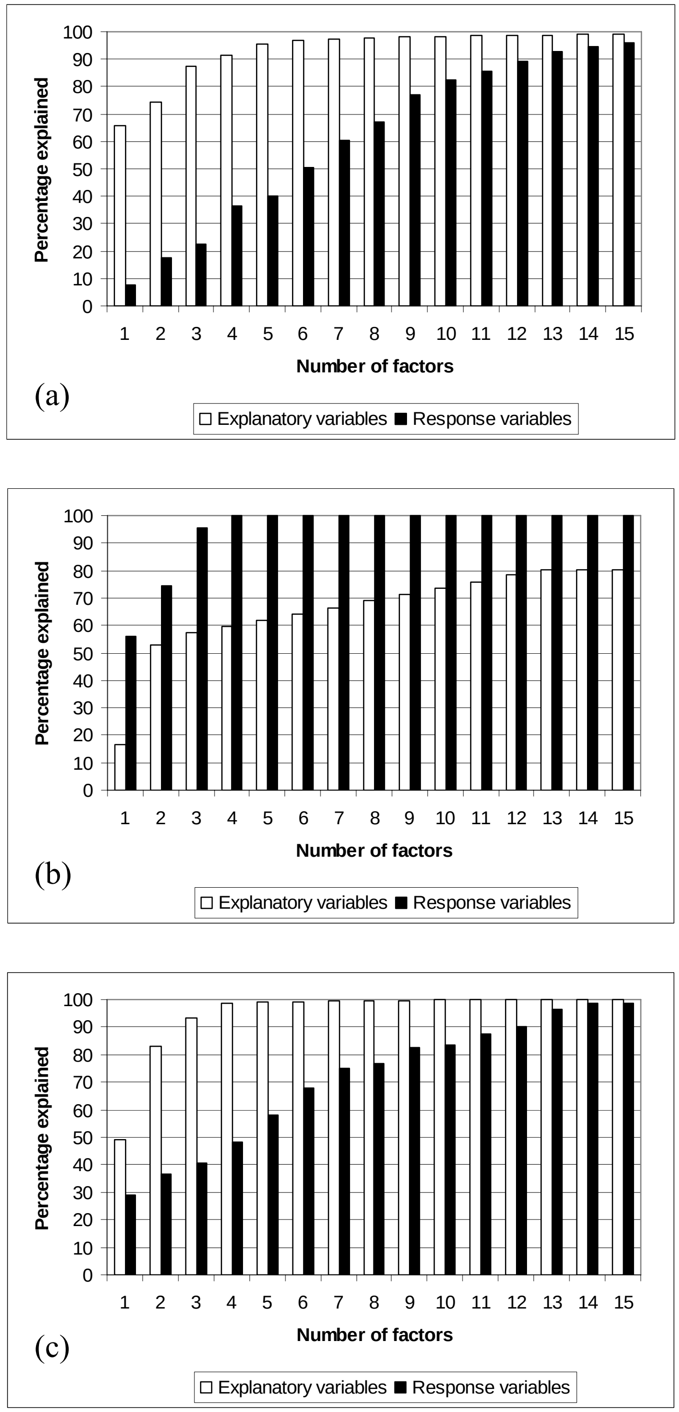

Figure 3.4 - Explanatory and response variables explained by the partial least squares calibration model in the (a) Green chain saw chip samples, (b) Dry rough chip samples, and (c) Dry ground chip samples.

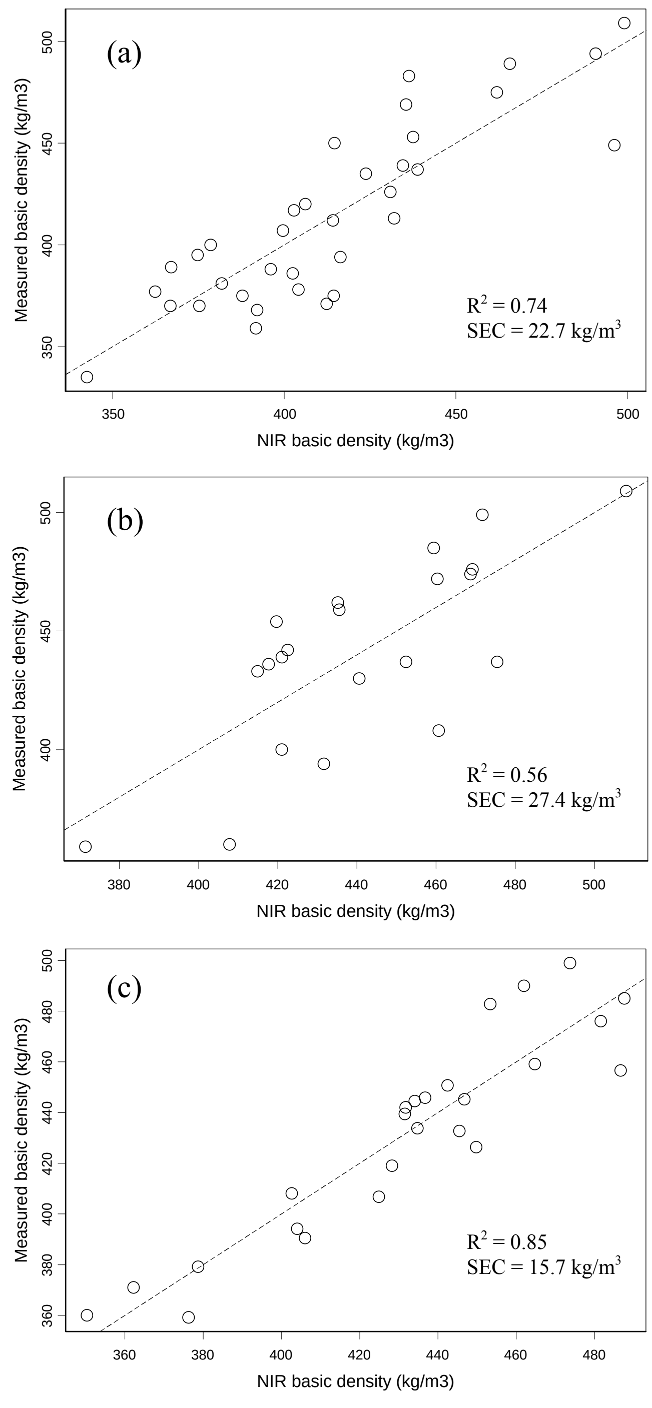

Figure 3.5 - Relationships between measured values and values predicted with near infrared (NIR) spectroscopy for (a) Green chain saw chip samples, (b) Dry rough chip samples, and (c) Dry ground chip samples. Results presented are those obtained for prediction.

In general, predictions of the density in each sample type were satisfactory, but the R^2 values were lower than the R^2 obtained for the calibration sets, with the greatest reduction occurring for the dry rough group. SEP values (15.7-27.4 kg m^{-3}) were considerably higher than the SEC values (6.9-15.2 kg m^{-3}). The dry rough group showed the greatest difference between the SEP and SEC values. The presence of three outliers in the dry rough sample group did not permit a good fit of the data. As some references point out (Dryden 2003), these outliers may be associated with either some mechanical errors inherent to the NIR spectrometer measurements or to the measurement and calculation of the density of the wood samples. Removing the outliers would only increase the R^2 to 0.60, however, for the dry rough group prediction set.

3.6.4 Development and application of PCA calibrations

Summary statistics for the PCA calibrations are presented in Table 3.2. The calibration statistics correspond to the number of components that gave a similar coefficient of determination in the prediction set to that obtained with PLS analysis. The calibrations developed for each sample group provided higher values of R^2, ranging from 0.80 to 0.96.

As with PLS, PCA calibrations developed using NIR spectra obtained from the dry ground group gave the best prediction results. For similar R^2 values in the prediction set (0.85 with PLS, 0.83 with PCA), similar R^2 values were obtained with the calibration model (0.90 with PLS, 0.91 with PCA). PCA yielded a higher R^2 for the green group calibration model (0.96) than PLS (0.89). Conversely, for the dry rough group PCA yielded a lower R^2 value (0.80) than PLS (0.95).

Both in the calibration and the prediction set, an important increase in the standard errors was observed with the use of PCA, revealing significant differences between the two statistical techniques. Basically, this is due to the mechanism used to develop the calibrations. PLS extracts latent variables which perform a decomposition of the explanatory and response variables that reduce the covariance between these two groups. PCA only extracts a number of components of a specific set of variables (usually the explanatory ones) which in a second step may be correlated with the response variable by a regression model (Abdi 2003). Since PCA does not capture information from the response variables at the same time as the explanatory variables, the final calibration model may have greater standard residual errors. Higher numbers of components are also needed to get similar R^2 values to those obtained with PLS.

3.7 DISCUSSION AND CONCLUSIONS

The usefulness and potential of NIR spectroscopy for predicting wood density of Douglas-fir based on chainsaw chip samples has been successfully demonstrated. In terms of both SEC and SEP, PLS yielded better results than PCA. With PLS, calibration models were found to perform best for both dry rough and dry ground samples; SEC's expressed as percentage of the mean were 1.6% and 2.7% respectively.

On the other hand, prediction models performed best for both the green and dry ground samples; SEP's expressed as a percentage of the mean were 5.5% and 3.6% respectively. The standard errors of the predictions using the dry rough samples were relatively large compared with the standard errors of the other two groups. We believe, however, that removing a couple of outliers would improve the prediction capability in the dry rough group and reduce the standard errors observed.

R^2 values for NIR-predicted basic densities ranged from 0.56 for the dry rough Douglas-fir chip samples to 0.85 for the dry ground chip samples. The green chainsaw chip samples had an intermediate R^2 value of 0.74. These R^2 values are similar to those reported by So *et al*. (2002) and by Schimleck *et al*. (2003) for loblolly pine solid wood; R^2 values of 0.67 and 0.74 respectively.

Thygesen (1994) reported R^2 values for green, augered shavings of Norway Spruce (0.75) that were similar to the green chainsaw chip samples in this study (0.74). However, Thygesen (1994) also reported substantially higher values for dry, augered shavings (0.89) than were found for the dry rough chainsaw chip samples in this study (0.56).

Kelley *et al*. (2001) have reported that NIR measurements of green solid wood samples can be used to accurately predict dry wood stiffness for poplar. Schimleck *et al*. (2003) found that NIR measurements of green wood can be used to predict air-dry wood density for loblolly pine. The results of our study confirm their work and reveal the possibility of using NIR spectroscopy of green chain saw chip samples to predict wood properties (such as density) in real time, negating the need to dry samples prior the analysis. These results open the doors to the use of NIR technology for log segregation by mechanized harvesting equipment (e.g. harvesters).

NIR spectra on the green chain saw chip group in this study were gathered from a loosely packed sample in a petri dish on a slowly revolving turntable. While it would be possible to collect "grab" samples of green chain saw chips for NIR measurement in this manner it would be preferable to undertake the measurements on green chips that are being ejected from the log as it is being cut. This would mean obtaining measurements on very dispersed chips moving at high speeds. Axrup *et al*. (2000) have successfully used NIR spectroscopy to quantify the chemistry of packed pulpwood chips moving at speeds of 1 m s^{-1} on a conveyor belt. Further research will be required to determine whether reliable measurements of wood density can be made from green chips ejected from a log as it is being cut.

To operate in "real-time" NIR measurements would need to take only a few seconds. In this study both spectrometers were using an average of about 30 scans to produce the spectral curves for the 400-2500 nm range. Scan rates for one spectrometer were 10 scans per second and for the other spectrometer 1.8 scans per second, implying overall scan times ranging from 3 to 17 seconds. Kelley *et al*. (2004b) have demonstrated that some wood properties, such as strength and stiffness, can be predicted with only a slight decrease (~ 0.05) in the R^2 value, when a reduced spectral range (650-1050 nm) is used. They comment that the reduced spectral range would allow the use of much smaller, faster, lighter and less expensive spectrometers.

Research by many others has highlighted the potential for measuring a wide range of wood properties using NIR spectroscopy. From this study we can conclude that:

(1) Useful calibrations for Douglas-fir wood density can be developed using NIR spectroscopy of chain saw chip samples.

(2) Green chain saw chip samples could provide NIR estimates of wood density that are only slightly degraded from those coming from dry ground chip samples.

(3) With either multivariate statistical techniques, PLS or PCA, it is possible to get calibration models to predict wood properties. Although PLS is a more involved technique and not included in many statistical packages, it can produce more accurate models given its ability to extract information of both explanatory and response variables.

(4) Further work is required to determine whether the promise of real-time, cost effective measurements of wood density (and other wood properties) using NIR technology is valid.

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3.9 REFERENCES

ABDI, H. 2003. Partial Least Squares (PLS) regression. *In*: Lewis-Beck M., Bryman, A., Futing T. (Eds.). Encyclopedia of Social Sciences Research Methods. Thousand Oaks (CA): Sage.

ACUNA, M.; MURPHY, G. 2006. Geospatial and within variation of wood density and spiral grain in Douglas-fir. *For. Prod. J.* (accepted for publication).

ANDREWS, M. 2002. Wood quality measurement – *son et lumiere. New Zealand J. For.* 47(3): 19-21.

ANTII, H. 1999. Multivariate characterization of wood related materials. Doctoral thesis. Umea University. Department of Chemistry. Umea. Sweden. 86 pp.

AXRUP, L.; MARKIDES, K.; NILSSON, T. 2000. Using miniature diode array NIR spectrometers for analyzing wood chips and bark samples in motion. *J. Chemometrics* 14:561-572.

BAILLERES, H.; DAVRIEUX, F.; HAM-PICHAVANT, F. 2002. Near infrared analysis as a tool for rapid screening of some major wood characteristics in a eucalyptus breeding program. *Ann. For. Sc.* 59:479-490.

BARBOUR, R.J.; KELLOGG, R.M. 1990. Forest Management and end-product quality: a Canadian perspective. *Can. J. For. Res.* 20: 405-414.

DAVIES, M.C. 2005. An introduction to near infrared spectroscopy. *NIR news* (16)7: 9-11.

DRYDEN, G. 2003. Near infrared reflectance spectroscopy: applications in deer nutrition. RIRDC Publication No. W03/007. Rural Industries Research and Development Corporation. Barton, ACT, Australia. 38 pp.

GARTNER, B. L.; NORTH, E.M.; JOHNSON, G.R.; SINGLETON, R. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. *Can. J. For. Res.* 32: 439-447.

GIVENS, D.I.; DE BOEVER, J.L.; DEAVILLE, E.R. 1997. The principles, practices and some future applications of near infrared spectroscopy for predicting the nutrient value of foods for animals and humans. *Nutrition Research Reviews*, 10:83-114.

HINDLE, P.H. 2001. Historical development. In: Handbook of Near-Infrared Analysis. Edited by D.A. Burns and E.W. Ciurczak. Marcel Dekker, Inc. New York. 814 p.

HUGHES, J.F. 1967. Density as an index of wood quality with special reference to the development of rapid and efficient methods of estimating density. In: Proceedings of the Tropical Forestry Meeting by Commonwealth Forestry Institution. Oxford. pp. 1-4.

JONES, P.D.; SCHIMLECK, L.R.; PETER, G.F.; DANIELS, R.F.; CLARK III, A. 2005. Nondestructive estimation of *Pinus taeda* L. wood properties for samples from a wide range of sites in Georgia. *Can. J. For. Res.* 35:85-92.

KELLEY, S.S.; HAMES, B.R.; MEGLEN, R.R. 2001. Use of near infrared spectroscopy for characterization of wood. Presentation abstract from 5th International Biomass Conference of the Americas. 2pp. http://www.bioproducts-bioenergy.gov/pdfs/bcota/abstracts/29/z362.pdf (accessed January 2006).

KELLEY, S.S.; RIALS, T.G.; SNELL, R.; GROOM, L.H.; SLUITER. 2004a. Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. *Wood Sci. Technol.* (38):257-276.

KELLEY, S.S.; RIALS, T.G.; GROOM, L.H.; SO, C-L. 2004b. Use of near infrared spectroscopy to predict the mechanical properties of six softwoods. *Holzforschung* 58(3):252-260.

KENNEDY, R.W. 1995. Coniferous wood quality in the future: concerns and strategies. *Wood Sci. Technol.* 29(5): 321–338.

KLUDT, K.D. 2003. Use of near infrared spectroscopy technology for predicting bending properties of clear wood specimens. MSc Thesis. Washington State University. USA. 86 pp.

MARTENS, H.; NAES, T. 1991. Multivariate calibration. Wiley 419 pp.

MARTIN, M.; ABER, J. 1994. Analyses of forest foliage III: determining nitrogen, lignin and cellulose of fresh leaves using near infrared reflectance data. *J. Near Infrared Spectr.* 2:25-32.

MCKEEVER, D.B. 2000. Timber and fiber demand and technology assessment: Demand for engineered products. USDA Forest Service, Forest Products Laboratory. 2 p.

MCLELLAN, T.; MARTIN, M.; ABER, J.; MELILLO, J.; NADELHOFFER, K.; DEWEY, B. 1991. Comparison of wet chemistry and near infrared reflectance measurements of carbon-fraction chemistry and nitrogen concentration of forest foliage. *Can. J. For. Res.* 21:1689-1693.

MEGRAW, R.A. 1986. Douglas-fir wood properties. P. 81-96 in Douglas-fir: Stand management for the future, Oliver, C., D. Hanley, and J. Johnson (eds.). Inst. of For. Res. Contrib. 55. College of Forest Resources, University of Washington, Seattle.

MICHELL, A.J. 1995. Pulpwood quality estimation by near infrared spectroscopic measurements on eucalypt woods. *APPITA J.* 48(6):425-428.

REEVES, J.B. III; DELWICHE, S.R. 2003. SAS partial least squares regression for analysis of spectroscopic data. *J. Near Infrared Spectr.* 11:415-431.

SCHULER A.; CRAIG, A. 2003. Demographics, the housing market, and demand for building materials. *For. Prod. J.* 53(5): 8-17.

SEFARA, N.L., CONRADIE, D.; TURNER, P. 2000. Progress in the use of near-infrared absorption spectroscopy as a tool for the rapid determination of pulp yield in plantation eucalypts. *TAPPSA J.*, November 2000. p15-17.

