ECONOMIC ANALYSIS OF RECOVERING SOLID WOOD PRODUCTS FROM WESTERN HEMLOCK PULP LOGS

by

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ABSTRACT

The purpose of this research was to quantify what value could be gained from cutting solid wood products from old-growth western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) logs that are used to produce pulp in British Columbia. These logs represent a significant portion of the resource and increasing their value recovery would be beneficial to the forest industry.

One hundred and sixteen logs were sampled from the coastal and interior regions of British Columbia. Dimension and quality attributes were measured to enable estimates of gross and merchantable volume. Logs deemed likely to yield lumber were sawn with the aim of maximizing value recovery. The nominal dimension and grade of all lumber recovered was recorded. Margins and breakpoints at which sawing became profitable were calculated. Models to predict the volume of lumber and proportion of Clear grade lumber recovered ("C Industrial" grade at the interior mill, "D Select" grade at the coastal mill) were developed.

Lumber recovery, especially Clear grade lumber, was significantly higher from logs from the coastal site. At current market prices, cutting lumber from these logs was profitable, with the highest margins achieved when chips were produced from the milling residue. It was not profitable to recover lumber from the interior logs regardless of whether chips were produced. The disparity between locations was attributed to differences between the logs, the sawmilling equipment, the sawyers' motivations and the lumber grades.

Between 60% and 67% of coastal logs and 13% to 21% of interior logs returned a profit, depending on whether chips were produced. Models were developed to better identify these logs using observable attributes. A linear model described the total volume of lumber recovered. Significant predictor variables in the model were the gross log volume, the average width of the sound collar and the stage of butt/heart rot at the large end. A second model predicted the proportion of Clear grade lumber. Regional models were developed to account for different Clear lumber grades between sawmills. Significant predictor variables were knot frequency, diameter at the large end, volume, length, taper and the width of the sound collar at the large end.

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CHAPTER 1. INTRODUCTION

1. Problem and its setting

1.1. Problem statement

Western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) is of growing importance to the forest industry in British Columbia. It is one of the most abundant species, yet it contributes relatively little value to the province in relation to the volume harvested. This is due to its susceptibility to a range of defects, which result in a higher proportion of low-quality logs and lumber downgrades compared with other species. Due to its abundance, increasing the value recovery of western hemlock will be vital to the long-term profitability of the forest industry in British Columbia.

A possible means to improve margins for western hemlock is to evaluate the economics of recovering solid wood products from logs that are currently used for pulp production. In some parts of British Columbia, a wide range of log grades are being used for pulp production, including some lower quality sawlog grades. This manufacturing outcome generates relatively little value from the logs. By better understanding when it becomes profitable to recover higher value products, log allocation decisions can be based on maximizing value recovery. This represents the central focus of this research.

1.2. Background

Western hemlock grows in the Pacific coastal region of North America from northern California to Alaska. In British Columbia, it is the most prevalent species on the western side of the Coastal Mountain Range (BC Forestry Innovation Investment 2008) and is also found in the interior wet belt, west of the Rocky Mountains. It is an important commercial species for both the sawn wood and pulp and paper industries. Its light, even textured wood and ease of machining make it suitable for dimension and shop lumber, moulding and panelling. The wood has relatively low levels of extractives (Keays and Hatton 1971) and good fibre qualities, making it a preferred species for market kraft pulp and newsprint production (King *et al.*1998).

Compared with other species, western hemlock is highly susceptible to stem decay (Clark 1957, Hennon and DeMars 1997, Scheffer and Morrell 1998). Stem decay is a natural process of wood decomposition that is caused by microorganisms, usually fungi (Shigo and Marx 1977). These break down one or more of the cellulose, hemicellulose and lignin components of the cell walls, decreasing wood strength and ultimately destroying cells (Eaton 2000). From a commercial perspective, decay reduces the merchantable volume and lowers the quality of wood available for sawn wood and chips. Decay fungi can also cause discoloration in sound wood, reducing the commercial value of lumber.

All hemlock species (*Tsuga* spp.) are prone to forming wetwood, which is heartwood that has become internally infused with water (Hartley *et al.* 1961, Ward and Pong 1980). It is distinguished from normal heartwood by a darker colour, wetter appearance and characteristic odour (Schroeder and Kozlik 1972). Wetwood is much more likely than normal heartwood to separate between (shake) and across (check) growth rings, particularly after kiln drying (Kozlik 1970, Schroeder and Kozlik 1972, Ward and Pong 1980). Check and shake reduce the volume of sawn wood recovered as split fibre is structurally unsound and is usually trimmed. Kiln dried lumber from logs containing wetwood is also more likely to have a brown stain defect, which often reduces the lumber value (Ward and Pong 1980). Production costs are also increased, as wetwood can take two to six times longer than normal sapwood to reach acceptable moisture levels when kiln dried (Sachs *et al.* 1974).

In British Columbia, logs are graded into quality classes using rules developed by the Ministry of Forests and Range (MoFR). Log sales combine western hemlock with other species with similar attributes into the market group hembal, which is also known as hem-fir. Western hemlock's susceptibility to decay, shake, check and stain causes more logs from the hembal species group to be downgraded to grades that are used for pulp production compared with other species (Figure 1-1). As a consequence, hembal generates a smaller proportion of value from log sales in British Columbia's open log markets relative to the volume of logs sold (Figure 1-2). From 2004 to 2008, hembal accounted for 44.4% of the volume sold on the open market in the coastal region but generated just 27.8% of total value (MoFR 2008).

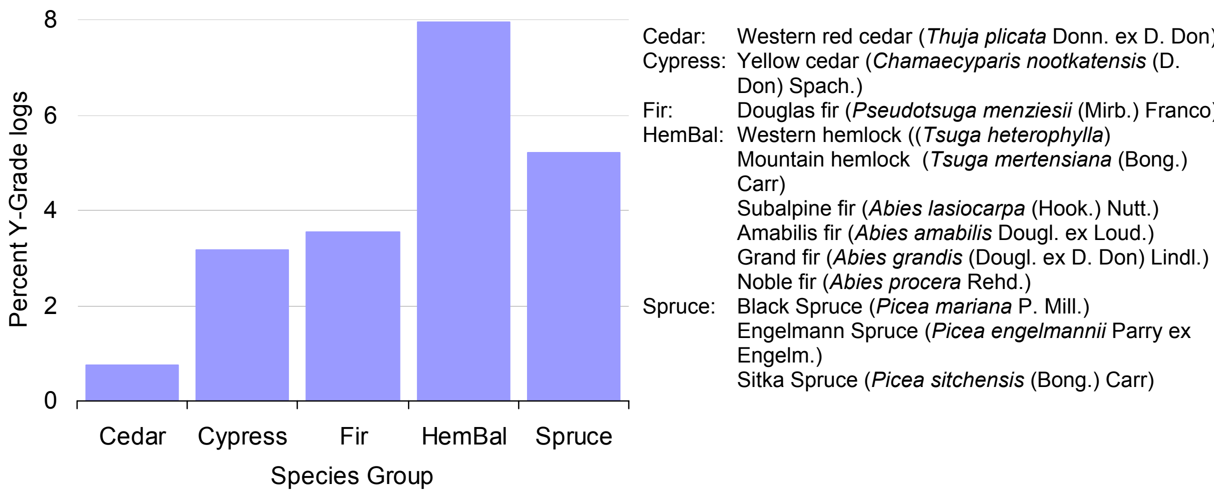

Figure 1-1 Volume of No. 7 chipper grade (Y) logs as a percentage of total volume sold on the open log market between January 1, 2002 and December 31, 2006 for the coastal region of British Columbia.
Source: MoFR Log Market Reports 2008.