SCHIMLECK, L.R.; MICHELL, A.J.; RAYMOND, C.A.; MUNERI, A. 1999. Estimation of basic density of *Eucalyptus globulus* using near-infrared spectroscopy. *Can. J. For. Res.* 29:194-201.

SCHIMLECK, L.R.; EVANS, R.; ILIC, J. 2001. Estimation of *Eucalyptus delegatensis* wood properties by near infrared spectroscopy. *Can. J. For. Res.* 31(10):1671-1675.

SCHIMLECK, L.R.; EVANS, R.; ILIC, J.; MATHESON, A.C. 2002. Estimation of wood stiffness of increment cores by near-infrared spectroscopy. *Can. J. For. Res.* 32(1):129-135.

SCHIMLECK, L.R.; YAZAKI, Y. 2003. Analysis of *Pinus radiata* D. Don bark by near infrared spectroscopy. *Holzforschung* 57:520-526.

SCHIMLECK, L.R.; MORA, C.; DANIELS, R.F. 2003. Estimation of the physical wood properties of green *Pinus taeda* radial samples by near infrared spectroscopy. *Can. J. For. Res.* 33:2297-2305.

SCHIMLECK, L.R.; JONES, P.D.; PETER, G.F.; DANIELS, R.F.; CLARK III, A. 2004. Nondestructive estimation of tracheid length from sections of radial wood strips by near infrared spectroscopy. *Holzforschung* 58:375-381.

SHAO, J. 2003. Linear model selection by cross-validation. *J. Am. Stat. Assoc.* 88:486-494.

SO, C.L.; GROOM, L.H.; RIALS, T.G.; SNELL, R.; KELLEY, S.; MEGLEN, R. 2002. Rapid assessment of the fundamental property variation of wood. In Outcalt, K.W. (Ed.) “Proceedings of the 11th Biennial Southern Silvicultural Research Conference”. USDA Forest Service, Southern Research Station, General Technical Report SRS-48. 622 p.

SO, C.L.; KIA, B.K.; GROOM, L.H.; SCHIMLECK, L.R.; SHUPE, T.F.; KELLEY, S.S.; RIALS, T.M. 2004. Near infrared spectroscopy in the forest products industry. *For. Prod. J.* 54(3):6-16.

TERDWONGWORAKUL, A.; PUNSUWAN, V.; THANAPASE, W.; TSUCHIKAWA, S. 2005. Rapid assessment of wood chemical properties and pulp yield of *Eucalyptus camaldulensis* in Thailand tree plantations by near infrared spectroscopy for improving wood selection for high quality pulp. *J. Wood Sci.* 51:167-171.

THYGESEN, L.G. 1994. Determination of dry matter content and basic density of Norway spruce by near infrared reflectance and transmittance. *J. Near Infrared Spectr.* 2:127-135.

TIGABU, M. 2003. Characterization of forest tree seed quality with near infrared spectroscopy and multivariate analysis. Doctoral thesis. Swedish University of Agricultural Sciences. Department of Silviculture. Umea. 56 p.

TIGABU, M.; ODEN, P.R.; SHEN, T.Y. 2004. Application of near-infrared spectroscopy for the detection of internal insect infestation in *Picea abies* seed lots. *Can. J. For. Res.* 34:76-84.

TOBIAS, R. 1995. An Introduction to Partial Least Squares Regression. *In*: Proceedings of the Twentieth Annual SAS Users Group International Conference, Cary, NC: SAS Institute Inc., 1250-1257.

VIA, B.K. 2004. Modeling Longleaf pine (*Pinus palustris* Mill) wood properties using near infrared spectroscopy. Doctoral thesis. Louisiana State University, Agricultural and Mechanical College. 141 pp.

VIA, B.K.; SHUPE, T.; GROOM, L.; STINE, M.; SO, C. 2003. Multivariate modeling of density, strength and stiffness from near infrared spectra for mature, juvenile and pith wood of longleaf pine (*Pinus palustris*). *J. Near Infrared Spectr.* 11:365-378.

WORKMAN, J.J. 2001. NIR Spectroscopy calibration basics. In: Handbook of Near-Infrared Analysis. Edited by D.A. Burns and E.W. Ciurczak. Marcel Dekker, Inc. New York. 814p.

WRIGHT, J.; BIRKETT, M.; GAMBINO, M. 1990. Prediction of pulp yield and cellulose content from wood using Near Infrared Reflectance spectroscopy. *TAPPI J.* 73:164-166.

YOUNG, G.G. 2002. Radiata pine wood quality assessments in the 21st century. *New Zealand J. For*. 47(3): 16-18.

CHAPTER 4

ESTIMATING LOG PRICES OF DOUGLAS-FIR THROUGH AN ECONOMIC ANALYSIS OF THE EFFECTS OF WOOD DENSITY ON LUMBER RECOVERY AND PULP YIELD

Mauricio Acuna and Glen Murphy

Department of Forest Engineering

Oregon State University

Corvallis, OR 97331-5706

USA

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Forest Product Society

2801 Marshall Court

Madison WI 53705-2295

USA

4.1 ABSTRACT

Traditionally forest products markets have required logs with particular external properties such as diameter, length and knot size. However, markets are now beginning to include requirements for new internal properties, such as basic density and stiffness. Although markets have not responded to these new requirements with prices which are an incentive for producers to meet such demands, the new characteristics are highly valued by these markets and are considered key for competitive forest companies to stay in business. This paper presents a general methodology to estimate log prices of Douglas-fir based on the net return obtained when logs of different wood density classes are processed and converted into end products (lumber and pulp). Three log density classes were evaluated. For the lowest basic density class (300-399 kg m^{-3}), net returns (and corresponding log prices) for pulp were about 28 percent lower than the middle class (400-499 kg m^{-3}). The upper class (500-600 kg m^{-3}) net return (log price) was 32 percent higher than the middle class. For lumber log-types, the percentage differences between the middle density class and lower and upper classes were 8 and 4 percent, respectively. These results show that premium prices for logs can be established when internal properties, such as basic density, are specified.

Keywords: log prices, wood density, lumber recovery, pulp yield, Douglas-fir

4.2 INTRODUCTION

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is of considerable economic importance, especially for the forest products industries of the United States, Canada, New Zealand, and some areas in Europe (Acuna and Murphy 2006; Gartner *et al*. 2002). It has been one of the most important raw material resources in the United States in recent years and the wood is valued for high-quality building and construction materials as well as for plywood, and pulp (USDA 1987; Aubry *et al*. 1998). It is expected that international and U.S. markets will continue to demand Douglas-fir log products, especially in the high-quality structural lumber market (Barbour and Kellogg 1990; McKeever 2000; Schuler and Craig 2003).

Timber resources in the Pacific Northwest have gradually shifted from unmanaged old growth to intensively managed young growth (Adams *et al*. 2002). As younger stands are harvested, wood quality is negatively affected in comparison to old growth wood because of the presence of a higher proportion of juvenile wood, which in turn affects properties, such as strength and dimensional stability (Gartner *et al*. 2002). In addition, harvesting of younger trees increases the variability in product performance, and affects log producers in their ability to meet the market demand of wood products (Murphy 2003; Murphy *et al*. 2003).

Traditionally, tree species, log dimensions and external quality characteristics such as branch size, sweep, scarring and decay have been used to specify a particular log-type. However, markets are now beginning to include additional characteristics to specify the logs they require. For instance, consideration is now being given to such wood properties as stiffness, strength, density, spiral grain, extractives content, and consumption of energy for processing (Andrews 2002; So *et al*. 2002; Young 2002). Corson (2001) noted, for example, that an integrated market-kraft pulp/newsprint operation in New Zealand required its pulp logs to be separated into eight different log grades based on wood density and the process (mechanical pulping or kraft) for which they were destined.

Wood quality can be defined according to attributes that make wood valuable for a given use by society (Jozsa and Middleton 1994; Gartner 2005). Although it has been noted that the factors controlling wood quality can be confusing and are frequently contradictory (Anon. 1965), optimally matching wood quality to markets can lead to improved product uniformity, productivity and profitability along the seedling to customer supply chain. For Douglas-fir, significant quality attributes for wood products include density, microfibril angle, fiber length, lignin content, ring width, knot size and distribution, grain angle and coarseness, color, etc. (Walker *et al*. 1993; Gartner 2005).

In general, density is one of the most important physical characteristics for wood products because it is an excellent predictor of strength, stiffness, hardness, and paper-making capacities (Megraw 1986; Kennedy 1995). With regard to density the most important pattern is the juvenile/mature wood pattern, the systematic change of anatomy, chemistry, and properties from the pith outward. Juvenile wood (which has a lower density) typically has characteristics that negatively impact a number of wood properties (Bendtsen and Senft 1986; Gartner 2005).

Accurately assessing density in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on density. Variables such as stand age and height within a tree have been used in the past as substitutes for accurate measurements of density. For example, in the early 1990's the second author of this paper participated in value recovery audits of ten New Zealand logging crews supplying a range of log types to many mills. One of the sawmills would only accept saw logs found at heights of less than 20 meters in a tree because of concerns about low density wood occurring above this height (G. Murphy, unpublished).

Acuna and Murphy (2006) examined the geospatial and within tree variation of density for Douglas-fir in Western Oregon, and found that the only statistically significant variable was the height within the tree; height accounted for less than 30% of the variation in density, however. Real-time measurements of density in the forest will be required if logs are to be optimally allocated to markets based on this wood property.

Forest harvesting has become increasingly mechanized during the last few decades. Among other things, mechanization provides a platform for innovative measurement systems which could lead to improved log segregation based on a wider range of wood properties (Murphy 2003). Segregation of logs, based on hand-held acoustic tools that measure stiffness, is already being used by some forest companies to improve the value of lumber recovery (Green and Ross 1997, Matheson *et al.* 2002). Fitting acoustic measuring systems to mechanized harvesters is currently being evaluated (P.Carter, pers. comm.). Acuna and Murphy (unpublished B) have demonstrated that near infrared technology (NIR) could be used to predict wood density from ejected chain saw chips as each stem was being cut into logs. The acoustic and NIR research efforts indicate that internal wood properties of logs are likely to be more commonly measured and specified by markets in the near future.

Despite many studies having reported that wood producers are sorting logs according to external and internal properties (Jappinen 2000; Matheson *et al*. 2002; Edlund and Warensjo 2005), there is no evidence to show markets are paying premium prices for logs with “desirable” internal characteristics, such as high density. However, it is recognized that logs with higher densities are desired by sawmills because of the larger proportion of highly graded lumber, and by pulpmills because of yield improvements when logs of a higher density are processed and converted into chips (Briggs 1994).

To estimate the effect of different wood characteristics on the basis of economic value, the best sources of information are product recovery studies in which volume and value of products are recorded (Ernst and Fahey 1986). The economic importance of different wood properties varies with the products milled from the stems measured in a recovery study, the grading methods applied, and the price structure used (Aubry *et al*. 1998). Because product recovery studies are expensive and labor intensive, it is possible to find only a few examples in the literature that relate to wood characteristics and their effects on product value for Douglas-fir (Lane *et al*. 1973; Fahey and Martin 1974; Fahey *et al*. 1991; Green and Ross 1997; Willits *et al*. 1997). One of the most extensive studies that makes an economic analysis of the wood characteristics and their impact on production and grade of Douglas-fir lumber was that sponsored by the Douglas-fir Stand Management Cooperative and whose results appear in a extensive report (Fahey *et al*. 1991). According to Aubry *et al*. (1998) the usefulness of this approach is dependent on the relationship between the two lumber grading systems (visual grading systems and mechanical or machine stress rated (MSR)) in use in the United States and the wood quality traits used to determine grading rules.

Despite the fact that some studies have looked at the effect of different traits on lumber and veneer recovery (Aubry *et al.* 1998), and also the effect of different silvicultural treatments on the quality and quantity of the final products (Sonne *et al*. 2004), none of them have made an estimation of the premium price that markets would be willing to pay for logs of better internal characteristics, such as a higher wood density or stiffness.

4.3 STUDY OBJECTIVES

This research is aimed at estimating log prices of Douglas-fir based on wood density. This is an important wood characteristic that affects lumber recovery and pulp yield, as well as the potential net return obtained from logs. Only two product types were included in the analysis. For lumber, a number of different grades and their prices were used to estimate the price that markets would be willing to pay for logs. Pulp log prices were estimated from the net product value per metric ton after non-wood and fixed cost were subtracted from the pulp sales price.

4.4 METHODS

4.4.1 Field site and tree data set

The data used in this study were collected from a dominant industrial Douglas-fir stand in the Pacific Northwest (Washington State). The site was selected based on logistics (location, and crew willingness to be studied) and the number of log grades being cut. Net stocked area of the stand was 12.18 ha (30.1 acres), with an average stand density of 273 stems per ha. It was on mainly flat ground with an access road through the middle, and was clearfelled. The average tree size was 2.35 m^3, and the average diameter at breast height (dbh) was 46 cm. These stand parameters were obtained from the owner's stand record system. They were based on field measurements made in 1997 and grown-on using tree growth models to give the stand parameters at the time of harvesting (Marshall 2005).

4.4.2 General procedure to estimate log prices

The approach used to estimate a set of prices for different log grades begins by determining the net return obtained at the end of the supply chain. For lumber, this is given by the recovery volume obtained in each grade and the price associated with it, and subtracting the processing costs to produce lumber from logs. For pulp logs, the net return per metric ton is given by the selling price per metric ton minus non-wood costs and fixed costs. This percent difference in net return is then applied to logs which are classified according to three different density classes. The goal is to estimate different log prices in each grade as a function of the wood density and the potential return of end products (lumber and pulp) obtained from logs. The sequence of steps needed to estimate the set of log prices was as follows:

1. Optimally bucking the stems and separating the logs produced by grade. Each grade has exactly one price associated with it, which corresponds to the price that markets currently pay for that log-type.
2. For each log-type (grade), determining an average log based on external and internal characteristics (stem length, small end diameter, juvenile wood percentage).
3. For the average log, calculating the net return as a function of the end products obtained (lumber or pulp) for a range of log densities (300, 320,…,600 kg m^{-3}).

Dividing the logs into three different density classes (300-399, 400-499, 500-600 kg m^{-3}) and computing the average net return for each class.

4. Calculating the percentage difference in net return between average density classes. Assigning the current single log price (from step 1) to the middle density class (400-499 kg m^{-3}). Multiply this log price by the percentage difference in net return to estimate the log prices of the other two classes (300-399 and 500-600 kg m^{-3}).

4.4.3 Optimal bucking procedure

A dynamic programming algorithm was implemented in a system called IP-BUCK (bucking with internal properties) which was developed in the programming language Visual C++™. The outputs given by IP-BUCK correspond to the volume and number of logs by each log-type (product), as well as the total volume and value produced after optimally bucking a set of stems.

One hundred stems were used for testing the bucking procedure which is based on both external and internal properties. Detailed measurements were recorded in the field to characterize each stem (Marshall 2005). The variables used in the bucking model were: length from the base of the stem, diameter, volume, quality, density. These were assessed at intervals of 0.1 m along the stems. The number of intervals used to collect the information for each stem is an important element since the accuracy of the dynamic programming procedure is strongly affected by the number of measurements along the stem.

The same market requirements (product specifications) were applied to all the stems (Acuna and Murphy [unpublished A]). Eight log-types, plus waste, were included in the analysis. Their prices are shown on Table 4.1. Seven of the log types included multiple lengths of 0.6 m. Fiber included multiple lengths of 0.1 m. A total of 122 log lengths were included in the analysis. Supply constrained markets were assumed. The log-types included were sawlogs for export, (log-types ES1, ES2, ES3, ES4), and for domestic markets (log-types DS1, DS2 and DS3) as well as pulpwood (log-type FIBER).

Table 4.1 - Log-types and prices used to optimally buck the stems.

Log-type	Relative market Prices ($/m^3)	Log-type	Relative market Prices ($/m^3)
ES1	149	DS1	104
ES2	132	DS2	97
ES3	125	DS3	77
ES4	93	FIBER	22

Two different files are required to run the dynamic programming algorithm: the stem file and the log specification file. The stem file contains information on length, diameter, volume, quality, and density for each stem. The log specification file contains requirements for each log-type to be produced, normally the smallest and largest end diameter (SED, LED), relative price, lengths, quality and density (Acuna and Murphy [unpublished A]).

4.4.4 MSR lumber grade recovery

No product recovery study was carried out. Instead, the proportion of lumber volume in the MSR lumber grade groups was computed by using the equations given by Fahey *et al*. (1991). Thus, grade recovery was estimated by an exponential model, developed by regression, using nonlinear least squares. Individual grades equations, rather than accumulating equations, were modeled (Table 4.2). Factors important in accounting for variability in grade recovery are less likely to be overlooked in the analysis of individual grades.

One of the variables used by Fahey *et al*. (1991) in their equations is the percentage of juvenile wood. For this study, a regression model relating juvenile wood percentage and basic density was developed using data supplied by OSU's Wood Science and Engineering Department. The model is as follow:

$$\text{JWC20} = 191.33 - 0.304 \text{ x (basic density), with basic density in kg m}^{-3}.$$

Table 4.2 - Coefficients for models predicting MSR grade recovery. Source: Fahey *et al*. (1991).

MSR grade	Model
2100f 1.8E	$18.69 * \exp(2.962 * LLAD + 0.025*JWPC20 - 2.95811*LLAD^2 - 0.000783*JWPC20^2$
1650f 1.5 E	$38.1 * \exp(0.79 * LLAD - 0.702 * LLAD^2 - 0.000105 * JWPC20^2)$
1450f 1.3E	Obtained by subtraction
No. 3	$0.93 * \exp(3.415 * LLAD - 0.761*LLAD^2) + 0.003 * JWPC20^2$
Economy	$2.93 * \exp(1.105 * LLAD - 0.0106 * JWPC20)$

LLAD: Large limb average diameter (average of largest limb in each log quadrant in inches).
JWPC20: Percentage of juvenile wood corresponding to 20-year annual rings from the pith (cubic feet of juvenile wood divided by cubic feet of log volume).

It was assumed that all logs produced by the bucking model could be converted into the five different lumber grades shown in Table 4.2. Percentage of grade recovery was predicted instead of absolute volume. Fahey *et al*. (1991) point out that the use of absolute volumes in prediction equations usually involves a correction for unequal variances. Also, estimates based on percentages are less affected by variation in volume recovery among logs.

In Fahey *et al*. (1991) (same methodology used by Aubry *et al*. (1998)) all logs were sawn into 2 x 4 in. (38 x 91 mm) and 2 x 6 in. (38 x 143 mm) lumber at a state-of-the-art sawmill in western Washington. Lumber was kiln dried, surfaced, and graded by using visual and MSR systems. Fahey *et al*. (1991) used this limited product mix to help ensure that lumber recovery would reflect the inherent quality of the wood and not the skill of the sawyer in making lumber. Also, most MSR-graded lumber is marketed in these two sizes. For the MSR testing each board was assigned a Fb (extreme fiber stress in bending) class by a lumber grade using the MSR visual grade requirements (WWPA 2005). Thus, boards meeting minimum visual grade criteria for MSR were machine tested and both average and low point of MOE (modulus of elasticity) were recorded. Boards not meeting minimum MSR criteria reverted to the assigned visual grade, and this value was used to estimate MSR stem dollar value (Aubry *et al*. 1998). Recovery of chips and sawdust was measured in the latter study. Their proportions were estimated by using the equations provided by Fahey *et al.* (1991) and presented in Table 4.3.

Table 4.3 - Cubic recovery percent equations for rough green lumber, sawdust, and chips. Source: Fahey *et al.* (1991).

Product	Equation	R2	SEE
RG Lumber	71.83 – 178/D – 12.4 taper	0.32	10.07
Sawdust	9.6 – 20/D – 1.9 taper	0.23	1.41
Chips	by subtraction: 100 – (RG lumber + sawdust)		

* D is small end diameter in inches. Taper is in inches per foot.

Prices of lumber in each grade are shown in Table 4.4. They were obtained from the Financial Evaluation of Ecosystem Management Activities (FEEMA) software (Chmelik *et al*. 1999) and updated to the year 2002.

Table 4.4 - Lumber prices for MSR and visual grades.

MSR grade	Lumber price ($/MBF)	Visual grade	Lumber price ($/MBF)
2100f 1.8E	441	No. 3	232
1650f 1.5 E	398	Economy	123
1450f 1.3E	338		

To obtain the total lumber revenue from a particular log, the following steps were carried out:

1. Obtaining the lumber recovery factor (LRF), the ratio of board feet lumber produced from a log divided by log volume in cubic feet. Values of LRF were obtained from tables which use log length and diameter as inputs (Hallock *et al*. 1979).
2. Obtaining grade yield percentages (with equation shown in Table 4.2)
3. Multiplying LRF by log volume to estimate the total yield of lumber
4. Multiplying the total yield of lumber by a grade yield percentage and price to get the value of the log in that grade.

The cost of processing logs into lumber was estimated (and then updated) using an equation developed by Briggs and Fight (1992). Basically, the cost is estimated as a function of small-end diameter and subtracted from the revenue estimate to yield net product value.

4.4.5 Pulp logs

The net product value per metric ton of pulp was calculated following the methodology presented by Briggs and Fight (1992). It estimates net product value per cubic foot of wood in the pulp yard. This is comparable to the net product value estimates for lumber and veneer. As mentioned by Briggs and Fight (1992) this approach should be considered just as a first approximation due to limitations of available research data for Douglas-fir.

The net return (NR) per metric ton of pulp is given by:

$$NR = SP - (WC + NWC + FC)$$

where:

SP = selling price per metric ton of pulp

WC = wood cost per metric ton of pulp

NWC = non-wood cost per metric ton of pulp (energy, chemicals, labor, etc.)

FC = fixed cost per metric ton of pulp (overhead, depreciation, interest)

To get the net product value (NPV) per metric ton of pulp, the following equation is used:

$$NPV = SP - NWC - FC \times (BDN / BD)$$

where:

BDN = "normal" basic density

BD = basic density of the actual log

Likewise, to convert \$ per metric ton of pulp to cunits of wood in the yard, the following expression is used (more details in Briggs and Fight, 1992):

$$\text{NPV per cunit} = 2.83 \times BD \times Y \times (SP - NWC - FC \times (BDN / BD)$$

where Y = pulp process yield (ratio of dry metric ton of pulp per dry metric ton of wood).

Inputs needed to estimate the NPV per cunit were obtained from different sources. The TD Bank Financial Group reports a pulp price of \$630 per metric ton (TD Bank Financial Group 2004). Costs were obtained from Briggs and Fight (1992) and updated by using a consumer price index table (NWC = \$143 per metric ton of pulp, FC = \$94 per metric ton of pulp). Yield was assumed as 0.5, and the “normal” basic density was estimated as the species average (450 kg m^{-3}) from Bowyer *et al*. (2003).

Basic density measurements were not gathered for the 100 Washington state trees used in this study. As an alternative, basic density was estimated for each 0.1-meter section of log by using a regression equation obtained from approximately 400 wood samples of trees (Douglas-fir) located in the Coastal and Cascade Ranges of Oregon (Acuna and Murphy 2006). This equation has basic density as the response variable and height within the tree as the explanatory variable.

4.5 RESULTS

Stems were optimally bucked and logs grouped according to log-types. Then, average values for log length, small end diameter, and log volume were calculated for these log-types. Table 4.5 shows a summary of these values.

Table 4.5 - Summary of the logs produced by the optimal bucking system.

Log-type	Number of logs	Average log length (ft.)	Average small end diameter (in.)	Average log volume (ft^3)	Average log volume (BF*)
ES1	93	29.6	15.4	46.3	523.4
ES2	5	38.9	14.9	55.6	628.3
ES3	15	27.7	14.3	38.2	432.2
ES4	2	32.2	9.2	16.8	173.4
DS1	34	17.7	12.8	18.7	193.0
DS2	2	40.0	13.5	48.2	496.1
DS3	24	19.4	8.5	9.3	95.6
FIBER**	108	17.0	9.5	11.2	----

*: Board feet
**: FIBER corresponds to pulplogs, the rest of types are sawlogs.

Of the 283 logs obtained through the optimal bucking procedure, 38 percent of them correspond to pulp logs (log-type FIBER) and 33 percent to log-type ES1. On the other hand, the lowest percentage of logs (less than 2 percent) was associated with log-types ES2, ES4, and DS2. With the exception of the log-type DS3, all average sawlogs have a volume larger than 150 board feet. The specifications for DS3 include shorter lengths and smaller diameters than the other saw log-types. Largest average dimensions were found in log-types ES1, ES2 and DS2 whose corresponding volumes are around 500 BF or even greater. Log-types ES1 and ES2 are the ones with highest prices and the more demanding specifications. Most of these logs correspond to butt logs. On the other hand, pulplogs are located on the top of the stem and have smaller diameters and less volume than sawlogs.

Figure 4.1 shows the proportion of logs associated with rough green lumber, chippable product, and sawdust as a product of the conversion process of logs into lumber. Equations show that the proportion of each product (Table 4.3) is only dependent on the small end diameter and taper of logs. We assumed a taper of 0.25 inch/foot (21 mm per m) for all logs, as used in the analysis carried out by Fahey *et al*. (1991). Thus, the only variable affecting the above proportion was the small end diameter of logs. From Figure 4.1 it is possible to observe that the proportions of the lumber, chip and sawdust remain relatively constant for all log-types. This means almost 60 percent for rough green lumber, 30 percent for chippable volume, and about 10 percent for sawdust. The exception to this pattern is given by log-types ES4 and DS3, in which the proportion of rough green lumber and chippable product ranges between 45 and 50 percent, whereas the proportion of sawdust remains at 10 percent. However, these two log-types have the smallest end diameters (9.2 and 8.5 inches [234 and 216 mm], respectively) which have a direct impact on the proportion of products in terms of the volume and revenue obtained.

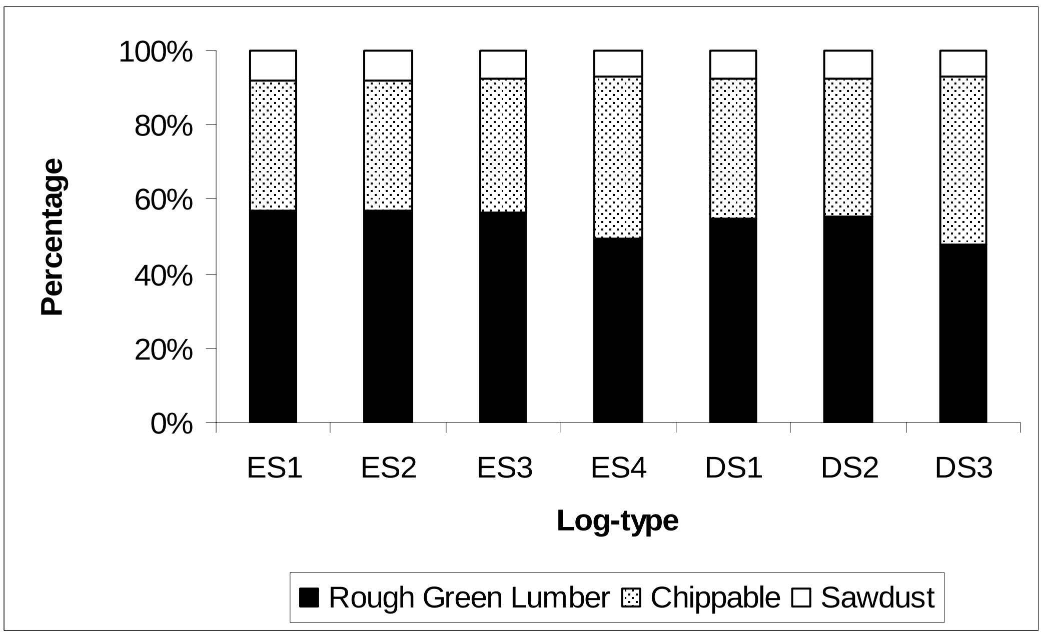

Figure 4.1 - Percentage of log volume by log-type in green lumber, chippable product and sawdust form.

Although the above proportions are dependent on taper and small end diameters, results obtained when changing these parameters show that proportions are not strongly sensitive to them. This explains the patterns observed in Figure 4.1, where for a range of diameters and log lengths, proportions remain practically constant.

Volume of products associated with visual and MSR grades are presented in Figure 4.2. The analysis was performed on each average log to see the effect of basic density on the volume of lumber grades by log-type. In Figure 4.2a, a basic density of 350 kg m^{-3} was used with every single log-type, whereas in Figure 4.2b, a density of 550 kg m^{-3} was employed. When a density of 350 kg m^{-3} was used, most volume was concentrated on the visual grade No. 3 as well as on machine stress grade 1450f 1.3E. Largest volumes were obtained for average logs in log-types ES1, ES2, ES3 and DS2. The percentages of lumber visual grade No. 3 associated with these log-types corresponds to a 49.7 percent of the total volume, whereas 31.9 percent corresponds to MSR lumber grade 1450f 1.3E. Likewise, the most valued grades (2100f 1.8E and 1650f 1.5E) only represent 0.1 and 12.2 percent of the total volume, respectively.

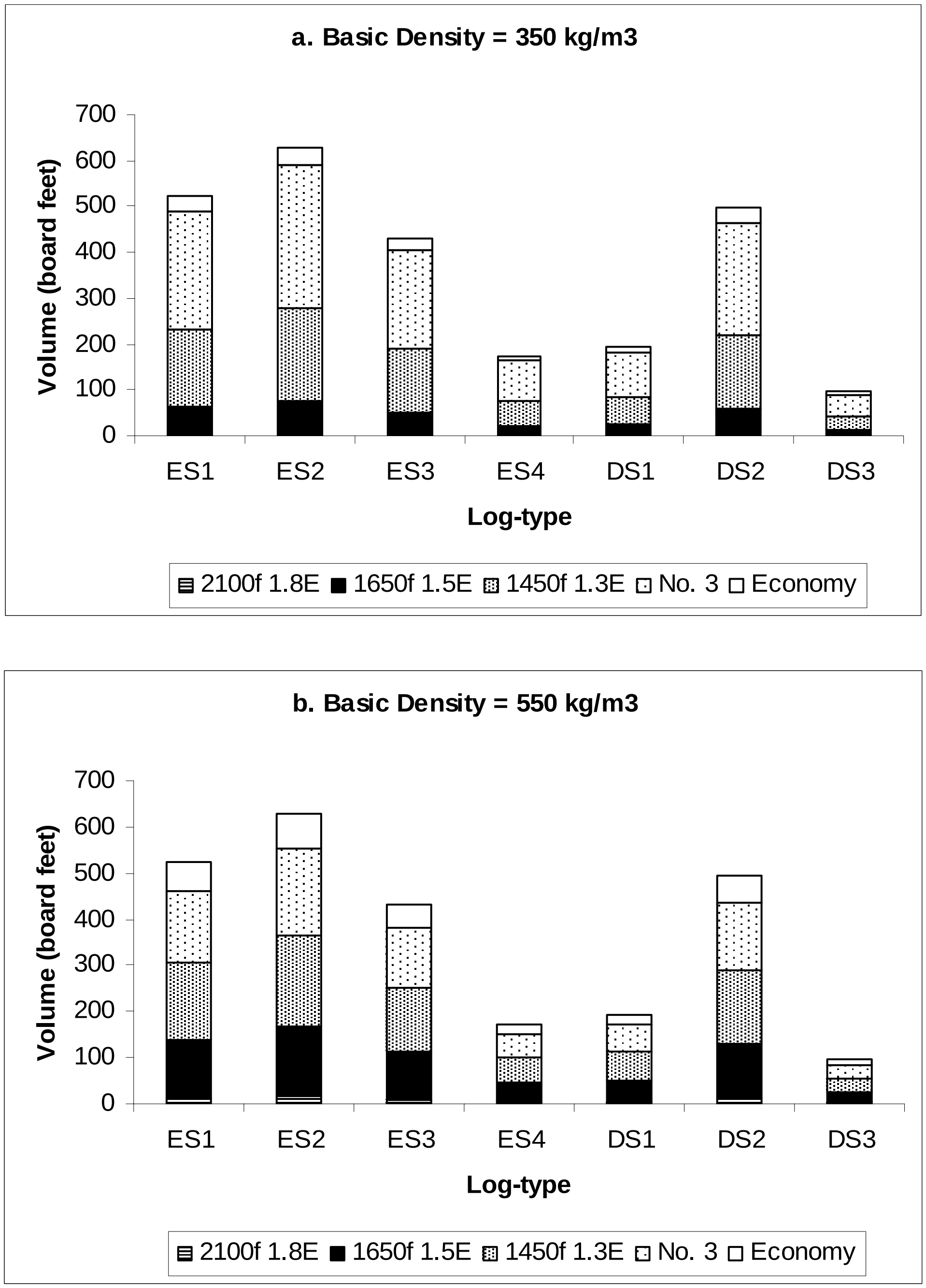

Figure 4.2 - Volume of green lumber, chippable product and sawdust by log-type for two basic densities.

Proportions and absolute values change when a density of 550 kg m^{-3} is used to compute the total volume in each lumber grade (Figure 4.2b). In this case, a more balanced output of products is observed in all log-types. MSR grades 2100f 1.8E, 1650f 1.5E and 1450f 1.3E account for 2.4, 24.2, and 31.6 percent of the total volume, respectively. Likewise, visual grades No. 3 and Economy account for 29.9 and 11.9 percent, respectively. This means that with this basic density, the volume is distributed with 60% for MSR and 40% for visual grades, whereas just the opposite tendency is observed with a density of 350 kg m^{-3}.

Returns ($ per log) for average logs associated with visual and MSR grades are presented in Figure 4.3. When a density of 350 kg m^{-3} was used (Figure 4.3a), most return is concentrated on the visual grade No. 3 as well as on MSR grade 1450f 1.3E, with 38.6 and 41.3 percent, respectively. As in the case of volume, largest returns were obtained for average logs in log-types ES1, ES2, ES3 and DS2. In this case, most valued grades (2100f 1.8E and 1650f 1.5E) only represent 0.1 and 17.2 percent of the total volume, respectively.

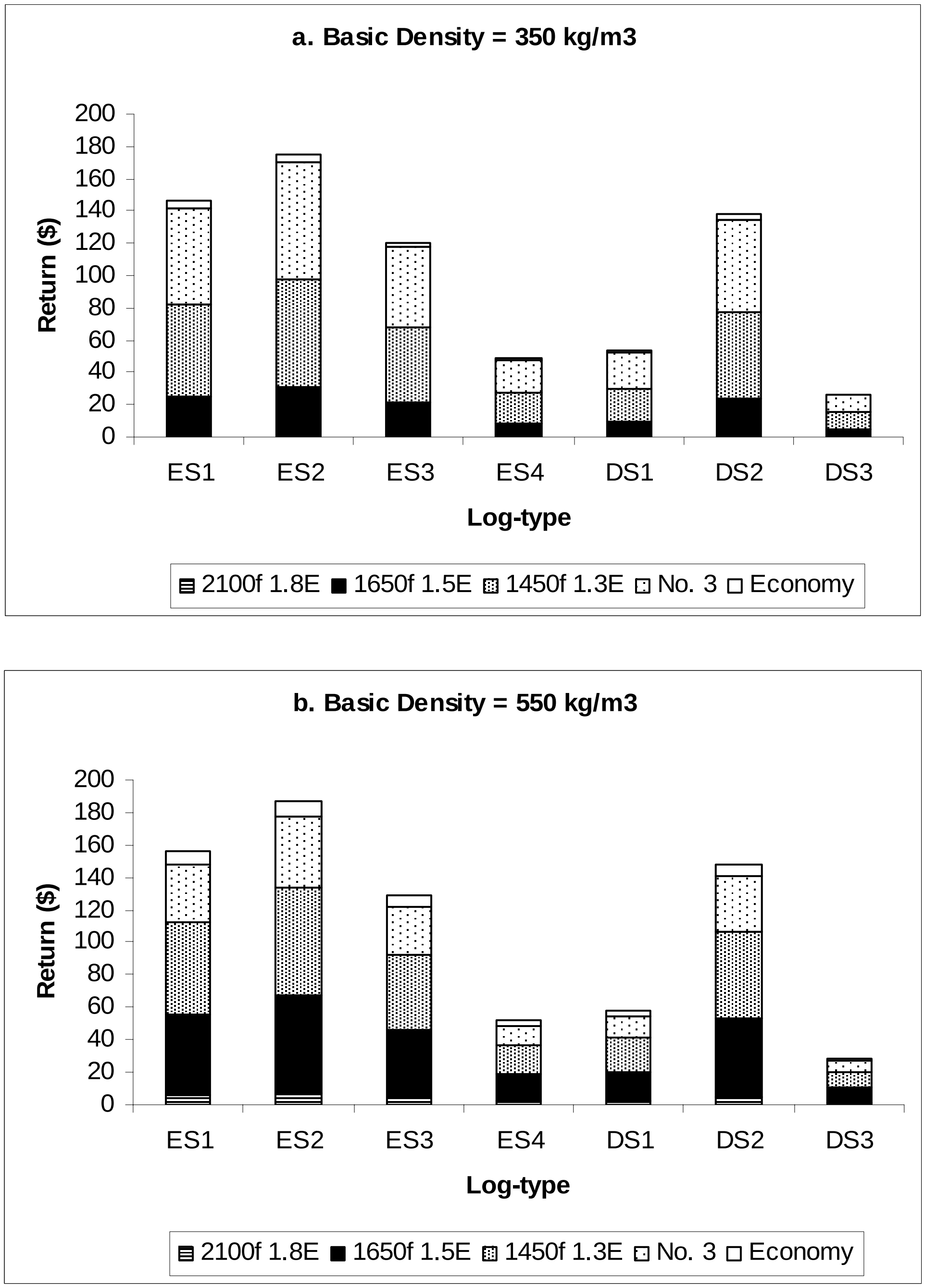

Figure 4.3 - Returns ($ per log) for green lumber, chippable product and sawdust by log-type for two density classes.