Historic records show that relative to its abundance, hembal has been underrepresented in sales in British Columbia's open log market. From 2004 until June 2008, just 11% of the volume of logs sold were hembal (MoFR 2008), while it is estimated western hemlock represents 17.7% of the growing stock volume (BC Forestry Innovation Investment 2008). The discrepancy was greatest in the coastal region, where hembal accounts for approximately 60% of the mature forests (Coast Forest Products Association 2003) yet represented only 42.4% of the open market log sales between 1990 and 2008 (Figure 1-3). Open market log sales constitute only 25% of all log sales in the province (Lewis 2008). If hembal has been similarly underrepresented in the remaining 75% of log sales, it likely will represent a greater proportion of the market in future years and finding ways of improving its value recovery will gain in importance.

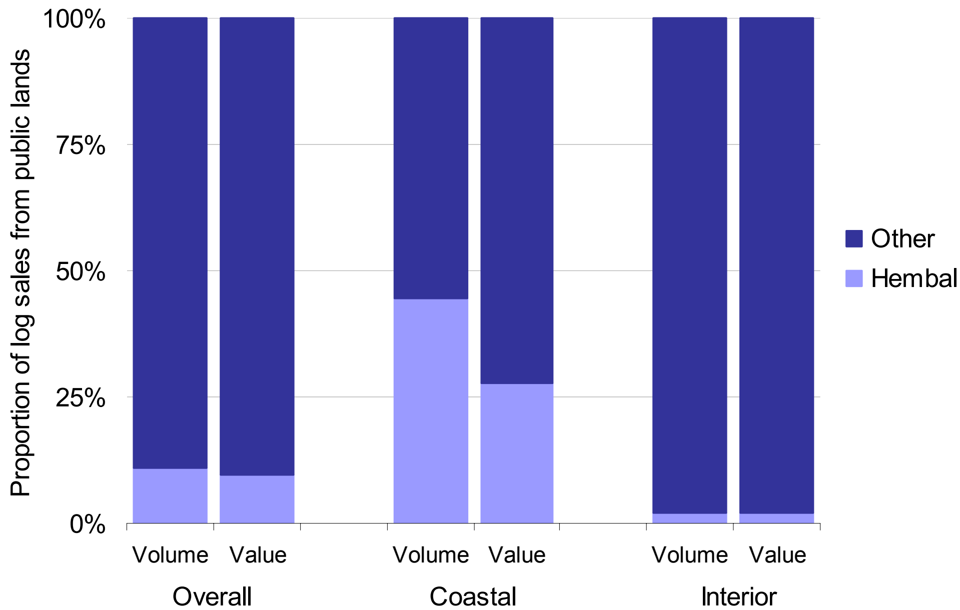

Figure 1-2 Volume and value of hembal logs as a percentage of all logs sold in British Columbia's open log market between 2004 and 2008.
Source: MoFR Log Market Reports 2008.

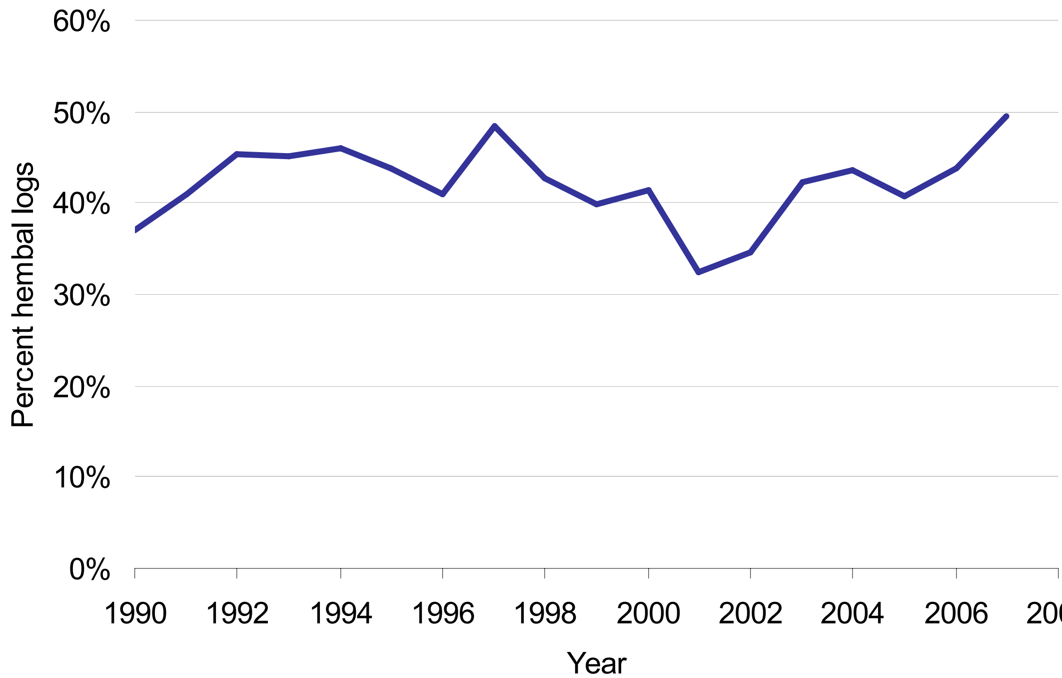

Figure 1-3 Hembal log volumes as a percentage of total log volumes sold in British Columbia's open log market between 1990 and 2007 for the coastal region.
Source: MoFR Log Market Reports 2008.

Due to its abundance and relatively poor economic contribution, increasing the value recovery of western hemlock will become more important to the long-term success of the forest industry. A potentially successful method to increase value recovery would be to better understand the critical breakpoints at which different manufacturing outcomes become profitable. Decisions around grading, log allocation and manufacturing could then be based on maximizing the expected margin of the log. This would allow more flexibility to accommodate changing prices and to take advantage of new market opportunities. This study used this approach to determine when it becomes profitable to produce solid wood products from western hemlock logs that are currently used for pulp.

1.3. Research hypothesis

The research hypothesis for this study is as follows:

It is profitable to recover sawn wood and to produce chips from the milling residue of a significant proportion of the western hemlock logs which are currently used to for pulp production in British Columbia.

1.4. Objectives

The objectives of this study were as follows. For western hemlock logs that are currently used for pulp production:

1. At what costs and prices does it become profitable to recover sawn wood?
2. How do the economics change if a chipping facility is established to process milling residue?
3. Which log features are the best predictors of lumber recovery?
4. Which log features are the best predictors of Clear grade lumber recovery?

1.5. Approach

To meet the objectives of this study, western hemlock logs that were intended for pulp production were collected from both the coastal and interior regions of British Columbia. Log dimensions and visible defects were measured and assessed according to the specifications used for log grading in British Columbia (MoFR 2007). Logs were then sawn at participating mills and the nominal dimension, length and grade of each piece of lumber recovered from each log was recorded. The log attributes were used to develop models to predict the total volume of lumber and the proportion of Clear grade lumber recovered from each log.

Estimates of costs and revenues, in conjunction with the measured recoveries were used to determine the overall margins of sawing these logs. Two scenarios were evaluated: the first considered the unused log portions as waste; the second considered the unused log portions as an additional source of revenue through chipping. Sensitivity analyses were conducted to determine the critical log prices, sawmilling costs and lumber recoveries at which it became profitable to recover sawn wood from logs that were intended for pulp production.

2. Literature review

2.1 The market for hembal

In British Columbia, log prices used in the stumpage appraisal process combine western hemlock, mountain hemlock, subalpine fir, grand fir, noble fir and Amabilis fir into the species group hembal. Hembal is one of the major commercial timber groups in British Columbia, accounting for 11% of the recorded timber sales by volume between 2004 and 2008 (Figure 1-2) (MoFR 2008). The species group is much more prevalent in the coastal region, representing 44.4% of the open market log sales during this period, compared with 2.1% in the interior region.

In 2005 and 2006, the open market price for western hemlock pulp logs in both the coastal and interior regions declined (Figure 1-4). This was considered likely due to the high volumes of lower grade logs produced from the salvage harvests of lodgepole pine (*Pinus contorta* Dougl.) stands affected by mountain pine beetle (*Dendroctonus ponderosae* Hopkins). During this period, many forest operations had difficulty finding a market for western hemlock pulp logs.

Sufficient chip volumes of mountain pine beetle affected wood were available to satisfy much of the demand of pulp mills, while many sawmills did not consider the investment in these lower grade logs justified. As a result, many western hemlock logs that would typically be used for pulp production were unsold.

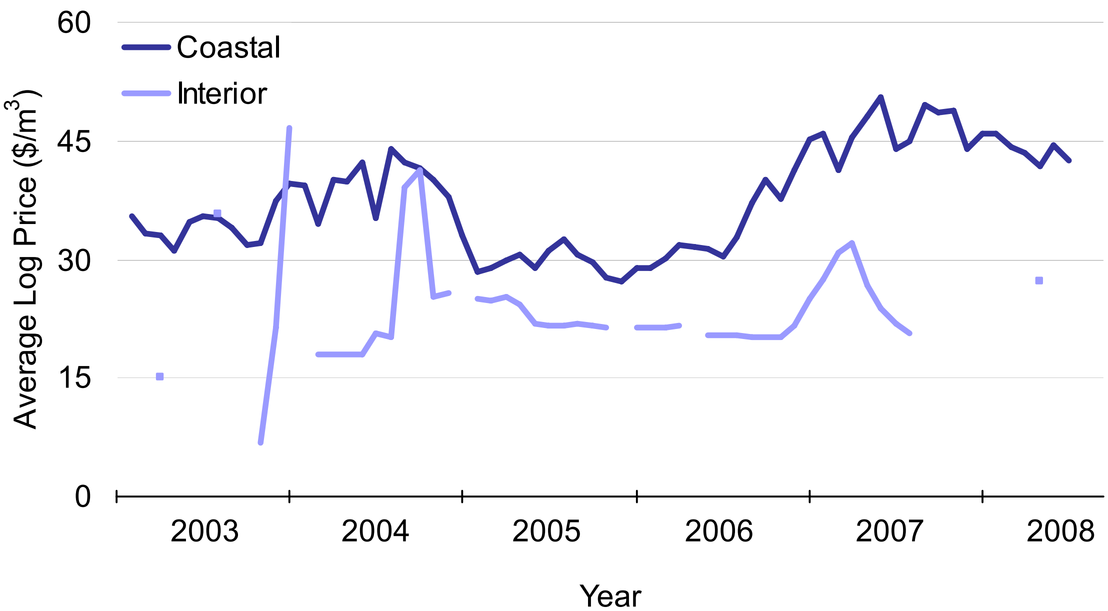

Figure 1-4 Average log price ($/m^3) at the end of each month between January, 2003 and June, 2008 for No. 7 chipper grade logs in the British Columbia coastal region and Lumber reject grade logs in the interior region.
Source: MoFR Log Market Reports 2008.

2.2 Log grading for western hemlock

In British Columbia, log grading specifications for western hemlock tend to be more stringent than for other species. In the interior region, if less than 75% of the gross volume is deemed suitable for lumber, western hemlock logs are graded as lumber reject. The only other log class with such a high threshold are western red cedar logs with a mid-diameter less than 50 cm. For balsam logs (alpine fir, grand fir, noble fir, amabilis fir) this critical value is 67% and for all other logs it is 50% (MoFR 2007). This partly explains the disproportionate volume of hembal pulp logs compared with other species (Figure 1-1).

Log grading specifications tend to be more stringent in the interior than in the coastal region. In the coastal region, a log will be graded as No. 7 chipper and thus considered only suitable for pulp production if any of the following conditions are met:

- less than 33.3% of the gross volume can be manufactured into lumber;
- less than 35% of the lumber will be merchantable;
- the number of oversized knots exceeds the maximum number permissible in any 3 m section (Table 1-1);
- twist exceeds either 13% of the diameter or 13 cm over a 30 cm length; or
- the length is less than 3 m (MoFR 2007).

Table 1-1 Diameter of oversize knots and number permitted in a 3 m section by log radius to meet No. 6 utility grade (X) in coastal region of British Columbia.