When a density of 550 kg m^{-3} is used (Figure 4.3b), it is observed that the return is distributed in a number of lumber grades. MSR grades 2100f 1.8E, 1650f 1.5E and 1450f 1.3E represent 3.5, 32.3, and 35.9 percent of the total return, respectively. Likewise, visual grades No. 3 and Economy represent 23.3 and 4.9 percent, respectively. With this value of basic density, the net return is distributed with about 70 percent for MSR and 30 percent for visual grades. For a density of 350 kg m^{-3}, MSR lumber represents about 56 percent, whereas visual grades account for 44 percent of the total return, being mostly associated with No.3 grade. It is necessary to mention that these values correspond to returns obtained by using the prices shown in Table 4.4 and the volumes of lumber in each grade. Returns associated with chippable product as well as sawdust are not presented in Table 4.4 although they were used in the analysis.

An important analysis made in this study had to do with the changes in net return for a range of different basic densities. For a number of log-types, net returns for average logs are presented in Figure 4.4. For lumber, the net return ($ per log) is given by the return of lumber, chippable product and sawdust minus the processing costs incurred to convert logs into lumber. For pulp, non-wood and fixed costs were subtracted from pulp selling price.

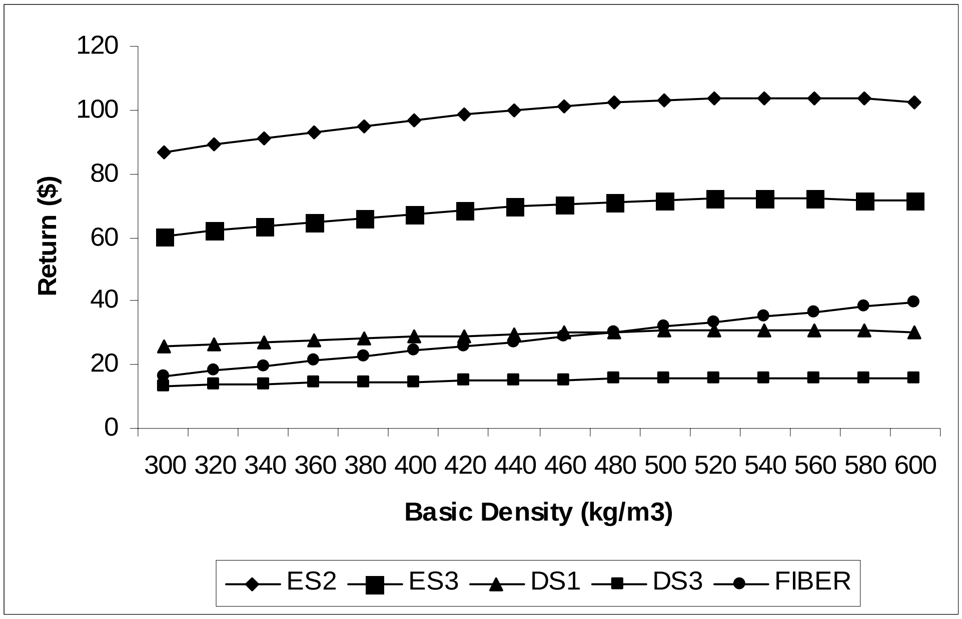

Figure 4.4 - Returns ($ per log) by log-type for a range of basic densities (300-600 kg m^{-3}).

Figure 4.4 shows that, for log-types ES2 and ES3, there is an important increment in net return when basic density is varied from 300 kg m^{-3} to 600 kg m^{-3}. For log-type ES2, the net return for the average log varies between $86.7 and $102.5, which accounts for 18 percent increment. The maximum net return is reached with a basic density of 540 kg m^{-3} and is equal to $103.8. Larger values of density diminish the volume of product associated with lumber grades 1450f 1.3E and Economy which slightly reduces the net return obtained. However, differences in net return for densities above 500 kg m^{-3} are not significant and present just a minimum variation. For log-type ES3, net return follows the same tendency as log-type ES2, with returns ranging from $60.4 to $71.3.

Different from the above patterns, log-types DS1 and DS3 have flatter curves, with net returns that vary just a little bit through the range of basic densities. Net return for log-type DS1 ranges from \$25.5 (300 kg m^{-3}) to \$30.3 (600 kg m^{-3}). However, their proportions still account for an increment of about 18 percent. In the case of log-type DS3, net return varies from \$13.2 (300 kg m^{-3}) to \$15.6 (600 kg m^{-3}), being the lowest range for an average log considered in the study.

On the other hand, net returns for log-type FIBER (pulplogs) vary from \$16.5 to \$39.7, which accounts for an increment of 141 percent. This important linear increment indicates that pulp, as an end product, is more sensitive to variations in basic density of logs than lumber. It is important to mention that net returns were calculated with current selling prices which have been relatively high in the last two years. With lower selling prices and higher costs, the effect of basic density may be neutralized and lower net returns may be expected. Another factor which impacts net returns is pulp yield, which was assumed here as 0.5 (Bowyer *et al*. 2003).

In the next step, the range of basic densities were grouped under three different classes, from 300 to 399 kg m^{-3} (lower class), 400 to 499 kg m^{-3} (middle class), and 500 to 600 kg m^{-3} (upper class), and an average net return was calculated for each class. The difference in net return of the lower and upper class in relation to the middle class is presented in Table 4.6. When considering all the log-types associated with lumber, maximum difference for the lower density class is reached by log-type DS2 with 9.1

percent, whereas for the upper density class it is 3.9 percent. For all the log-types, bigger differences are found in the lower density class than in the upper density class. This is explained by the fact that basic density increases the net return up until a certain point. Beyond that, the effect of density is reduced and its marginal effect is less important than for lower densities. This may be corroborated by observing the tendency of volume and return presented in Figures 4.2 and 4.3.

Table 4.6 - Net return ($ per log) by basic density classes and log-types. Percentage differences between the middle class and lower or upper class are shown in parentheses.

Log-type	Lower Class (300-399 kg m^{-3})	Middle Class (400-499 kg m^{-3})	Upper Class (500-600 kg m^{-3})
ES1	75.1 (-8.7)	82.3	85.4 (+3.7)
ES2	91.1 (-8.7)	99.7	103.4 (+3.7)
ES3	63.5 (-8.6)	69.4	71.9 (+3.6)
ES4	25.3 (-8.6)	27.7	28.7 (+3.7)
DS1	26.8 (-9.0)	29.5	30.6 (+3.8)
DS2	67.9 (-9.1)	74.7	77.6 (+3.9)
DS3	13.8 (-8.7)	15.2	15.7 (+3.7)
FIBER	19.6 (-28.3)	27.3	35.8 (+31.2)

For log-type FIBER, considerable marginal gains are obtained by going from lower to upper density classes. Lower class net return is 28.3 percent lower than that of the middle class, which represents a reduction of more than 3 times in comparison to that of lower classes associated with lumber log-types. On the other hand, upper class average net return is 31.2 percent higher than that of the middle class, representing an increase of almost 4 times with regard to this class. These values confirm the effect of basic density on the net return to be obtained by the pulp industry as well as the importance of a proper segregation of logs as soon as possible in the supply chain from the forest to the mill.

Lastly, percentages of reduction and increment presented in Table 4.6 were assigned to log prices for each basic density class. Current log prices in each log-type were arbitrarily assigned to the middle class. Then, with the above reduction and increment percentages it was possible to estimate the log prices for lower and upper classes (Table 4.7).

Table 4.7 - Log prices (\$ per m^3) by basic density classes and log-types

Log-type	Lower Class (300-399 kg m^{-3})	Middle Class (400-499 kg m^{-3})	Upper Class (500-600 kg m^{-3})
ES1	136.0	149.0	154.5
ES2	120.3	131.7	136.5
ES3	114.7	125.4	129.9
ES4	85.2	93.2	96.6
DS1	94.2	103.5	107.4
DS2	88.0	96.8	100.5
DS3	70.0	76.6	79.4
FIBER	15.7	21.9	28.7

The number of classes was also chosen arbitrarily, but taking into account the capability of harvesters with computers aboard. Although theoretically it is possible to assign prices to logs with different basic densities based on a price function, adjusting a list with more than three prices can be a difficult task to carry out, especially if a considerable number of log-types are being used. Also, it is less likely that markets can assign more than two or three prices to the same log-type; in general, prices of wood products are volatile and are always changing.

4.6 DISCUSSION AND CONCLUSIONS

This study shows that it is possible to estimate log prices of Douglas-fir based on wood density, by calculating the net return of end-products (lumber and pulp) obtained from logs. For lumber, a number of different grades and their prices are used to estimate the price that markets would be willing to pay for logs. For pulp logs, the price is estimated from the net product value per metric ton which considers pulp selling price and non-wood costs and fixed costs.

The importance of including density into a bucking system is that its inclusion may reduce the total value recovered by the forest owner, unless appropriate premiums are paid for additional properties. Therefore, it is essential to elaborate methodologies that allow companies to estimate the price that markets are willing to pay for logs with different external characteristics, such as basic density. Previous studies have shown that the requirement of minimum levels of basic density for log-types (without premium prices for additional properties) can reduce the total value by as much as 40% (Acuna and Murphy, [unpublished A]). The results presented in this study are valid for a supply-constrained market which takes as much or as little volume of each log-type as each wood owner can produce at the stated market prices. Hence the wood owner's objective should be to maximize the value of each and every individual tree.

The authors are unaware of any studies that have tried to make an estimation of the premium price that markets would be willing to pay for logs with better internal characteristics, such as a higher wood density. They are also unaware of any studies that have analyzed the economic effects of optimally bucking logs based on prices differentiated according to an internal wood characteristic.

There are limitations associated with this study which could have affected the results and our conclusions: only one stand was used, one set of market conditions were evaluated, the equation to convert basic density to percent of juvenile wood was built from a small sample, only lumber and pulp were considered as end-products to calculate net returns, equations used to calculate the proportion of lumber in each grade as well as the proportion of sawlogs available to be sawn were extracted from a previous study (Fahey *et al*. 1991), arbitrary density classes were used, and a density function was used, rather than actual density, to calculate the density at each segment of a stem.

Results obtained show that pulp as an end product is more sensitive to variations in basic density of logs than lumber. However, the real effect of density is also determined by selling prices and processing costs. With lower selling prices and higher costs, the effect of basic density may be neutralized and lower net returns may be expected. For the lower basic density class, net returns (and log prices) for pulp were about 28 percent lower than the middle class, whereas the upper class net return was 32 percent higher than the middle class. For lumber log-types, the percentage differences between lower and upper class with the middle class were on average 8 and 4, respectively.

The next steps in this research should be the analysis of the effect of density on revenue in demand-constrained markets, as well as an assessment of the impact of new additional wood properties in increasingly competitive markets. The study of new approaches to estimate premium prices for logs based on internal wood characteristics will allow for validation of the results presented here and facilitate the elaboration of a standard methodology for estimating log price premiums.

Finally, although the methodology presented in this study is subject to limitations and based on some assumptions, the results presented give an indication of the potential impacts of new market requirements and how these can affect companies' decision-making in the future. In the meantime, wood producers can expect the evolution of markets for new requirements and be prepared for such changes.

4.7 REFERENCES

ACUNA, M.A.; MURPHY, G.E. 2006. Geospatial and within tree variation of wood density and spiral grain in Douglas-fir. *For. Prod. J.* (accepted for publication).

ACUNA, M.A.; MURPHY, G.E. (unpublished A). Optimal bucking considering external wood properties and wood density. *New Zealand J. For. Sci.* (in review).

ACUNA, M.A.; MURPHY, G.E. (unpublished B). Use of near infrared spectroscopy and multivariate analysis to predict wood density of Douglas-fir from chain saw chips. *For. Prod. J.* (in review).

ADAMS, D.M.; SCHILLINGER, R.R.; LATTA, G.; VAN NALTS, A. 2002. Timber harvest projections for private land in Western Oregon. Oregon State University, Forest Research Laboratory. Reseach Contribution 37. 44 p.

ANDREWS, M. 2002. Wood quality measurement – *son et lumiere. New Zealand J. For.* 47(3): 19-21.

ANONYMOUS. 1965. Western wood density survey. Report Number 1. USDA Forest Research Paper FPL-27. 58pp.

AUBRY, C.L.; ADAMS, W.T.; FAHEY, T.D. 1998. Determination of relative economic weights for multitrait selection in coastal Douglas-fir. *Can. J. For. Res.* 28: 1164-1170.

BARBOUR, R.J.; KELLOGG, R.M. 1990. Forest Management and end-product quality: a Canadian perspective. *Can. J. For. Res.* 20: 405-414.

BENDTSEN, B.A.; SENFT, J. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. *Wood and Fiber Sci.* 18(1): 23-38.

BOWYER, J.L.; SHMULSKY, R.; HAYGREEN, J.G. 2003. Forest Products and Wood Science: An Introduction. Fourth edition. Iowa State University Press. 554 p.

BRIGGS, D.G. 1994. Forest products measurements and conversion factors: With special emphasis on the U.S. Pacific Northwest. College of Forest Resources, University of Washington. 154 p.

BRIGGS, D.G.; FIGHT, R.D. 1992. Assessing the effects of silvicultural practices on product quality and value of coast Douglas-fir trees. *For. Prod. J.* 42(1): 40-46.

CHMELIK, J.T.; FIGHT, R.D.; BARBOUR, R.J. 1999. Softwood lumber prices for evaluation of small-diameter timber stands in the Intermountain West. USDA Forest Service, Forest Product Laboratory. Research Note FPL–RN–0270.

CORSON, S.R. 2001. Optimal allocation and use of today's trees for wood and paper products – the New Zealand experience. Presentation to the Markus Wallenberg Prize Ceremony, Stockholm, Sweden, 2 October. 18 p.

EDLUND, J.; WARENSJO, M. 2005. Repeatability in automatic sorting of curved Norway Spruce saw logs. *Silva Fennica* 39(2): 265-275.

ERNST, S.; FAHEY, T.D. 1986. Changes in product recovery of Douglas-fir from old growth to young growth. *In* Proceedings of a Symposium, Douglas-fir: Stand Management for the Future, 18–20 June 1985, Seattle, Wash. Edited by C.D. Oliver, D.P.

FAHEY, T.D.; MARTIN, D.C. 1974. Lumber recovery from second-growth Douglas-fir. USDA Forest Service. Research paper PNW-RP-437. 25 p.

FAHEY, T.D., CAHILL, J.M.; SNELLGROVE, T.A.; HEATH, L.S. 1991. Lumber and veneer recovery from intensively managed young growth Douglas-fir. Res. Pap. PNW-RP-437. USDA Forest Serv. Pacific Northwest Research Station. Portland, Oregon.

GARTNER, B.L. 2005. Assessing wood characteristics and wood quality in intensively managed plantations. *J. For.* 100(2): 75-77.

GARTNER, B.L.; NORTH, E.M.; JOHNSON, G.R.; SINGLETON, R. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. *Can. J. For. Res.* 32: 439-447.

GREEN, D.W.; ROSS, R. 1997. Linking log quality with product performance. Role of wood production in ecosystem management. *In* Proceedings of the Sustainable Forestry Working Group at the IUFRO All Division 5 Conference, Pullman, Washington, July 1997. p. 53-58.

HALLOCK, H.; STEELE, P.; SELIN, R. 1979. Comparing lumber yields from board-foot and cubically scaled logs. USDA Forest Service, Forest Products Laboratory. Research Paper FPL 324.

JAPPINEN, A. 2000. Automatic sorting of sawlogs by grade. Doctoral thesis. Department of Forest Management and Products, Swedish University of Agricultural. Uppsala, Sweden.

JOZSA, L.A.; MIDDLETON, G.R. 1994. A discussion of wood quality attributes and their practical implications. Forintek Canada Corp., Vancouver, BC. Special Publ. No. SP-34.

KENNEDY, R.W. 1995. Coniferous wood quality in the future: concerns and strategies. *Wood Sci. and Technol.* 29(5): 321–338.

LANE, P.H., WOODFIN, R.O.; HENLEY, J.W.; PLANK, M.E. 1973. Lumber recovery from old-growth coast Douglas-fir. Res. Pap. RP-PNW-154. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station.

MARSHALL, H. 2005. An investigation of factors affecting the optimal output log distribution from mechanical harvesting and processing systems. Ph.D. Thesis, Oregon State University. 200 p.

MATHESON, A.C.; ROSS, L.D.; SPENCER, D.J.; JOE, B.; ILIC, J. 2002. Acoustic segregation of *Pinus radiata* logs according to stiffness. *Ann. For. Sci.* 59(2002): 471-477.

MCKEEVER, D.B. 2000. Timber and fiber demand and technology assessment: Demand for engineered products. USDA Forest Service, Forest Products Laboratory. 2 p.