Log Radius (cm)	Oversize knot diameter (cm)	Number permitted over 3 m section
5-7	4	1
8-13	6	1
14-18	8	1
19-24	10	1
25-37	12	2
38-49	14	2
50+	16	2

In comparison, in the interior regions, western hemlock logs are graded as lumber reject code 4 and thus considered suitable for pulp production if any of the following conditions are met:

- less than 75% of the gross volume can be manufactured into lumber;
- less than 50% of the lumber will be merchantable;
- the number of oversized knots exceeds the maximum number permissible in any 2.5 m section (Table 1-2); or
- the length is less than 2.5 m (MoFR 2007).

Table 1-2 Diameter of oversize knots and number permitted in a 2.5 m section by log radius to meet sawlog code 2 in interior regions of British Columbia.

Log Radius (cm)	Oversize knot diameter (cm)	Number permitted over 2.5 m section
5-7	4	0
8-13	6	1
14-18	8	1
19-24	10	1
25-37	12	1
38+	14	1

2.3 Stem decay

Stem decay is a natural process that involves the degradation of cell walls within the tree, usually by fungi, but often also involving bacteria and other non-decay fungi (Shigo and Marx 1977). It is a vital forest process that contributes to nutrient cycling, renewal, soil development and wildlife habitat. It becomes a problem in commercial forest settings as decay reduces the amount and quality of wood available, increases logging and milling costs and introduces uncertainty into yield estimates (Holsten *et al.* 2001).

Decay fungi are described by the part of the stem which they generally affect. Heart rot fungi are classified into those that typically affect the lower portion of the stem above (butt rot) or below ground (root rot), those that are limited to a series of growth rings within the stem (ring rot), those that affect a region outside of the central core (pocket rot) and those that affect the core of central heartwood through the stem (heart rot). Sap rot fungi affect the outermost part of the stem and are most common on dead trees.

Decay is most prevalent in the heartwood of living trees and rarely spreads within the living sapwood of the tree, due to fungitoxic extractive compounds in the sapwood (Hillis 1962, Hart 1964, Hart and Johnson 1970, Shigo and Marx 1977, Boddy and Raymer 1983). Some believe that trees actively respond to decay by depositing extractives to develop a barrier to further lateral spread (Hillis 1962, Shigo and Marx 1977, Shain 1979), while others suggest that the barriers are developed to prevent the entry of air or loss of moisture from the functional sapwood (Boddy and Raymer 1983).

The heartwood of certain tree species are more resistant to decay than others. Decay resistance develops during heartwood formation, when reactions convert stored sugars and starch into fungitoxic extractive compounds (Hillis 1962, Scheffer and Cowling 1966). Western hemlock has a low resistance to decay, due to its low levels of fungitoxic extractive compounds (Clark 1957, Scheffer and Morell 1998). A study testing the resistance of the heartwood of various conifers to three common fungi found western hemlock to be amongst the least resistant (Clark 1957). In an evaluation of the decay resistance of international tree species, western hemlock was classified as non-resistant (Scheffer and Morrell 1998).

2.4 Fungal pathogens

Approximately fifty types of fungi that cause heart rot in western hemlock are known, although around twenty are common (Table 1-3) (Kimmey 1964, Allen *et al.* 1996). Heart rot has been attributed to the loss of one quarter of the gross volume of western hemlock across its range (Kimmey 1964). In British Columbia, Indian paint fungus (*Echinodontium tinctorium* Ellis & Everh.) is considered the major cause of heart rot in mature western hemlock (Allen *et al.* 1996). In British Columbia, Washington and Oregon, it is most prevalent in the interior regions and virtually nonexistent in the coastal regions (Kimmey 1964).

The primary entry point of Indian paint fungus into trees is through the living stubs of exceptionally small branches (<1 mm) (Etheridge *et al.* 1972). After entry, the fungus can sit dormant for 50 years or more before initiating decay (Etheridge *et al.* 1972). Detecting its presence within living trees is therefore extremely difficult. The rate of tree growth is a critical factor to a trees susceptibility to the fungus. It gains entry through the branch stubs in the period immediately before they become overgrown. In slow growing stands, the window of opportunity

Table 1-3 Common types of fungi that cause decay within the stems of living western hemlock in British Columbia.

Scientific Name	Common Name/s
Ceriporiopsis rivulosa (Berk. & Curtis) Gilb. & Ryvarden	White butt rot, White laminated rot
Echinodontium tinctorium	Brown stringy trunk rot, Indian paint fungus
Fomitopsis officinalis (Villars:Fr.)	Brown trunk rot, Quinine fungus, Quinine conk
Fomitopsis pinicola (Sw.:Fr.) P. Karst	Brown crumbly rot, Red belt fungus
Ganoderma applanatum (Pers.) Pat.	White mottled rot
Gleophyllum sepiarium (Wulfen:Fr.) P. Karst.	Brown cubical sap rot
Hericium abietis (Weir ex Hubert) K. A. Harrison	Yellow pitted rot
Heterobasidion annosum (Fr.) Bref.	Annosus root and butt rot
Laetiporus sulphureus (Bull.:Fr.) Murrill	Brown cubical rot, Sulfur fungus
Neolentinus kauffmanii (A. H. Smith) Redhead & Ginns	Brown pocket rot of sitka spruce
Perenniporia subacida (Peck) Donk	Stringy butt rot
Phaelous schweinitizii (Fr.:Fr.) Pat.	Velvet top fungus, Schweinitzii butt rot
Phellinus hartigii (Allesch. & Schnabl.) Bondartsev	White trunk rot of conifers
Phellinus pini (Thore:Fr.) Ames	Red ring rot
Postia sericeomollis (Romell) Jülich	Brown cubical butt & pocket rot of cedar
Stereum sanguinolentum (Albertini & Schwein.:Fr.) Fr.	Red heart rot, Bleeding fungus
Trichaptum abietinum (Dickson:Fr.) Ryvarden	Pitted sap rot
Veluticeps fimbriata (Ellis & Everh.) Nakas.	Brown cubical pocket rot

is longer and the infection rate is more prevalent (Etheridge and Craig 1976). Indian paint fungus is rarely detected in branches less than 40 years of age, but becomes increasingly prevalent as age increases (Etheridge *et al.* 1972).

Annosus root and butt rot is one of the main causes of heart rot in western hemlock (Kimmey 1964, Holsten *et al.* 2001). The stumps of surrounding trees are its primary entry point (Holsten *et al.* 2001). After colonizing the stump's root system, the fungus then spreads into the root systems of adjacent live trees before progressing into the bole of the tree (Holsten *et al.* 2001). This means there are often no visible symptoms of Annosus butt rot in living trees.

2.5 Wetwood

Heartwood that has become internally infused with water is called wetwood, which is also known as sinker heartwood, sinker and heavy wood (Ward and Pong 1980). It is generally higher in moisture content, specific gravity and extractive chemicals than surrounding normal heartwood but may be higher, lower or equal in moisture content to sapwood (Schroeder and

Kozlik 1972, Ward and Pong 1980). It commonly has a characteristic odour and a darker or wetter appearance than normal heartwood (Schroeder and Kozlik 1972).