MEGRAW, R.A. 1986. Douglas-fir wood properties. P. 81-96 in Douglas-fir: Stand management for the future, Oliver, C., D. Hanley, and J. Johnson (eds.). Inst. of For. Res. Contrib. 55. College of Forest Resources, University of Washington, Seattle.

MURPHY, G.E. 2003. Mechanisation and value recovery: worldwide experiences. Pp. 23-32 *in* Proceedings of the "Wood for Africa 2002 Conference", July 2002, Pietermaritzburg, South Africa. College of Forestry, Forest Engineering Department, Oregon State University, Corvallis, Oregon.

MURPHY, G.; MARSHALL, H.; CONRADIE, I. 2003. Market complexity and its effect on variables that gauge the economics of harvesting production. *New Zealand J. For. Sci.* 32(2): 281-292.

SCHULER, A.; CRAIG, A. 2003. Demographics, the housing market, and demand for building materials. *For. Prod. J.* 53(5): 8-17.

SO, C.L., GROOM, L.H.; RIALS, T.G.; SNELL, R.; KELLEY, S.; MEGLEN, T. 2002. Rapid assessment of the fundamental property variation of wood. *In* Outcalt, K.W. (Ed.) "Proceedings of the 11th Biennial Southern Silvicultural Research Conference". USDA Forest Service, Southern Research Station, General Technical Report SRS-48. 622 p.

SONNE, E.; TURNBLOM, E.; BRIGGS, D. 2004. Log and lumber grades and value from a Douglas-Fir stand 20 years after thinning and biosolids fertilization. *Western J. Appl. For.* 19(1): 34-41.

TD BANK FINANCIAL GROUP. 2004. TD Commodity price report. December, 2004. www.td.com/economics (Accessed November 2005).

USDA FOREST PRODUCTS LABORATORY. 1987. Wood Handbook: Wood as an Engineering Material. Agri. Handb. 72. USDA Forest Service, Washington, D.C.

WALKER, J.C.; BUTTERFIELD, B.G.; LANGRISH, T.A.; HARRIS, J.M.; UPRICHARD, J.M. 1993. Primary Wood Processing. Chapman and Hall, London. 595 pp.

WILLITS, S.A.; LOWELL, E.C.; CHRISTENSEN, G.A. 1997. Lumber and veneer yields from small-diameter trees. *In* Proceedings of the Sustainable Forestry Working Group at the IUFRO All Division 5 Conference, Pullman, Washington, July 1997. p. 73-79.

WWPA. 2005. Western lumber grading rules. Western Wood Products Association. Portland, Oregon.

YOUNG, G.G. 2002. Radiata pine wood quality assessments in the 21st century. *New Zealand J. For*. 47(3): 16-18.

CHAPTER 5

OPTIMAL BUCKING CONSIDERING EXTERNAL PROPERTIES AND WOOD DENSITY OF DOUGLAS-FIR

Mauricio Acuna and Glen Murphy

Department of Forest Engineering

Oregon State University

Corvallis, OR 97331-5706

USA

New Zealand Journal of Forestry Science (in press)
SCION

Te Papa Tipu Innovation Park, 49 Sala Street

Private Bag 3020, Rotorua

New Zealand

5.1 ABSTRACT

During recent years niche markets have begun to demand forest products with specific characteristics. Traditionally markets required products with particular external log properties such as diameter, length and knot size. However today's log markets are beginning to include new wood properties, such as basic density and stiffness. Although markets have not responded to these new requirements with price incentives for producers to meet such demands, the new characteristics are nevertheless valued by these markets. This paper focused on basic density as an example of a new wood property to be included when bucking stems into logs. An optimal bucking procedure, which included wood density, was developed. Four hypothetical market scenarios, covering a range of density specifications and price incentives, were evaluated. The economic implications as well as the distribution of the log-types, when including this variable, are presented. Results show that in a density-constrained scenario the total revenue can be substantially reduced when compared to a scenario without the requirement of this wood property.

Keywords: Optimal bucking, internal wood properties, basic density, value recovery

5.2 INTRODUCTION

Forest harvesting has become increasingly mechanized during the last few decades. The drivers for this worldwide trend are the potential for improving productivity and reducing costs, as well as labor-related and safety issues. Mechanization brings along with it innovative communication and measurement systems, as well as powerful on-board computers into the forest. These provide opportunities to: reduce the variability in product performance by sorting for niches uses, capture and store detailed descriptions of many stems within each stand, reduce the variability in decision-making about which are the best markets to supply from each tree, and optimally control the bucking of logs at harvesting time (Murphy *et al*. 2004).

The objective of wood allocation from the forest owners' perspective is to maximize the economic return from the logs optimally bucked from each tree. The log buyers' objective is to obtain logs which can be optimally processed to yield maximum economic return and the best product performance based on solid wood and fibre qualities. The price the buyer is willing to pay depends on how well the supplier's logs meet his objectives.

Differences in tree architecture and chemistry within the stem of a tree, and between trees and growth sites can result in a different wood and fibre structure and product performance characteristics leading to different economic returns for forest products producers. (Corson 2001). Industry has begun to strategically incorporate these differences and specifications to achieve optimal allocation and processing of the forest estate.

Each tree can be segmented for wood utilization on the basis of stem quality, as determined by its macro-scale properties. Value recovery operations, therefore, must ensure the extraction of the more valuable solid wood grades. Poor attention to value recovery can result in substantial losses for the forest owner; value losses during bucking of 30% and higher have been reported (Geerts and Twaddle 1984; Sessions 1988; Haynes and Visser 2004; Boston and Murphy 2003; Murphy 2003). If separation into multiple logs-sorts is done in-forest to meet market needs, it can have an impact on a range of harvesting production variables such as equipment requirements, value recovery, waste generation, productivity, cost, and landing size. These in turn can affect the overall economics of the operation.

The number of characteristics used to specify log-types is increasing. Traditionally, species, dimensions and external quality characteristics such as branch size, sweep, scarring and decay have been used to specify a particular log-type. However, today markets are beginning to include additional characteristics to specify the logs they require. For instance, consideration is now being given to such wood properties as stiffness, strength, density, spiral grain, extractives content, and consumption of energy for processing (Andrews 2002; So *et al.* 2002; Walker 2000; Young 2002).

Douglas- fir (*Psudotsuga menziesii* (Mirb.) Franco) was selected for this study since it has a large economic importance, especially for the forest products industries of the United States, New Zealand, and some parts of Europe (Gartner *et al.*, 2002), due to its primary uses as dimension lumber, piles, plywood, and pulp. Basic density was chosen for this study since it is an internal property measure which is preferred by most markets, as it provides an excellent means of predicting end-use characteristics of wood such as strength, stiffness, hardness, heating value, machinability, pulp yield and paper making quality (Jozsa and Brix 1989). Knowles *et al.* (2004) have shown, for example, that outerwood density cores provided a reasonably accurate method for assessing breast height stiffness of individual standing Douglas-fir trees. Although today there are no formal markets paying a differentiated price for logs with a determined basic density, they show a clear willingness to prefer products with a higher density (Corson 2001). For this reason it was considered important to evaluate the economic consequences of hypothetical market scenarios which wood producers might face in coming years.

The distribution of Douglas-fir tree basic density from Canada, USA, Europe and New Zealand tends to be bell shaped with a mean between 400 and 500 kg m^{-3}. Density for individual trees in the Western USA ranges between 330 and 570 kg m^{-3} (Anon 1965). Understanding the sources of variability of properties such as density will allow industry to better match wood to markets. In 1959, Knigge (1962), cited in Anon. (1965), selected five trees from each of 51 second growth (< 100 years old) Douglas fir stands situated between the Canadian border and northern California and from the

Coast Range to the western slopes of the Cascades. In general, density increased with age, improved with site class, increased with average growing season temperature and decreased with increasing growing season precipitation and increasing elevation. However, only 34% of the variation between individual trees could be accounted for. Acuna and Murphy (2006) studied the spatial variation of density for Douglas-fir in Western Oregon, and found that the only statistically significant variable (albeit weakly significant) was the height within the tree. Silvicultural management (e.g. pruning and spacing) has also been shown to affect density in some cases (Megraw 1986a, 1986b).

Bucking individual Douglas-fir stems into logs based on wood density will require tools for rapidly assessing density in the forest. Near infrared spectroscopy is one of the emerging technologies that shows promising potential for this task (Acuna and Murphy [unpublished B]; So *et al.* 2004).

5.2.1 Bucking algorithms

One of the most important processes during harvesting is bucking. The reasons for bucking a tree into sections are reduction of weight, segregation of defects and unmerchantable portions of the bole, adaptation to method of transportation and manufacture, and adaptation to market requirements (Conway 1982). Not all parts of a tree stem are merchantable. Therefore a key decision is how to cut the tree stem into different sections, which are commonly referred as to logs.

The process of producing logs from tree stems which achieves the highest value is known the bucking optimization problem (Pickens *et al.* 1997). Optimization can be seen from different perspectives. Bucking optimization problems may occur at the stem level, at the stand level and at the forest level. At the stem level, the bucking pattern that maximizes the individual stem value is determined. At the stand level, the best pattern for each stem and class is established (e.g. based on diameter at breast height), and the aggregate production value is maximized (Arce *et al*. 2002). At a forest level, the bucking pattern for each stand which maximizes global profit is established. A second segregation of problems (models) is referred as to buck-to-value and buck-to-order. The former deals with the optimal bucking of an individual tree, whereas the latter solves the problem of bucking multiples trees subject to demand constraints (Kivinen and Uusitalo 2002; Marshall 2005).

Most of the optimization techniques used to solve the bucking problem at the stem level are based on the use of techniques such as dynamic programming (DP), network programming, simulation and integer-linear programming (Briggs 1980; Nasberg 1985; Sessions 1988). Among these DP is the mathematical technique most employed by researchers. The first detailed and published description of the algorithm appeared in a paper of Pnevmaticos and Mann in 1972. In New Zealand, Geerts and Twaddle (1984) developed a dynamic programming algorithm which was implemented in a software package called AVIS (Assessment of Value by Individual Stems). Their formulation considered stem quality deterministically and each potential log was checked to make sure that the stem qualities in each state did not violate the required log type quality.

Studies on optimal bucking, which have incorporated internal (or non-traditional) variables in the bucking decisions, are difficult to find in the literature. Wood density has been included in at least one commercial bucking system (ATLAS 2006). Given the changing markets requirements for forest products, it is important that the economic impact of a wider range of variables be evaluated.

In the early 1990's value recovery audits of 10 logging crews were undertaken for a New Zealand forest company. One of the sawmills supplied by the forest company would only accept sawlogs found at heights of less than 20 meters in a tree because of concerns about low density wood occurring above this height. The 20-metre breakpoint for density was incorporated into the optimal bucking based value recovery audits (G. Murphy pers. comm.).

5.3 OBJECTIVE OF THE STUDY

The objective of this study was to determine the effect on the volume by log-type, as well as total volume and revenue, when requirements of density for each log-type are included in the log specifications. The study used hypothetical scenarios with different market requirements for density of the log-types in order to see the potential impact of density on decision-making and on the economics of the forest operation.

5.4 METHODS

5.4.1 Field site and tree data set

The data used in this study were collected from a dominant industrial Douglas-fir stand in the Pacific Northwest (Washington State). The site was selected based on logistics (location, and crew willingness to be studied) and the number of log-types being cut. Net stocked area of the stand was 12.18 ha, with an average stocking of 273 stems/ha. It was on mainly flat ground with an access road through the middle, and was clearfelled. The estimated average tree size was 2.35 m^3, and average diameter at breast height (dbh) was 46 cm based on field measurements made in 1997 and grown-on using tree growth models to give the stand parameters at the time of harvesting (Marshall 2005).

One hundred stems were used for testing the bucking procedure which is based on both external and internal properties. Detailed measurements were recorded in the field to characterize each stem (Marshall 2005). The variables used in the bucking model were: height, diameter, volume, quality, density. These were assessed at intervals of 0.1 m along the stem because log lengths were in multiples of 0.1 m.

Density was not measured by Marshall (2005). Basic density was, therefore, estimated for each 0.1 m section of the stem by using a regression equation obtained from 391 wood samples of trees (Douglas-fir) located in 17 young growth stands in the Coastal and Cascade Ranges of Oregon (Acuna and Murphy 2006). The density equation used is as follows:

$$\mu\{\mathrm{DENSITY} \mid \mathrm{HEIGHT}\} = 427.1 - 3.3\,\mathrm{HEIGHT}$$

$$(R^2 = 0.26)$$

where,

DENSITY = basic density (kg m^{-3})

HEIGHT = height above the base of the tree (m)

This density function should not be taken as being representative of all Douglas-fir stands.

5.4.2 Market requirements

The same market requirements (product specifications) were applied to all the stems (Table 5.1). Ten log types plus waste were included in the analysis. Nine of the log types included multiple lengths of 0.6 m. Fiber included multiple lengths of 0.1 m. A total of 122 log lengths were included in the analysis. Supply constrained markets were assumed – this meant that production of any particular log type was not limited by demand. The log supplier could, therefore, cut as much or as little volume of each log-type so that his value recovery was maximized. The quality required for each type of log was considered by the bucking model. The log-types included were sawlogs for export, (log-types ES1, ES2, ES3, ES4), and sawlogs and chipsaw logs for domestic markets (log-types DS1, DS2, DS3, CNS1 and CNS2). Pulpwood was included in the analysis (log-type FIBER).

Table 5.1 - Market requirements and constraints for the test stems.

Log-type	Lengths	Minimum Small-end Diameters	Relative Market Prices*	Quality Required
	(m)	(mm)	($/m^3)	
ES1	8.0 to 9.8	305	149	A
ES2	11.0 to 12.2	305	132	A
ES3	8.0 to 9.8	305	125	ABC
ES4	9.8 to 11.0	229	93	A
DS1	4.9 to 7.3	305	104	ABC
DS2	11.0 to 12.2	305	97	ABCD
DS3	4.9 to 7.3	203	77	ABCD
CNS1	4.9 to 7.3	127	68	ABCDE
CNS2	7.3 to 9.1	127	68	ABCDE
FIBER	3.7 to 12.2	127	22	ABCDE

* Prices reflect market conditions as of late 2002.

The qualities codes in Table 5.1 mainly relate to the size of knots (Table 5.2).

Table 5.2 - Quality codes and their characteristics

Code	Knot size (cm)	Code	Knot size (cm)
A	< 3.8	D	> 6.3 and < 7.6
B	> 3.8 and < 5.1	E	> 7.6
C	> 5.1 and < 6.3	W	Waste

5.4.3 Density scenarios

Density could be specified in at least three different ways: the minimum density found at any point along the length of a log, the average density found for a series of measurements along the length of a log, and the average density weighted by volume for a series of measurements along a log. The latter density definition most closely relates to weight scaling of logs. The density scenarios used in this paper refer to average basic density weighted by volume.

Four different scenarios were used to model the impact of density on volume recovery by log-type and on total value recovery (Table 5.3). These were chosen to reflect a range of possible market conditions and are by no means exhaustive.

Table 5.3 - Scenarios for density requirements used in the analysis

Logs	*Scenario 1 Minimum Density Required (kg m^{-3})	Scenario 2 Minimum Density Required (kg m^{-3})	Scenario 3 & 4 Minimum Density Required (kg m^{-3})
ES1	0	450	450
ES2	0	450	400
ES3	0	450	400
ES4	0	400	350
DS1	0	400	350
DS2	0	400	300
DS3	0	350	300
CNS1	0	350	300
CNS2	0	300	300
FIBER	0	300	300

* Control scenario.

The first scenario is the control scenario where no density requirements were imposed (current situation for traditional bucking procedures). The second scenario requires the highest densities. Each log-type required a high density to meet the constraints imposed by the market especially for the most valuable products, domestic and export sawlogs. No price premiums were specifically allocated to higher density logs. The third scenario could be considered as one with average density requirements and was less constrained than the second scenario. Again no price premiums for density were included in the third scenario.

Scenario 4, however, does use a differential price for each log-type, according to the wood density of logs. For this purpose, three density classes were established with corresponding prices for each type-log. These prices are shown in Table 5.4 and are based on expected product yields, revenues and processing costs for each log-type. A more detailed description of how the prices were calculated can be found in Acuna and Murphy (unpublished A). Again it is stressed that Scenarios 2, 3, and 4 are not based on real markets. They were selected only for demonstration purposes.

Table 5.4 - Log prices (\$ per m^3) by basic density classes and log-types

Log-type	Lower Class (300-399 kg m^{-3})	Middle Class (400-499 kg m^{-3})	Upper Class (500-600 kg m^{-3})
ES1	136.0	149.0	154.5
ES2	120.3	131.7	136.5
ES3	114.7	125.4	129.9
ES4	85.2	93.2	96.6
DS1	94.2	103.5	107.4
DS2	88.0	96.8	100.5
DS3	70.0	76.6	79.4
FIBER	15.7	21.9	28.7

5.4.4 Dynamic programming algorithm

A dynamic programming algorithm was implemented in a system called IP-BUCK (bucking with internal properties) which was developed by the first author of this paper in the programming language Visual C++™. The outputs given by the system correspond to the volume and number of logs by each log-type, as well as the total volume and value produced after optimally bucking a set of stems.

Two different files are required to run the dynamic programming algorithm: the stem file and the log specification file. For each stem, the stem file contains information on height, diameter, volume, quality, and density. The log specification file contains requirements for each log-type to be produced, normally, the smallest and largest end diameter (SED, LED), relative market prices, lengths, quality and density (see Table 5.1). This file also includes the possible lengths of each product (multiple lengths) which correspond to the different stages in the DP algorithm. The basic steps of the algorithm can be summarized as follows:

1. Starting from the butt of the stem (stage = 0), look at all feasible next lengths for each log-type.
2. Move to the minimum stage (given by the smallest multiple length of the set of log-types).
3. For each log-type check SED and LED within bounds given by the list.
4. From the last stage to the current location, read and check Quality and Density.

5. Calculate cumulative value to current stage and keep the highest solution.
6. Repeat steps 1-5 with the rest of the stages until the whole stem is analyzed.

5.5 RESULTS

The effect of density on the volume per log-type is shown in Figure 5.1. There were large variations for the four scenarios. In the control scenario more than half of the total volume (54%) is assigned to ES1. Another 15% is assigned to pulpwood (FIBER). The waste in this case remains relatively low representing 7% of the total volume.

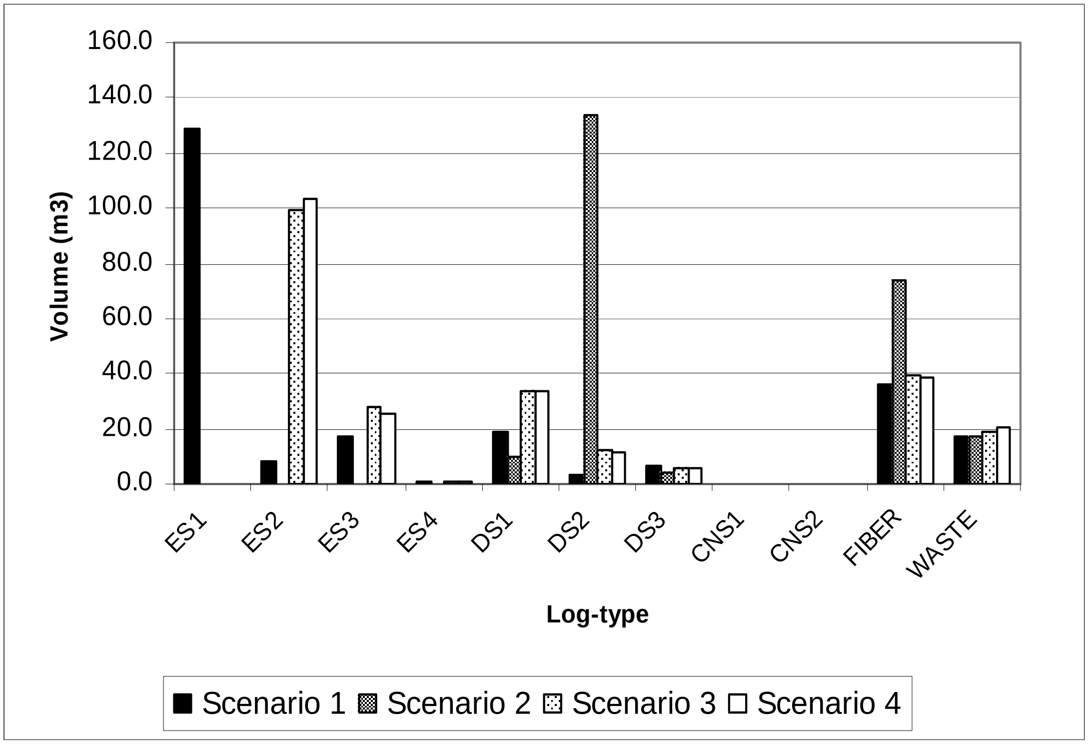

Figure 5.1 - Effect of density on the volume per log-type

In scenario 2, the export sawlogs (ES1, ES2 and ES3) require a basic density of at least 450 kg m^{-3} which is not met by any log. Hence the volume is concentrated in a domestic sawlog DS2 (56% of the total volume). Also there is a substantial increase in the volume of pulpwood (FIBER) compared to the first scenario, increasing from 15% to 31%. The waste volume remains the same as the first scenario.

In scenario 3, volume is distributed across more products than the previous scenarios. Although most volume is concentrated in an export sawlog grade ES2 (42%), there are other products with a high share of volume, such as ES3, DS1 and FIBER with 12%, 14% and 17%, respectively. This means that there are logs which can meet a basic density requirement of 400 kg m^{-3}, but not of 450 kg m^{-3}. Also it is important to mention that, in this scenario, there is a reduction in the pulpwood (FIBER) volume compared to the second scenario (from 31% to 17%) and a slight increase in the waste volume (from 7% to 8%).

Scenario 4 shows similar percentage values as scenario 3 in terms of the volume per log-type. Where there are differences, they are minimal: the export sawlog grade ES2 represents 43% of the total volume in scenario 4 and 42% in scenario 3, log-type ES3 represents 11% in scenario 4 and 12% in scenario 3, and FIBER represents 16% in scenario 4 and 17% in scenario 3. Waste constitutes the same percentage in both scenarios (8%).

The effect of density on the distribution of the number of logs per log-type is shown in Figure 5.2. In the control scenario the number of logs is concentrated in basically three products, ES1, DS1, and FIBER, with 27%, 10% and 31% of the total number of logs produced, respectively. The number of pieces considered as waste in this scenario is about 19% of the total number of logs (348 pieces).

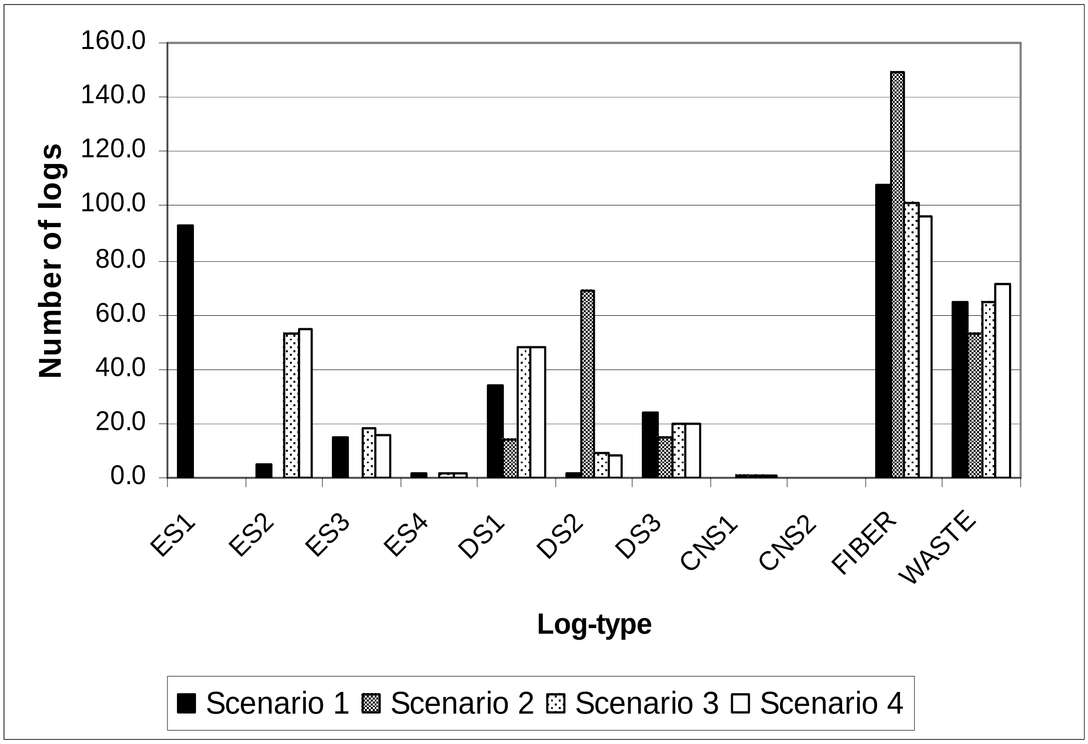

Figure 5.2 - Effect of density on the number of logs per log-type

In the second scenario, half of the total number of logs produced were pulp logs (FIBER, 149 logs), followed by 23% of the logs concentrated in the product DS2. There is a reduction in the total number of logs compared to the first scenario (from 348 to 301 logs). The proportion of pieces considered as waste in this scenario remains the same as the first scenario (19%).

In scenario 3 more logs are distributed across more products than the previous two scenarios. The highest percentages of logs are found in products ES2 (17%), DS1 (15%) and FIBER (32%). There is an increase in the total number of logs compared to the second scenario (from 301 to 317 logs) and an increase in percentage of pulpwood (FIBER) from 18% to 21%.

In scenario 4, only the log-type FIBER shows a different percentage of logs in comparison to scenario 3, decreasing from 32% (scenario 3) to 30% (scenario 4). Conversely, waste increases one percent from scenario 3 (21%) to scenario 4 (22%). Although the total number of logs produced in scenarios 3 and 4 is the same (317 logs), the distribution of them by log-type presents some changes. The most important variation is found in log-type FIBER, whose number of logs reduces from 101 (scenario 3) to 96 (scenario 4). This difference is due to the variation in price that occurs for logs with different wood density. In scenario 3 just one price is used which corresponds to the price associated with the middle class (400-499 kg m^{-3}) of scenario 4. However, as the density market requirements for FIBER is 300 kg m^{-3} or greater, most logs that barely meet this requirement now receive the price corresponding to the lower density class (<400 kg m^{-3}), which is considerable lower than that of the middle class ($21.9 per m^3 versus $15.7 per m^3). This explains the reduction of the number of logs in the log-type FIBER, and the increase in other log-types, such as ES2, which increases from 53 (scenario 3) to 55 (scenario 4).

The effect of density on the total value recovered is shown in Figure 5.3. Total value recovered decreases as the density becomes more constrained. However, what is important to evaluate is the magnitude of these changes. Taking scenario 2 and comparing it with the control scenario, there is 40% of reduction in the total revenue (from $25,890 to $15,550). This is in response to the high density constraints, which do not allow the production of the most profitable log-types (saw-wood for exporting). Pulpwood becomes the predominant log-type in this scenario. Similarly, comparing the first with the third and fourth scenarios, the total value recovered decreased 13.5% and 15.7%, respectively. These results are very sensitive to the assumed market density requirements and to the density equation used.

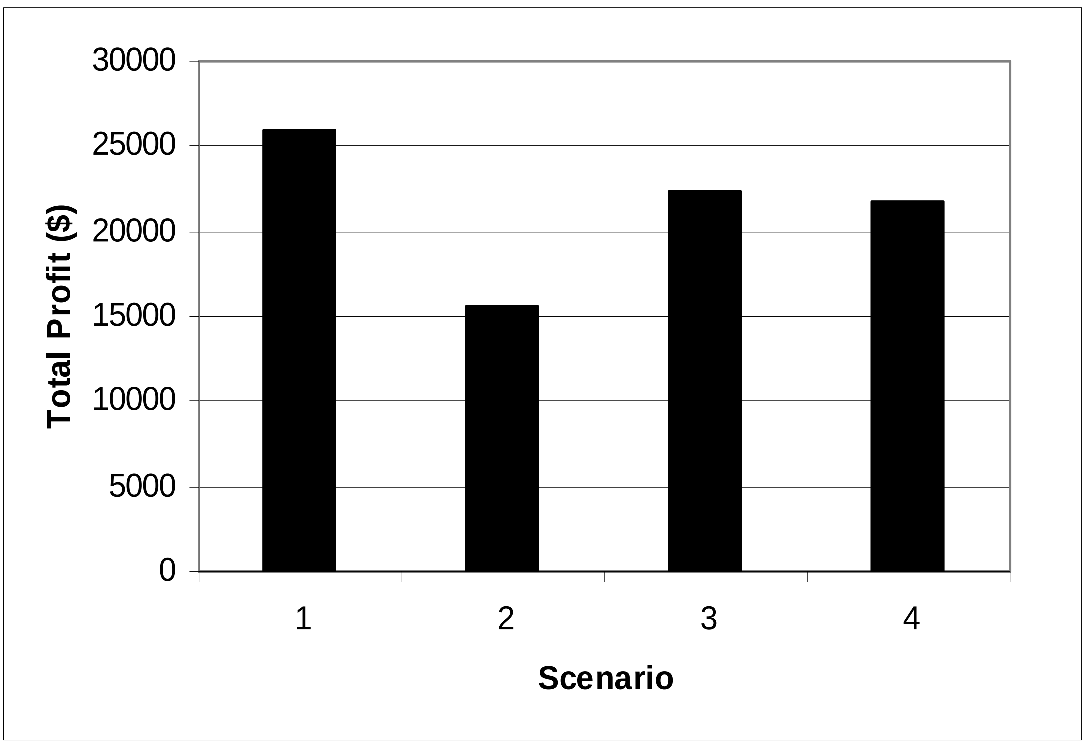

Figure 5.3 - Effect of density on total value recovery

5.6 DISCUSSION AND CONCLUSIONS

Bucking and sorting based on density could be expected to improve mill economic recoveries. This study shows that optimal bucking algorithms can be easily modified to include internal wood properties such as density. The inclusion of this new property, however, could be expected to change the distribution of the number of logs as well as the merchantable volume of each log-type. This has implications for log handling costs. In addition, optimally bucking stems based on basic density may reduce the total value recovered by the forest owner, unless appropriate premiums are paid for additional properties. Assuming no increase in price for higher density wood, could result in value losses as high as 40% for the forest owner. We demonstrate, however, that this change in recovered value is very sensitive to the density requirements we assumed and to the tree characteristics we modeled.

There are limitations associated with this study, which affected the results and our conclusions: only one stand was used, only two sets of market conditions were evaluated (one with and one without premiums for log-types meeting a specific density requirement), hypothetical density classes (scenarios) were used, and a density function was used rather than actual densities, to calculate the density at each segment of a stem.

A particular limitation, which requires additional comment, is that the maximum density that could be predicted by the density model used in the study was 427.1 kg m^{-3}.

This was below the 450 kg m^{-3} limit for the most valuable log types used in the analyses. It was also well below the upper limit reported for Douglas-fir density for individual stems (~ 570 kg m^{-3}) (Anon. 1965). Use of an alternative density model, or real density measurements, could result in a different set of changes in log product yields and value recovery.

Future research should cover a number of topics. These include:

- The effect of a wider range of stand conditions and market scenarios on log product yields and value recovery when density is included as a log quality attribute.
- The impact of inaccurate density measurements or predictions on optimal bucking and value recovery.
- The effect on revenue of including density in demand-constrained markets.
- The impact of the new wood properties, other than density, in increasingly competitive markets.
- The effect of the new requirements on the cost of log production. We observed that there were different distributions of products and a tendency for a reduced number of logs when using a constrained-density scenario. Generally, as the number of logs increases the bucking cost increases and the value-recovery diminishes. Studies indicate that an increase in the complexity of the decision-making by adding more log-types can result in a drop in actual value-recovery (Parker *et al.* 1995; Murphy *et al.* 2003).

Log producers should expect the evolution of log markets with new requirements and be prepared for such changes. Although the scenarios (markets) evaluated here were hypothetical, the results presented gave an indication of the potential impacts of the new market requirements on log product yields and value recovery from the forest owner's perspective, and demonstrated how internal properties could be included in optimal bucking systems.

5.7 REFERENCES

ACUNA, M.; MURPHY G. 2006. Geospatial and within variation of wood density and spiral grain in Douglas-fir. *For. Prod. J.* (in press).

ACUNA, M.A.; MURPHY, G.E. (unpublished A). Estimating log prices of Douglas-fir through an economic analysis of the effects of wood density on lumber recovery and pulp yield. *For. Prod. J.* (in review).

ACUNA, M.A.; MURPHY, G.E. (unpublished B). Use of near infrared spectroscopy and multivariate analysis to predict wood density of Douglas-fir from chain saw chips. *For. Prod. J.* (in review).

ANDREWS, M. 2002. Wood quality measurement – *son et lumiere. New Zealand J. of For.* 47(3): 19-21.

ANONYMOUS. 1965. Western wood density survey. Report Number 1. USDA Forest Service Research Paper FPL-27. 58pp.

ARCE, J.E.; CARNIERI, C.; SANQUETTA, C.R.; FILHO A.F. 2002. A forest-level bucking optimization system that considers customer's demand and transport cost. *For. Sci.* 48(3): 504-507.

ATLAS 2006. www,atlastech.com (accessed January 24, 2006).

BOSTON, K.; MURPHY, G.E. 2003. Value recovery from two mechanized bucking operations in the southeastern United States. *Southern J. of Appl. For.* 27(4):259-263.

BRIGGS, D.G. 1980. A dynamic programming approach to optimizing stem conversion. Ph.D. Thesis, University of Washington. 409 p.

CONWAY, S. 1982. Logging Practices: Principles of timber harvesting systems. Miller Freeman Publications, Revised Edition. 432 p.

CORSON, S.R. 2001. Optimal allocation and use of today's trees for wood and paper products – the New Zealand experience. Presentation to the Markus Wallenberg Prize Ceremony, Stockholm, Sweden, 2 October. 18 p. http://www.mwp.org (Accessed January 2006).

GARTNER, B.L., NORTH, M.N., JOHNSON, G.R. and SINGLETON, R. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. *Can. J. For. Res.* 32: 439-447.

GEERTS, J.M.; TWADDLE, A.A. 1984. A method to assess log value loss caused by cross-cuting practice on the skidsite. *New Zealand J. of For. Sci.* 29(2): 173-184.

HAYNES, H.J.; VISSER, R.J. 2004. An applied hardwood value recovery study in the Appalachian hardwood region of Virginia and West Virginia. *Int. J. For. Eng.* 15(1):25-31.

JOZSA, L.A.; BRIX, H. 1989. The effects of fertilization and thinning on wood quality of a 24-year-old Douglas-fir stand. *Can. J. For. Res.* **19**: 1137–1145.

KIVINEN, V.; UUSITALO, J. 2002. Applying fuzzy logic to tree bucking control. *For. Sci.* 48(4): 673-684.

KNIGGE, W. 1962. Untersuchungen uber die Abhagigkeit der mittleren Rohdichte nordamerikanische Douglasienstamme von untershiedlichen Wuchsbedingungen. *Holz als Roh- und Werkstoff* 20:352-360.

KNOWLES, R.L.; HANSEN, L.W.; WEDDING, A.; DOWNES, G. 2004. Evaluation Of Non-Destructive Methods For Assessing Stiffness Of Douglas Fir Trees. *New Zealand J. of For. Sci.* 34(1): 87–101 (2004).

MARSHALL, H. 2005. An investigation of factors affecting the optimal output log distribution from mechanical harvesting and processing systems. Ph.D. Thesis, Oregon State University. 200 p.

MEGRAW, R.A. 1986a. Douglas-fir wood properties. *In* Proceedings, Douglas-fir: Stand Management for the Future. *Edited by* C.D.O Oliver, D.P. Hanley, and J.A. Johnson. Institute of Forest Resources, University of Washington, Seattle, Wash. Contrib. 55. pp. 81–96.

MEGRAW, R.A. 1986b. Effect of silvicultural practices on wood quality. *In* Proceedings: TAPPI R&D Conference, 29 Sept. 1986, Raleigh, N.C. Technical Association of the Pulp and Paper Industry, Atlanta, Ga. pp. 27–34.