Wetwood is a problem commercially as fibre separation is far more common where moisture gradients are variable (Kozlik 1970, Schroeder and Kozlik 1972). When dried, timber cut from wetwood is prone to shrink, crack and collapse (Ward 1972). Kiln dried lumber from logs containing wetwood is also more likely to have a brown stain defect (Ward and Pong 1980). Fibre separation, shrinkage, collapse and stain reduce both the quantity and value of lumber produced. Kiln drying wetwood also takes two to six times longer than sapwood to reach acceptable moisture levels, increasing production costs (Sachs *et al.* 1974).

The causes of wetwood formation are unclear. Wetwood is almost always associated with bacterial infection of the inner heartwood and outer sapwood of the tree (Wilcox and Oldham 1972, Ward and Kozlik 1975, Tiedmann *et al.* 1977, Kamp *et al.* 1979, Scott 1984, Shaw *et al.* 1995). Whether bacteria initiate wetwood formation or take advantage of the advantageous conditions is unclear (Bauch *et al.* 1975, Coutts and Rishbeth 1977). Anaerobic bacteria in wetwood are thought to weaken the middle lamella causing shake (Ward and Kozlik 1975). The source of water has been attributed to both direct entry through stem openings (Bauch *et al.* 1975) and internal origins through the roots or sapwood (Coutts and Rishbeth 1977).

Like all hemlocks, western hemlock is prone to forming wetwood (Hartley *et al.* 1961). It is not known what causes this increased susceptibility. Log scaling and grading regulations in British Columbia do not account for wetwood, but do account for the associated defects of shake or check (MoFR 2007).

2.6 Lumber recovery studies

Many factors affect the volume of lumber that is recovered from logs in sawmilling. These include log size and quality, the cutting decisions made, the sawing methods, kerf width, oversizing of rough green lumber, the type and condition of the mill equipment and the mix of products produced (Steele 1984).

A number of studies have investigated product recovery from western hemlock logs. In 1976, a U.S. Department of Agriculture (USDA), Forest Service study considered the utilization, lumber recovery and chip yields of western hemlock logs in south-eastern Alaska (Woodfin and Snellgrove 1976). At 12 different locations, 30 logs were sampled and scaled using the Puget Sound Log Scaling and Grading Bureau rules. The majority of logs were graded as No. 2 or No. 3 sawlog. Logs were then cut into 3.0 to 8.5 metre lengths and sawn primarily into nominal 102 x 102 mm (4 x 4 inch) pieces. For logs that were graded as cull, 26% of the gross log volume was recovered as green lumber. For all other logs, 48% of the gross log volume was recovered as green lumber (Woodfin and Snellgrove 1976).

A study commissioned by the USDA Forest Service in Alaska evaluated the product recovery of western hemlock pulp logs (Fahey 1983). In this study, 263 pulp grade logs were sawn primarily into nominal 51 mm (2 inch) thick framing lumber at stud or dimension mills (Fahey 1983). The logs sampled were considered representative of the range of logs used for pulp in Alaska although they had relatively small diameters (127 - 356 mm). While the logs were not graded, it was stated that due to diameter limits in the grading system, the majority of the sample would have been grade 3. The expected yield of high value lumber for grade 3 logs is 20-40%. It was stated that had the grading been based on surface characteristics rather than diameter, most logs would have met grade 2 requirements, with 40-60% high value lumber expected (Fahey 1983). Therefore, the pulp log classification in this study was based on size rather than log quality. At the stud mill, 60% of the log volume was recovered as rough green lumber. When converted to surfaced-dry lumber, the average recovery was 47.5% of the original log volume. The remaining volume available for woodchips represented 31.6% of the original log volume. At the dimension mill, 53.2% of the original volume was recovered as rough green lumber. This equated to 41.5% of the original log volume when converted to surfaced-dry lumber. The remaining volume available for woodchips represented 40.6% of the original log volume (Fahey 1983).

In 2000, a study was conducted in Alaska to investigate the product recovery of western hemlock pulp logs in response to the demise of local pulping facilities (Green *et al.* 2000). A total of 409 western hemlock pulp logs were selected at random and then graded and scaled using the Scribner scale. Logs were cut into 4.3 m lengths and then milled with the aim of maximizing 51 x 102 mm (2 x 4 inch), 51 x 152 mm (2 x 6 inch) and 51 x 254 mm (2 x 10 inch) lumber. The volume of lumber recovered represented 156% of the estimated net log volume using the Scribner log scale. The recovery in relation to the cubic log volume was not provided. The rough, green lumber was graded according to the Western Wood Products Association (WWPA) lumber grading rules (WWPA 1998). As a percentage of the total volume of lumber recovered, 52% was graded as No. 2 or better and 73% as No. 3 or better, indicating that a high percentage of the wood would be suitable for structural framing lumber.

In 2002, the volume recovery, grade yield and lumber properties from young-growth Sitka spruce and western hemlock in southeast Alaska was investigated (Christensen *et al.* 2002). A total of 136 western hemlock trees were selected from two 90 year old stands containing both unthinned and thinned sections. After being felled, hemlock logs were bucked into 3.15 m and 4.05 m lengths. These produced 690 mill-length logs, representing a gross volume of 177.1 m^3 and a net volume of 157.3 m^3. Log defect was extremely low with the greatest source of deduction caused by excessive fluting. The logs were sawn into export lumber with dimensions of 45 x 90 mm and 90 x 90 mm. For logs without fluting from unthinned stands, 44.5% of the total volume was recovered. For logs with fluting from unthinned stands, 42.7% of the total volume was recovered as surfaced green lumber. For logs from thinned stands, 41.9% of the total volume was recovered as surfaced green lumber. The percentage lumber recovery was lower than in other studies and was attributed to the sawmill product objectives and the surfacing of the lumber. It was suggested that recoveries would have been 15-20% higher had the objective been to maximize lumber yield. The lumber was then graded according to WWPA lumber grading rules. Over 92% of lumber by volume was graded as No. 2 or better (Christensen *et al.* 2002).

2.7 Estimating volume and value recovery

A number of studies have developed models to predict the volume and value of recoverable products for both trees and logs. Most predictive models include diameter and length (Howard and Gasson 1989) or diameter, height and taper (Liu and Zhang 2005, Zhang and Tong 2005, Zhang and Liu 2006). Other models have also incorporated additional features including sweep, crook, twist and out-of-roundness (Kellogg and Warren 1984).