MURPHY, G. 2003. Mechanization and value recovery: worldwide experiences. Pp. 23-32 *in* Proceedings of the “Wood for Africa 2002 Conference”, July 2002, Pietermaritzburg, South Africa. College of Forestry, Forest Emgineering Department, Oregon State University, Corvallis, Oregon.

MURPHY, G.; MARSHALL, H.; CONRADIE I. 2003. Market complexity and its effect on variables that gauge the economics of harvesting production. *New Zealand J. of For. Sci.* 32(2): 281-292.

MURPHY, G.; MARSHALL, H.; BOLDING C. 2004. Adaptive control of bucking on harvesters to meet order book constraints. *For. Prod. J.* 54(12): 114-121.

NASBERG, M. 1985. Mathematical programming model for optimal log bucking. Dissertation No. 132. Linkoping University. Sweden. 200 p.

PARKER, R.; PARK, R.; CLEMENT, B.; GIBBONS, W. 1995. Effect of number of log grades on log making errors. *Logging Industry Research Organization*, *LIRO Report* 20(23): 1-7.

PICKENS, J.B.; THROOP, S.A.; FRENDEWAY, J.O. 1997. Choosing prices to optimally buck hardwood logs with multiple log-length demand restrictions. *For. Sci.* 43(3):403:413.

PNEVMATICOS, S.M. and MANN, S.H. 1972. Dynamic programming in tree bucking. *For. Prod. J.* 22(2): 26-30.

SESSIONS, J. 1988. Making better tree-bucking decisions in the woods. *J. of For.* 86(10): 43-45.

SO, C.L., GROOM L.H., RIALS T.G., SNELL R., KELLEY S., MEGLEN R. 2002. Rapid assessment of the fundamental property variation of wood. In Outcalt, K.W. (Ed.) “Proceedings of the 11th Biennial Southern Silvicultural Research Conference”. *USDA Forest Service, Southern Research Station, General Technical Report SRS-48.* 622 p.

SO, C.L., KIA, B.K., GROOM, L.H., SCHIMLECK, L.R., SHUPE, T.F., KELLEY, S.S. and RIALS, T.M. 2004. Near infrared spectroscopy in the forest products industry. *For. Prod. J.* 54(3):6-16.

WALKER, J. 2000. Dream merchants: why forestry practices will change. *New Zealand J. of For.* 45(3): 27-33.

YOUNG, G.G. 2002. Radiata pine wood quality assessments in the 21st century. *New Zealand J. of For.* 47(3): 16-18.

CHAPTER 6

GENERAL CONCLUSIONS

The work presented in this dissertation corresponds to a comprehensive study of internal wood properties and sensor technology to improve optimal bucking and value recovery in Douglas-fir. There are a number of wood properties which affect the quality of forest products such as lumber and pulp. Of these, wood density is considered by some to be the single most important physical characteristic because it is an excellent predictor of strength, stiffness, hardness, and paper-making capacities. Accurately assessing density in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on density. Mechanized harvesting machines are frequently fitted with computer technology and rudimentary sensor systems for measuring external stem dimensions. Research into technologies for measuring stem quality attributes is progressing on a number of fronts with varying levels of success. Some of these scanning technologies could be integrated into the design of mechanized harvesting systems.

Chapter 2 summarized the results of an investigation into modeling the effects of variation in site and within tree spatial characteristics - in particular, elevation, aspect, and height within trees - on Douglas-fir wood density and spiral grain from seventeen sites in western Oregon. From the results obtained, it is possible to conclude that neither wood property was related to elevation or aspect. Density was weakly related to height in the tree, height being the only statistically significant variable. Having a measure of density low down in the tree would slightly improve the predictive capability for density higher up the tree. If density and spiral grain wood properties are to be optimally matched to markets, it is likely that tools will need to be developed to measure these properties in the forest in real time for individual logs.

Chapter 3 demonstrated the usefulness and potential of NIR spectroscopy for predicting wood density of Douglas-fir based on chainsaw chip samples. In terms of both standard error of calibration (SEC) and standard error of prediction (SEP), partial least squares (PLS) yielded better results than principal component analysis (PCA). With PLS, calibration models were found to perform best for both dry rough and dry ground samples; SEC's expressed as percentage of the mean were 1.6% and 2.7% respectively. On the other hand, prediction models performed best for both the green and dry ground samples; SEP's expressed as a percentage of the mean were 5.5% and 3.6% respectively. The standard errors of the predictions using the dry rough samples were relatively large compared with the standard errors of the other two groups. It is believed, however, that removing a couple of outliers would improve the prediction capability in the dry rough group and reduce the standard errors observed. Coefficient of determination (R^2) values for NIR-predicted basic densities ranged from 0.56 for the dry rough Douglas-fir chip samples to 0.85 for the dry ground chip samples. The green chainsaw chip samples had an intermediate R^2 value of 0.74.

The results of our study confirm earlier work on the utility of NIR to the forest products industry and reveal the possibility of using NIR spectroscopy of green chain saw chip samples to predict wood properties (such as density) in real time. Using green chips negates the need to dry the samples prior the analysis. These results indicate that NIR technology may be applied to log segregation by mechanized harvesting equipment (e.g. harvesters). From this study it is possible to conclude that:

(1) Useful calibrations for Douglas-fir wood density can be developed using NIR spectroscopy of chain saw chip samples.

(2) Green chain saw chip samples could provide NIR estimates of wood density that are only slightly degraded from those coming from dry ground chip samples.

(3) With either multivariate statistical techniques, PLS or PCA, it is possible to get calibrations models to predict wood properties. Although PLS is a more involved technique and not included in many statistical packages, it can produce more accurate models given its ability to extract information of both explanatory and response variables.

(4) Further work is required to determine whether the promise of real-time, cost effective measurements of wood density (and other wood properties) using NIR technology is valid.

Including new wood properties into a log bucking and allocation system may reduce the total value recovered by the forest owner, unless appropriate premiums are paid for the additional properties. Therefore, it is essential to develop methodologies that allow companies to estimate the price that markets should be willing to pay for logs with different internal characteristics, such as basic density. Chapter 4 presents a methodology to estimate log prices of Douglas-fir based on wood density, by calculating the net return of end-products (lumber and pulp) obtained from logs. For lumber, a number of different grades and their prices were used to estimate the price that markets should be willing to pay for logs. For pulp logs, the price is estimated from the net product value per metric ton which considers pulp selling price and non-wood costs and fixed costs.

For the purpose of demonstrating the methodologies, basic density was split into three classes; 300-399, 400-499, 500-600 kg m^{-3}. For the lower basic density class, net returns (and log prices) for pulp were about 28 percent lower than the middle class, whereas the upper class net return was 32 percent higher than the middle class. For lumber log-types, the differences between lower and upper classes with the middle class were on average 8 percent and 4 percent, respectively.

The next steps in this research should be the analysis of the effect density on revenue in demand-constrained markets, as well as an assessment of the impact of new additional wood properties in increasingly competitive markets. The study of new approaches to estimate premium prices for logs based on internal wood characteristics will allow for validation of the results presented here and facilitate the development of a standard methodology for estimating log price premiums.

Chapter 5 demonstrated that optimal bucking algorithms can be easily modified to include internal wood properties such as basic density. According to the results obtained in this analysis, the inclusion of this new property, however, could be expected to change the distribution of the number of logs as well as the merchantable volume of each log-type. In addition, the inclusion of basic density into the bucking system may reduce the total value recovered by the forest owner, unless appropriate premiums are paid for additional properties.

Four scenarios were evaluated for a supply constrained market; a control scenario with no density requirements, a scenario with high log density requirements and no price premiums, a medium log density requirement and no price premiums, and a medium log density requirements with price premiums. When comparing the control scenario with the high density scenario value is as much as 40% lower. This change in recovered value is very sensitive to density requirements assumed and to the tree characteristics we modeled.

There are limitations associated with this bucking study, which could have affected the results and our conclusions: only one stand was used, two sets of market conditions were evaluated (one with, one without, price premiums for log-types meeting a specific density requirement), hypothetical density classes were used, and a density function was used rather than actual densities, to calculate the density at each segment of a stem.

The next steps in this research should be the analysis the effect of a wider range of stand conditions and market scenarios on log product yields and value recovery when density is included as a log quality attribute, the impact of inaccurate density measurements or predictions on optimal bucking and value recovery, the impact of the new wood properties, other than density, in increasingly competitive markets, and the effect of the new requirements on the cost of log production.

Log producers should expect the evolution of log markets with new requirements and be prepared for such changes. Although the scenarios (markets) evaluated here were hypothetical, the results presented gave an indication of the potential impacts of the new market requirements on log product yields and value recovery from the forest owner's perspective, and demonstrated how internal properties could be included in optimal bucking systems.

To remain competitive and successfully face the new market scenarios, the forest sector needs to look for new and innovative processes and technologies to increase value through the forest supply chain. Keeping this in mind, the dissertation presented four studies which investigated areas either not studied before or applied new or standard solution techniques to meet the objectives established in each study. The unique contribution of this thesis is the breadth and scope of the topics that were evaluated as well as the relationship between them: a statistical methodology to predict wood density, the potential of a non-destructive technique to predict this property in real time, a new economical methodology for determining prices of logs with different wood densities, and a system that incorporates all these elements to optimally buck stems into logs. It is expected that the knowledge from these studies will help improve value recovery and competitiveness of the forest sector.

BIBLIOGRAPHY

ABDI, H. 2003. Partial Least Squares (PLS) regression. *In*: Lewis-Beck M., Bryman, A., Futing T. (Eds.). Encyclopedia of Social Sciences Research Methods. Thousand Oaks (CA): Sage.

ACUNA, M.; MURPHY, G. 2006. Geospatial and within variation of wood density and spiral grain in Douglas-fir. *For. Prod. J.* (accepted for publication).

ACUNA, M.A.; MURPHY, G.E. (unpublished A). Optimal bucking considering external wood properties and wood density. *New Zealand J. For. Sci.* (in review).

ACUNA, M.A.; MURPHY, G.E. (unpublished B). Use of near infrared spectroscopy and multivariate analysis to predict wood density of Douglas-fir from chain saw chips. *For. Prod. J.* (in review).

ADAMS, D.M.; SCHILLINGER, R.R.; LATTA, G.; VAN NALTS, A. 2002. Timber harvest projections for private land in Western Oregon. Oregon State University, Forest Research Laboratory. Reseach Contribution 37. 44 p.

ANDREWS, M. 2002. Wood quality measurement – *son et lumiere. New Zealand J. For.* 47(3): 19-21.

ANONYMOUS. 1965. Western wood density survey. Report Number 1. USDA Forest Research Paper FPL-27. 58pp.

ANTII, H. 1999. Multivariate characterization of wood related materials. Doctoral thesis. Umea University. Department of Chemistry. Umea. Sweden. 86 pp.

ARCE, J.E.; CARNIERI, C.; SANQUETTA, C.R.; FILHO A.F. 2002. A forest-level bucking optimization system that considers customer's demand and transport cost. *For. Sci.* 48(3): 504-507.

ATLAS 2006. www,atlastech.com (accessed January 24, 2006).

AUBRY, C.L.; ADAMS, W.T.; FAHEY, T.D. 1998. Determination of relative economic weights for multitrait selection in coastal Douglas-fir. *Can. J. For. Res.* 28: 1164-1170.

AXRUP, L.; MARKIDES, K.; NILSSON, T. 2000. Using miniature diode array NIR spectrometers for analyzing wood chips and bark samples in motion. *J. Chemometrics* 14:561-572.

BAILLERES, H.; DAVRIEUX, F.; HAM-PICHAVANT, F. 2002. Near infrared analysis as a tool for rapid screening of some major wood characteristics in a eucalyptus breeding program. *Ann.For. Sc.* 59:479-490.

BARBOUR, R.J.; KELLOGG, R.M. 1990. Forest Management and end-product quality: a Canadian perspective. *Can. J. For. Res.* 20: 405-414.

BENDTSEN, B.A.; SENFT, J. 1986. Mechanical and anatomical properties in individual growth rings of plantation-grown eastern cottonwood and loblolly pine. *Wood and Fiber Sci.* 18(1): 23-38.

BOSTON, K.; MURPHY, G.E. 2003. Value recovery from two mechanized bucking operations in the southeastern United States. *Southern J. of Appl. For.* 27(4):259-263.

BOWYER, J.L.; SHMULSKY, R.; HAYGREEN, J.G. 2003. Forest Products and Wood Science: An Introduction. Fourth edition. Iowa State University Press. 554 p.

BRIGGS, D.G. 1980. A dynamic programming approach to optimizing stem conversion. Ph.D. Thesis, University of Washington. 409 p.

BRIGGS, D.G. 1994. Forest products measurements and conversion factors: With special emphasis on the U.S. Pacific Northwest. College of Forest Resources, University of Washington. 154 p.

BRIGGS, D.G.; FIGHT, R.D. 1992. Assessing the effects of silvicultural practices on product quality and value of coast Douglas-fir trees. *For. Prod. J.* 42(1): 40-46.

CHAMPION, H.G. 1925. Contributions towards a knowledge of twisted fibre in trees. Indian Forestry Record (Silv. Ser.) 11 (part II): 11-80.

CHMELIK, J.T.; FIGHT, R.D.; BARBOUR, R.J. 1999. Softwood lumber prices for evaluation of small-diameter timber stands in the Intermountain West. USDA Forest Service, Forest Product Laboratory. Research Note FPL–RN–0270.

CLARKE, C.R.; BARNES R.D.; MORRIS A.R. 2002. Effect of environment on wood density and pulping of five pine species grown in Southern Africa. Paper presented at the 2002 Technical Association of the Pulp and Paper Industry of Southern Africa Conference, Durban, October 2002. (http://tappsa.co.za/archive/APPW2002/Title/Effect_of_environment_on_wood_/effect_of_environment_on_wood_.html, (Accessed February 2005).

CONWAY, S. 1982. Logging Practices: Principles of timber harvesting systems. Miller Freeman Publications, Revised Edition. 432 p.

CORSON, S.R. 2001. Optimal allocation and use of today's trees for wood and paper products – the New Zealand experience. Presentation to the Markus Wallenberg Prize Ceremony, Stockholm, Sweden, 2 October. 18 p. http://www.mwp.org (Accessed January 2006).

COWN, D.J.; MCCONCHIE, D.L.; YOUNG, G.D. 1991. Radiata pine wood properties survey. New Zealand Forest Research Institute Bulletin No. 50. 50pp.

COWN, D.J.; YOUNG, G.D.; BURDON, R.D. 1992. Variation in wood characteristics of 20 year old half-sib families of Radiata pine. *New Zealand J. For. Sci*. 22(1):63-76.

DAVIES, M.C. 2005. An introduction to near infrared spectroscopy. *NIR news* (16)7: 9-11.

DILUCCA, C.M. 1989. Juvenile–mature wood transition. *In* Second growth Douglas-fir: its management and conversion for value: a report of the Douglas-fir task force. *Edited by* R.M. Kellogg. Forintek Canada Corp., Vancouver, B.C. pp. 23–38.

DONALDSON, L.A.; EVANS, R.; COWN, D.J.; LAUSBERG, M.J. 1995. Clonal variation of wood density variables in Pinus radiata. *New Zealand J. For. Sci.* 25(2):175-188.

DRYDEN, G. 2003. Near infrared reflectance spectroscopy: applications in deer nutrition. RIRDC Publication No. W03/007. Rural Industries Research and Development Corporation. Barton, ACT, Australia. 38 pp.

EDLUND, J.; WARENSJO, M. 2005. Repeatability in automatic sorting of curved Norway Spruce saw logs. *Silva Fennica* 39(2): 265-275.

ERNST, S.; FAHEY, T.D. 1986. Changes in product recovery of Douglas-fir from old growth to young growth. *In* Proceedings of a Symposium, Douglas-fir: Stand Management for the Future, 18–20 June 1985, Seattle, Wash. Edited by C.D. Oliver, D.P.

FAHEY, T.D.; MARTIN, D.C. 1974. Lumber recovery from second-growth Douglas-fir. USDA Forest Service. Research paper PNW-RP-437. 25 p.

FAHEY, T.D., CAHILL, J.M.; SNELLGROVE, T.A.; HEATH, L.S. 1991. Lumber and veneer recovery from intensively managed young growth Douglas-fir. Res. Pap. PNW-RP-437. USDA Forest Serv. Pacific Northwest Research Station. Portland, Oregon.

FOREST PRODUCTS LABORATORY. 1999. Wood handbook: wood as an engineering material. Forest Products Laboratory, Forest Products Society, Madison, Wis.

GARTNER, B.L. 2005. Assessing wood characteristics and wood quality in intensively managed plantations. *J. For.* 100(2): 75-77.

GARTNER, B.L.; NORTH, M.N.; JOHNSON, G.R.; SINGLETON. R. 2002. Effects of live crown on vertical patterns of wood density and growth in Douglas-fir. *Can. J. For. Res.* 32: 439-447.

GEERTS, J.M.; TWADDLE, A.A. 1984. A method to assess log value loss caused by cross-cuting practice on the skidsite. *New Zealand J. of For. Sci.* 29(2): 173-184.

GIVENS, D.I.; DE BOEVER, J.L.; DEAVILLE, E.R. 1997. The principles, practices and some future applications of near infrared spectroscopy for predicting the nutrient value of foods for animals and humans. *Nutrition Research Reviews*, 10:83-114.

GREEN, D.W.; ROSS, R. 1997. Linking log quality with product performance. Role of wood production in ecosystem management. *In* Proceedings of the Sustainable Forestry Working Group at the IUFRO All Division 5 Conference, Pullman, Washington, July 1997. p. 53-58.

HALLOCK, H.; STEELE, P.; SELIN, R. 1979. Comparing lumber yields from board-foot and cubically scaled logs. USDA Forest Service, Forest Products Laboratory. Research Paper FPL 324.

HANNRUP B.; GRABNER, M.; KARLSSON, B.; MÜLLER, U.; ROSNER, S.; WILHELMSSON, L.; WIMMER,R. 2002. Genetic parameters for spiral-grain angle in two 19-year-old clonal Norway spruce trials. *Ann. For. Sci.* 59 (2002) 551–556.