A USDA study considered the volume and value recovery of western hemlock logs that were to be used as a source of "pulpwood". The actual volume and value of lumber recovered were found to have a linear relationship with the estimated recoverable volume using the cubic log scale (Fahey 1983). The cubic log scale uses diameter at both ends and log length to estimate the gross log volume, then makes deductions for defects including shake, check, rot, sweep and crook to estimate the recoverable volume (Anon. 1978). The coefficient of determination (r^2) between the actual lumber volume recovered and the estimated volume based on the scale was 0.85 at a stud mill and 0.93 at a dimension mill. The coefficient of determination between the actual lumber value and the estimated recoverable volume was 0.82 at a stud mill and 0.89 at a dimension mill (Fahey 1983).

In 1984, a study was conducted to evaluate the effect of various characteristics of western hemlock trees on recoverable product value (Kellogg and Warren 1984). The effects of diameter, height, taper, sweep, crook and stem eccentricity (out-of-roundness and rotation) on the value of lumber recovered were considered using a simulated sawing technique. Diameter and height were most related to lumber value due to their strong relationship with total volume. Of the other selected tree characteristics, taper was the most important predictor of lumber value for trees of a given diameter. This was considered due to its affect on total volume and the geometric effect of taper on sawing recovery. The remaining characteristics were found to have statistically significant, although minor, effects on product value. The most severe cases of crook were found to have a 1% impact on total value under optimized bucking conditions (Kellogg and Warren 1984).

2.8 Log scanning

Advances in technology have enabled the grading of logs using scanners which measure both external and internal features. Optical three-dimensional (3D) scanners can measure external properties such as surface unevenness, size and taper (Jäppinen and Beauregard 2000). Various technologies such as x-rays (Lindgren 1991), nuclear magnetic resonance (Chang *et al.* 1989), ultrasound (Sandoz 1996) and longitudinal stress waves (Ross *et al.* 1997) have been used to measure internal log features. Internal properties measured include wood density, knot size and the stiffness of centre boards (Lindgren 1991, Ross *et al.* 1997, Oja *et al.* 2001). Using knowledge of the internal and external log features during log merchandizing, allocation and breakdown decisions can lead to better value recovery.

Scanning technology has been shown to be successful at sorting logs into quality grades. Optical 3D scanning was found to correctly assign approximately 70% of logs into two groups based on the expected board grade recovery (Grace 1994, Lundgren and Jäppinen 1998). By enabling internal log features to be measured, x-ray scanning gave better results with 77% to 83% of logs correctly assigned to one of three quality groups (Oja *et al.* 2000).

Predicting the grade of boards within logs is more complex than sorting logs into different quality classes, as logs may contain boards of differing grades. A study was conducted to compare the ability of 3D optical scanning and x-ray scanning to predict the grades of centre boards in logs (Oja *et al.* 2004). The 3D optical scanner measured diameter, taper and surface unevenness. The x-ray scanner measured diameter, taper and density variation, enabling the identification of internal knots. Using two x-ray scanners in conjunction with a 3D scanner was found to be best at predicting centre board grade, with 65% accuracy. This was an improvement over using only a 3D optical scanner (57%), two x-ray scanners (62%) and one x-ray scanner in conjunction with a 3D optical scanner (64%) (Oja *et al.* 2004).

Scanning technologies have been shown to be useful at predicting the total value of boards cut from logs. A study considered the ability of 3D optical scanners alone and in conjunction with x-ray scanners at predicting the value of boards cut from *Pinus sylvestris* (L.) sawlogs (Nordmark and Oja 2004). Using both scanning systems gave a slightly better coefficient of determination (0.75) than using only 3D scanning (0.72) (Nordmark and Oja 2004). These studies suggest that there may be benefits in using scanning technologies to identify the internal characteristics of pulp logs to assist with log grading, merchandizing, allocation and breakdown.

3. Conclusion

Western hemlock is an important commercial species in British Columbia. The market group hembal, which includes western hemlock, represented 11% of the open market log sales between 2004 and 2008 (MoFR 2008). Relative to its volume abundance, it generates proportionally less value. This is in part due to its susceptibility to a range of defects. Low levels of fungitoxic extractive compounds make western hemlock highly susceptible to decay. The species also commonly develops wetwood, which causes the resulting issues of shake, check, shrinkage, collapse and stain. These defects result in a high proportion of logs being classified into lower quality grades and more lumber downgrades, particularly after kiln drying. Due to its abundance, increasing the value recovery of western hemlock would be highly beneficial to the forest industry.

No published studies in British Columbia have investigated the recovery of sawn wood from western hemlock logs that are used for pulp production. Similar studies have been conducted in Alaska with promising results. A study investigating the lumber recovery from western hemlock pulp logs found that 53.2% and 60% of the gross log volume was recovered as rough green lumber at a dimension and stud mill respectively (Fahey 1983). Another study investigating the product recovery of western hemlock pulp logs found that 52% of lumber recovered was graded as No. 2 or better (Green *et al.* 2000). These studies suggest that a high percentage of western hemlock pulp wood may be suitable for solid wood manufacturing. While the conditions in these studies are not identical to those in British Columbia, they indicate that there is considerable potential for the recovery of higher value products from logs which are used to produce pulp.

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CHAPTER 2. DATA COLLECTION AND ANALYSIS PROCEDURES[1]

1. Introduction

Two phases of data collection were required to meet the objectives of this research. Phase one involved measuring various dimension and log quality attributes of western hemlock logs that were intended for pulp production. Phase two involved milling the logs and recording the dimension, grade and length of each piece of solid wood recovered from each log. The data were then used to determine the margins of sawing the logs and to identify the most important log characteristics for lumber and grade recovery.

2. Data collection procedures

2.1 Site selection

Western hemlock grows in two distinct biogeoclimatic zones within British Columbia; the Coastal Western Hemlock Zone (CWH), which lies to the west of the Coastal and Cascade Mountains; and the Interior Cedar-Hemlock Zone (ICH), which occupies the western side of the Columbia Mountains (MoFR 2008a). A single replicate was used in each zone to reflect this distinction in the resource.

The first study site was located in Tree Farm License (TFL) 56, located approximately 45 km north of Revelstoke in the Columbia Mountains. TFL 56 occupies the ICH biogeoclimatic zone and is managed by the Revelstoke Community Forest Corporation (RCFC) on behalf of the City of Revelstoke. The selection of this location over other potential locations within the province was determined by the City of Revelstoke, as it was at their request that this research was undertaken.

The second study site was located in the Malcolm Knapp Research Forest (MKRF) situated in Maple Ridge, 60 km east of Vancouver. The forest is managed by the University of British

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[1] A version of this chapter will be submitted for publication. Mortyn, J and T. Maness. *Methods for measuring lumber volume and grade recovery from western hemlock pulp logs.* 22 pp.

Columbia and occupies the CWH biogeoclimatic zone. The study site was chosen over other potentially suitable sites as the MKRF management were willing to provide and mill the sample of logs for the study.

2.1.1 Interior sample selection

Logs from the interior site were sourced from cut block 1 in cutting permit 315, which was situated on the lower slopes of the Gold Stream River valley, 40 km north of Revelstoke. The site had a northerly aspect and was logged in March 2007. The existing forest was at least 250 years old (Bob Clarke pers. comm. 2007) and is classified as part of the Wet-Cool Interior Cedar-Hemlock biogeoclimatic zone (ICHvk1).

Pre-harvest cruise data indicated that the forest consisted predominantly of western red cedar and western hemlock, with small amounts of Sitka spruce (Table 2-1). More than 40% of the trees on site were western hemlock but these represented less than 20% of the standing volume. This was due to the average diameter of western hemlock trees being considerably less than those of western red cedar. Decay was estimated to be present on one third of the standing western hemlock on site.

Table 2-1 Summary of pre-harvest assessment of cut block 1 from cutting permit 315 in TFL 56.

	Western red cedar	Western hemlock	Sitka Spruce
Gross merchantable volume	80.2%	18.8%	1.0%
Net merchantable volume	81.0%	17.8%	1.2%
Stems per hectare	57.4%	40.6%	2.0%
Percentage of decayed trees	30%	33%	25%

The harvest site was selected by RCFC management and was described as being representative of the old-growth western hemlock resource in TFL 56. After being sorted at the log landing, the logs were transported to a log sorting yard in March, 2007. While the grade of each log was not known, all logs in the sample were intended for pulp production.

2.1.2 Coastal sample selection

The coastal trees sampled were felled in September 2007 from cutblock 2007-H140-02 in the MKRF. The site was located in the foothills of the Coastal Mountains, approximately 15 km north of the township of Maple Ridge. The cutblock straddled a ridge, with approximately equal proportions of easterly and westerly aspects, a maximum elevation of 597 m and a maximum slope of 50%. The existing forest was considered old-growth and was classified as part of the very wet subzone of the Coastal Western Hemlock biogeoclimatic zone (CWHvm). No pre-harvest site assessment was conducted although the cutting block was estimated to have a net merchantable volume of 550 m^3 per hectare (Paul Lawson pers. comm. 2007). The existing forest was estimated to consist of 55% western hemlock, 25% western red cedar, 12% yellow cedar and 8% Douglas fir (Paul Lawson pers. comm. 2007).

A sample of western hemlock logs that were intended for pulp production was selected by MKRF staff. The logs were independently graded which showed that the sample consisted of all grades from No. 2 sawlog to No. 7 chipper (Table 2-2). Just six logs, representing 9.3% of the total firmwood, were classified as the grade designed for pulp logs, No. 7 chipper grade. Twenty-six logs, representing 63.9% of the firmwood in the entire sample, were considered a sawlog by the grading rules. This range of grades was representative of those being used for pulp production at the time of the study. This was due to a combination of low demand for lower grade sawlogs and utility logs and historically high prices for No. 7 chipper logs. The intention of this study was to consider logs that were being used for pulp production rather than just logs graded as pulp. This was so the true economic implications of this practice could be determined.

2.2 Log measurement procedures

Logs were measured to enable accurate estimates of gross volume and firmwood volume. Gross volume was considered the volume of the complete cylinder of the log excluding bark.

Table 2-2 Log grade and estimated firmwood volume for the coastal log sample.

Log grade	Code	Logs	Firmwood Volume (m^3)
No. 2 sawlog	H	8	19.4
No. 3 sawlog	I	15	36.2
No. 4 sawlog	J	3	5.4
No. 5 utility	U	9	19.7
No. 6 utility	X	4	5.9
No. 7 chipper	Y	6	8.8

Firmwood volume was considered the gross volume minus the volume of rot, hole, char or missing wood. In British Columbia, firmwood volume is the most commonly used measure of log volume and is the basis for buying and selling wood.

At Revelstoke, 71 logs were measured to enable accurate estimates of gross volume. Of these, 57 that were deemed to have the potential for lumber recovery by Joe Kozek, General Manager of Joe Kozek Sawmills Ltd., were measured to enable accurate estimates of firmwood volume. At Maple Ridge, 45 logs were measured to enable accurate estimates of both gross volume and firmwood volume.

Identical log measurement procedures were used at both study sites. Prior to measurement, logs were numbered at each end with spray paint to enable identification at the sort yard and sawmill.

2.2.1 Log dimension measurement procedures

A series of log dimension measurements were made to enable accurate estimates of the gross volume of each log. Measurement procedures were based to the rules outlined in the MoFR Log Scaling Manual (2007). Diameter under-bark was measured twice at both ends of each log to the nearest centimetre using a measuring tape. The first diameter measurement was taken across the largest axis of the log. The second diameter was measured at right angles to the first. Abnormal protuberances such as knots and swellings were excluded from diameter measurements.

Where sections of wood were missing at either end of the log, an estimate of the complete diameter was made if the missing portion represented less than 50% of the end area (Figure 2-1). If the missing portion represented greater than 50% of the end area, diameter measurements were taken at the point where the missing portion ended. For logs with shattered or split ends, over-bark diameters were made using callipers at the first point along the log where the diameter was obtainable. These were adjusted to under-bark diameter estimates by subtracting two bark thickness measurements from a log of similar size.

For logs with irregularly shaped ends, diameter measurements were made by envisioning a circle or ellipse which best represented the area of the irregular shape.

For logs with flared butt ends, the measured diameter represented the estimated normal line of taper projected through the end of the log.