HANNRUP, B.; CAHALAN, C.; CHANTRE, G.; GRABNER, M.; KARLSSON, B.; LE BAYON, I.; LLYOD JONES, G.; MULLER, U.; PEREIRA, H.; RODRIGUES, J.; ROSNER, S.; ROZENBERG, P.; WILHELMSSON, L.; WIMMER, R. 2004. Genetic parameters of growth and wood quality traits in Picea abies. *Scandinavian J. For. Res.* 19(1):14-29.

HARDING, K.J.; COPLEY, T.R. 2000. Wood property variation in Queensland grown Slash X Caribbean pine hybrids. In: "Hybrid breeding and genetics of forest trees." Proceedings of QFRI/CRC-SPF Symposium, April 2000, Noosa, Queensland, Australia. (Compiled by Dungey, H.S., M.J. Dieters, and D.G. Nikles). Department of Primary Industries, Brisbane. Pages 160-167.

HARRIS, J.M. 1989. Spiral Grain and Wave Phenomena in Wood Formation. Springer-Verlag, Berlin. 214p.

HAYNES, H.J.; VISSER, R.J. 2004. An applied hardwood value recovery study in the Appalachian hardwood region of Virginia and West Virginia. *Int. J. For. Eng.* 15(1):25-31.

HINDLE, P.H. 2001. Historical development. In: Handbook of Near-Infrared Analysis. Edited by D.A. Burns and E.W. Ciurczak. Marcel Dekker, Inc. New York. 814 p.

HUGHES, J.F. 1967. Density as an index of wood quality with special reference to the development of rapid and efficient methods of estimating density. In: Proceedings of the Tropical Forestry Meeting by Commonwealth Forestry Institution. Oxford. pp. 1-4.

JAPPINEN, A. 2000. Automatic sorting of sawlogs by grade. Doctoral thesis. Department of Forest Management and Products, Swedish University of Agricultural. Uppsala, Sweden.

JONES, P.D.; SCHIMLECK, L.R.; PETER, G.F.; DANIELS, R.F.; CLARK III, A. 2005. Nondestructive estimation of *Pinus taeda* L. wood properties for samples from a wide range of sites in Georgia. *Can. J. For. Res.* 35:85-92.

JOZSA, L.A.; BRIX, H. 1989. The effects of fertilization and thinning on wood quality of a 24-year-old Douglas-fir stand. *Can. J. For. Res.* **19**: 1137–1145.

JOZSA, L.A.; KELLOGG, R.M. 1986. An exploratory study of the density and annual ring width trends in fast-growth coniferous wood in British Columbia. CFS Contract Report No. 02-80-55-017. Forintek Canada Corp., Vancouver, BC. 43 pp.

JOZSA, L.A.; MIDDLETON, G.R. 1994. A discussion of wood quality attributes and their practical implications. Forintek Canada Corp., Vancouver, BC. Special Publ. No. SP-34.

JOZSA, L.A.; RICHARDS, J.; JOHNSON, S.G. 1989. Relative density. *In* Second growth Douglas-fir: its management and conversion for value: a report of the Douglas-fir task force. *Edited by* R.M. Kellogg. Forintek Canada Corp., Vancouver, B.C. pp. 5–22.

JOZSA, L.A.; MUNRO, B.D.; GORDON, J.R. 1998. Basic wood properties of second-growth Western Hemlock. Forintek Canada Corp. Special Publication No. SP-38. 51pp.

JOZSA, L.A.; MIDDLETON, G.R. 2004. Discussion of wood quality attributes and their practical implications. Web page: http://www.lumber.com/products/pro_01130.asp, (Accessed July 2005)

KELLEY, S.S.; HAMES, B.R.; MEGLEN, R.R. 2001. Use of near infrared spectroscopy for characterization of wood. Presentation abstract from 5th International Biomass Conference of the Americas. 2pp. http://www.bioproducts-bioenergy.gov/pdfs/bcota/abstracts/29/z362.pdf (Accessed January 2006).

KELLEY, S.S.; RIALS, T.G.; SNELL, R.; GROOM, L.H.; SLUITER. 2004a. Use of near infrared spectroscopy to measure the chemical and mechanical properties of solid wood. *Wood Sci. Technol.* (38):257-276.

KELLEY, S.S.; RIALS, T.G.; GROOM, L.H.; SO, C-L. 2004b. Use of near infrared spectroscopy to predict the mechanical properties of six softwoods. *Holzforschung* 58(3):252-260.

KENNEDY, R.W. 1995. Coniferous wood quality in the future: concerns and strategies. *Wood Sci. Technol.* 29: 321–338.

KINDSETH, P. (n.d.) Solvinn og rangvinn Skog. (Abstracted in Intern. Review Agri. 19(3):310).

KIVINEN, V.; UUSITALO, J. 2002. Applying fuzzy logic to tree bucking control. *For. Sci.* 48(4): 673-684.

KLUDT, K.D. 2003. Use of near infrared spectroscopy technology for predicting bending properties of clear wood specimens. MSc Thesis. Washington State University. USA. 86 pp.

KNIGGE, W. 1962. Untersuchungen uber die Abhagigkeit der mittleren Rohdichte nordamerikanische Douglasienstamme von untershiedlichen Wuchsbedingungen. *Holz als Roh- und Werkstoff* 20:352-360.

KNOWLES, R.L.; HANSEN, L.W.; WEDDING, A.; DOWNES, G. 2004. Evaluation Of Non-Destructive Methods For Assessing Stiffness Of Douglas Fir Trees. *New Zealand J. of For. Sci.* 34(1): 87–101 (2004).

LANE, P.H., WOODFIN, R.O.; HENLEY, J.W.; PLANK, M.E. 1973. Lumber recovery from old-growth coast Douglas-fir. Res. Pap. RP-PNW-154. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station.

MARSHALL, H. 2005. An investigation of factors affecting the optimal output log distribution from mechanical harvesting and processing systems. Ph.D. Thesis, Oregon State University. 200 p.

MARTENS, H.; NAES, T. 1991. Multivariate calibration. Wiley 419 pp.

MARTIN, M.; ABER, J. 1994. Analyses of forest foliage III: determining nitrogen, lignin and cellulose of fresh leaves using near infrared reflectance data. *J. Near Infrared Spectr.* 2:25-32.

MATHESON, A.C.; ROSS, L.D.; SPENCER, D.J.; JOE, B.; ILIC, J. 2002. Acoustic segregation of *Pinus radiata* logs according to stiffness. *Ann. For. Sci.* 59(2002): 471-477.

MCKEEVER, D.B. 2000. Timber and fiber demand and technology assessment: Demand for engineered products. USDA Forest Service, Forest Products Laboratory. 2 p.

MCLELLAN, T.; MARTIN, M.; ABER, J.; MELILLO, J.; NADELHOFFER, K.; DEWEY, B. 1991. Comparison of wet chemistry and near infrared reflectance measurements of carbon-fraction chemistry and nitrogen concentration of forest foliage. *Can. J. For. Res.* 21:1689-1693.

MEGRAW, R.A. 1986a. Douglas-fir wood properties. *In* Proceedings, Douglas-fir: Stand Management for the Future. *Edited by* C.D.O Oliver, D.P. Hanley, and J.A. Johnson. Institute of Forest Resources, University of Washington, Seattle, Wash. Contrib. 55. pp. 81–96.

MEGRAW, R.A. 1986b. Effect of silvicultural practices on wood quality. *In* Proceedings: TAPPI R&D Conference, 29 Sept. 1986, Raleigh, N.C. Technical Association of the Pulp and Paper Industry, Atlanta, Ga. pp. 27–34.

MICHELL, A.J. 1995. Pulpwood quality estimation by near infrared spectroscopic measurements on eucalypt woods. *APPITA J.* 48(6):425-428.

MURPHY, G.E. 2003. Mechanisation and value recovery: worldwide experiences. Pp. 23-32 *in* Proceedings of the "Wood for Africa 2002 Conference", July 2002, Pietermaritzburg, South Africa. College of Forestry, Forest Engineering Department, Oregon State University, Corvallis, Oregon.

MURPHY, G.; MARSHALL, H.; CONRADIE, I. 2003. Market complexity and its effect on variables that gauge the economics of harvesting production. *New Zealand J. For. Sci.* 32(2): 281-292.

MURPHY, G.; MARSHALL, H.; BOLDING C. 2004. Adaptive control of bucking on harvesters to meet order book constraints. *For. Prod. J.* 54(12): 114-121.

NASBERG, M. 1985. Mathematical programming model for optimal log bucking. Dissertation No. 132. Linkoping University. Sweden. 200 p.

NORTHCOTT, P.L. 1957. Is spiral grain the normal growth pattern? *For. Chron.* 33(4): 335-351.

NOSKOWIAK, A.F. 1963. Spiral grain in trees – a review. *For. Prod. J.* 13(7):266-275.

O'SULLIVAN, P. 1976. The influence of initial espacement and thinning regime upon wood density in Sitka spruce (Picea sitchcensis [Bong] Carr.). M.Agr.Sci. thesis, University College, Dublin.

PARKER, R.; PARK, R.; CLEMENT, B.; GIBBONS, W. 1995. Effect of number of log grades on log making errors. *Logging Industry Research Organization*, *LIRO Report* 20(23): 1-7.

PICKENS, J.B.; THROOP, S.A.; FRENDEWAY, J.O. 1997. Choosing prices to optimally buck hardwood logs with multiple log-length demand restrictions. *For. Sci.* 43(3):403:413.

PNEVMATICOS, S.M. and MANN, S.H. 1972. Dynamic programming in tree bucking. *For. Prod. J.* 22(2): 26-30.

POLGE, H. 1969. [Density of planting and pruning of live brnahces, or why, when and how to prune.] RFF 21 Special "Silviculture" 31:451-462.

RAMSEY, F.L.; SHAFER, D.W. 2002. The statistical sleuth: a course in methods of data analysis. Duxbury Press. Second Edition. 742 pp.

RAULT, J.P.; MARSH, E.K. 1952. The incidence and silvicultural implications of spiral grain in *Pinus longifolia* Roxb. in South Africa and its effect on converted timber. South African Forest Products Institute, Pretoria West.

REEVES, J.B. III; DELWICHE, S.R. 2003. SAS partial least squares regression for analysis of spectroscopic data. *J. Near Infrared Spectr.* 11:415-431.

SCHULER A.; CRAIG, A. 2003. Demographics, the housing market, and demand for building materials. *For. Prod. J.* 53(5): 8-17.

SCHIMLECK, L.R.; MICHELL, A.J.; RAYMOND, C.A.; MUNERI, A. 1999. Estimation of basic density of *Eucalyptus globulus* using near-infrared spectroscopy. *Can. J. For. Res.* 29:194-201.

SCHIMLECK, L.R.; EVANS, R.; ILIC, J. 2001. Estimation of *Eucalyptus delegatensis* wood properties by near infrared spectroscopy. *Can. J. For. Res.* 31(10):1671-1675.

SCHIMLECK, L.R.; EVANS, R.; ILIC, J.; MATHESON, A.C. 2002. Estimation of wood stiffness of increment cores by near-infrared spectroscopy. *Can. J. For. Res.* 32(1):129-135.

SCHIMLECK, L.R.; YAZAKI, Y. 2003. Analysis of *Pinus radiata* D. Don bark by near infrared spectroscopy. *Holzforschung* 57:520-526.

SCHIMLECK, L.R.; MORA, C.; DANIELS, R.F. 2003. Estimation of the physical wood properties of green *Pinus taeda* radial samples by near infrared spectroscopy. *Can. J. For. Res.* 33:2297-2305.

SCHIMLECK, L.R.; JONES, P.D.; PETER, G.F.; DANIELS, R.F.; CLARK III, A. 2004. Nondestructive estimation of tracheid length from sections of radial wood strips by near infrared spectroscopy. *Holzforschung* 58:375-381.

SEFARA, N.L., CONRADIE, D.; TURNER, P. 2000. Progress in the use of near-infrared absorption spectroscopy as a tool for the rapid determination of pulp yield in plantation eucalypts. *TAPPSA J.*, November 2000. p15-17.

SESSIONS, J. 1988. Making better tree-bucking decisions in the woods. *J. of For.* 86(10): 43-45.

SHAO, J. 2003. Linear model selection by cross-validation. *J. Am. Stat. Assoc.* 88:486-494.

SMYTHIES, E.A. 1915. Notes on the twisted fibre in chir pine. *Indian Forester* 41(3):69-75.

SO, C.L.; GROOM, L.H.; RIALS, T.G.; SNELL, R.; KELLEY, S.; MEGLEN, R. 2002. Rapid assessment of the fundamental property variation of wood. In Outcalt, K.W. (Ed.) "Proceedings of the 11th Biennial Southern Silvicultural Research Conference". USDA Forest Service, Southern Research Station, General Technical Report SRS-48. 622 p.

SO, C.L.; KIA, B.K.; GROOM, L.H.; SCHIMLECK, L.R.; SHUPE, T.F.; KELLEY, S.S.; RIALS, T.M. 2004. Near infrared spectroscopy in the forest products industry. *For. Prod. J.* 54(3):6-16.

SONNE, E.; TURNBLOM, E.; BRIGGS, D. 2004. Log and lumber grades and value from a Douglas-Fir stand 20 years after thinning and biosolids fertilization. *Western J. Appl. For.* 19(1): 34-41.

TD BANK FINANCIAL GROUP. 2004. TD Commodity price report. December, 2004. www.td.com/economics, (Accessed November 2005).

TERDWONGWORAKUL, A.; PUNSUWAN, V.; THANAPASE, W.; TSUCHIKAWA, S. 2005. Rapid assessment of wood chemical properties and pulp yield of *Eucalyptus camaldulensis* in Thailand tree plantations by near infrared spectroscopy for improving wood selection for high quality pulp. *J. Wood Sci.* 51:167-171.

TESSIER DU CROS, E.; KLEINSCHMIT, J.; AZOEUF, P.; HOSLIN, R. 1980. Spiral grain in beech, variability and heredity. *Silvae Genetica* 29:5-13.

TIGABU, M. 2003. Characterization of forest tree seed quality with near infrared spectroscopy and multivariate analysis. Doctoral thesis. Swedish University of Agricultural Sciences. Department of Silviculture. Umea. 56 p.

TIGABU, M.; ODEN, P.R.; SHEN, T.Y. 2004. Application of near-infrared spectroscopy for the detection of internal insect infestation in *Picea abies* seed lots. *Can. J. For. Res.* 34:76-84.

TOBIAS, R. 1995. An Introduction to Partial Least Squares Regression. *In*: Proceedings of the Twentieth Annual SAS Users Group International Conference, Cary, NC: SAS Institute Inc., 1250-1257.

TROUP, R.S. 1921. The Silviculture of Indian Trees. Oxford Press, London. Pp 1056-61.

THYGESEN, L.G. 1994. Determination of dry matter content and basic density of Norway spruce by near infrared reflectance and transmittance. *J. Near Infrared Spectr.* 2:127-135.

USDA FOREST PRODUCTS LABORATORY. 1987. Wood Handbook: Wood as an Engineering Material. Agri. Handb. 72. USDA Forest Service, Washington, D.C.

VIA, B.K. 2004. Modeling Longleaf pine (*Pinus palustris* Mill) wood properties using near infrared spectroscopy. Doctoral thesis. Louisiana State University, Agricultural and Mechanical College. 141 pp.

VIA, B.K.; SHUPE, T.; GROOM, L.; STINE, M.; SO, C. 2003. Multivariate modeling of density, strength and stiffness from near infrared spectra for mature, juvenile and pith wood of longleaf pine (*Pinus palustris*). *J. Near Infrared Spectr.* 11:365-378.

WAHLGREN, H.E.; BAKER, G.; MAEGLIN, R.R.; HART, A.C. 1968. Survey of specific gravity of eight Maine conifers. USDA Forest Service, Research Paper FPL-95. 11p.

WALKER, J. 2000. Dream merchants: why forestry practices will change. *New Zealand J. of For.* 45(3): 27-33.

WALKER, J.C.; BUTERFIELD, B.G.; LANGRISH, T.A.; HARRIS, J.M.; UPRICHARD, J.M. 1993. Primary Wood Processing. Chapman and Hall, London. 595 pp.

WARD, D. 1975. The influence of tree spacing upon tracheid length and density density in Sitka spruce (Picea sitchcensis [Bong] Carr.). M.Agr.Sci. thesis, University College, Dublin.

WELLNER, C.A. 1955. Summaries of results from studies of western larch poles. Inland Empire Research Center. Intermountain Forest Range Experiment Station. Report prepared for Cooperators, Jan. 25.

WILHEMSSON, L. 2001. Characterisation of wood properties for improved utilisation of Norway Spruce and Scots Pine. Doctor's dissertation. Department of Forest Management and Products Uppsala. Swedish University of Agricultural Sciences.

WILLITS, S.A.; LOWELL, E.C.; CHRISTENSEN, G.A. 1997. Lumber and veneer yields from small-diameter trees. *In* Proceedings of the Sustainable Forestry Working Group at the IUFRO All Division 5 Conference, Pullman, Washington, July 1997. p. 73-79.

WORKMAN, J.J. 2001. NIR Spectroscopy calibration basics. In: Handbook of Near-Infrared Analysis. Edited by D.A. Burns and E.W. Ciurczak. Marcel Dekker, Inc. New York. 814p.

WRIGHT, J.; BIRKETT, M.; GAMBINO, M. 1990. Prediction of pulp yield and cellulose content from wood using Near Infrared Reflectance spectroscopy. *TAPPI J.* 73:164-166.

WWPA. 2005. Western lumber grading rules. Western Wood Products Association. Portland, Oregon.

YANG, J-C.; CHIU, C-M; LIN, T-P; KUNG, F-H. 2001. No clinal variation in Cunninghamia lanceolata wood density sampled from thirteen Chinese provinces. *Taiwan J For Sci* 16(2):65-80.

YOUNG, G.G. 2002. Radiata pine wood quality assessments in the 21st century. *New Zealand J. For.* 47(3): 16-18.

ZOBEL, B.J.; VAN BUIJTENEN, J.P. 1989. Wood variation, its causes and control. Springer, New York. 363 pp.

ZOBEL, B.J.; JETT, J.B. 1995. Genetics of wood production. Springer-Verlag, Berlin. 337 pp.