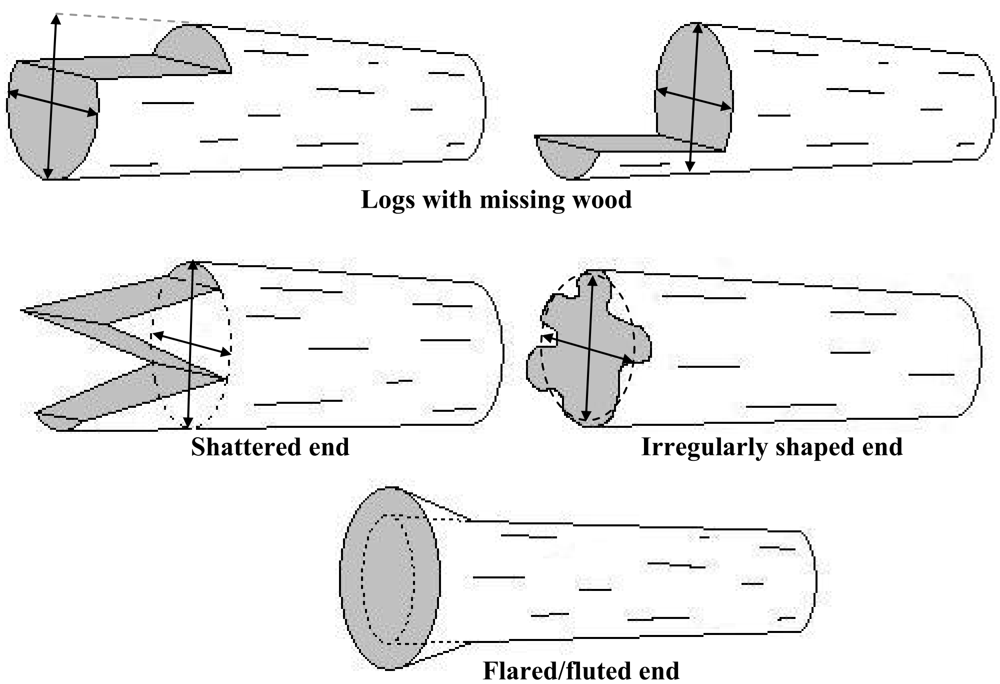

Figure 2-1 Methods for measuring end diameters for logs with missing wood, shattered ends, irregularly shaped ends and flared ends.

Two bark thickness measurements were made at the large end of each log to the nearest millimetre. Measurements were made where the bark was not damaged or missing. In cases where bark was missing from the entire circumference of the log at the large end, measurements were made at the first point along the log with undamaged bark.

At each 3 m interval along the log from the large end, two over-bark diameter measurements were made using callipers. The first measurement was taken parallel to the ground, while the second was taken perpendicular to the ground. If the log was resting on the ground, preventing the calliper from reaching under the log, the diameter at the angle closest to perpendicular to the ground was measured. If a knot, swelling or goitre prevented the true measurement of the bole, the diameters were measured at the closest point in either direction that was free of the defect. If bark was missing at the point of measurement, the measured diameter was adjusted to an estimated over-bark diameter. The distance from the large end to the point of each diameter measurement was recorded to the nearest 0.1 m.

Total log length was measured to the nearest 0.1 m. The measured length represented the distance between the geometric centers of each end (Figure 2-2). For logs that were cut on a bias, the length was measured from the points directly above the geometric centers of each end.

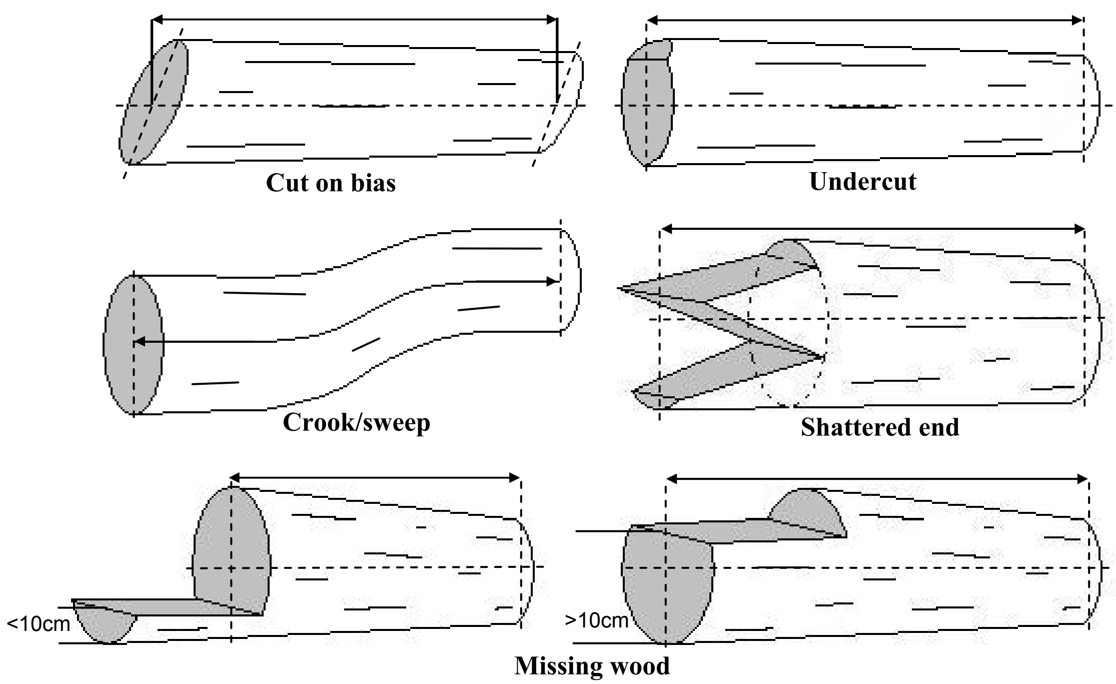

Figure 2-2 Methods for measuring length for logs with biased cuts, undercut, crook, sweep, sniped ends and shattered ends.

Undercuts were not considered in length measurements. For logs with crook or sweep, the measuring tape was aligned with the contour of the log. For logs with shattered ends, the length of the shatter was included in the log measurement. Volume deductions due to missing wood in the shattered end were later accounted for. When trees are felled, a portion of the stem may remain attached to the stump, leaving the log with a sniped end. For these logs, the section containing missing wood was included in the length measurement if it was more than 10 cm in thickness. No logs with forks or slab ends were present in either sample.

2.2.2 Log defect measurement procedures

Defects that were considered likely to reduce the volume of wood suitable for manufacturing were measured. Defects considered were limited to those outlined in the MoFR Log Scaling Manual (2007) and included rotten, holed, charred, scarred, split, knotted or missing wood and protrusions such as burls and swellings. Defect size was recorded to the nearest centimetre and the distance to the large end of the log was recorded to the nearest 10 cm.

Butt rot was identified by the presence of stained or decayed wood in, but not necessarily limited to the heart wood at the large end of a flared first cut log. When present, two diameter measurements were recorded, the first across the longest axis of the decayed portion, the second perpendicular to the first measurement.

Heart rot was identified by the presence of stained or decayed wood in, but not necessarily limited to the heart wood at either end of the log. If it occurred at the large end of a flared first cut log, it was identified as butt rot. When present, two diameter measurements were recorded, the first across the longest axis of the decayed section, the second perpendicular to the first measurement.

Ring rot was identified by the presence of stained or decayed wood in a series of growth rings with sound wood observed on both sides. Where ring rot formed a full circle, the outside and inside diameters of the affected rings were recorded. When not forming a full circle, the outside diameter, inside diameter and percentage of a projected full circle affected were recorded.

Sap rot was identified by the presence of stained or decayed wood in the sapwood of the log at any point along its length. When observed at the log ends, the minimum diameter of the sound core, the diameter perpendicular to this measurement and the length of log affected were recorded. If the rot did not extend around the log, the percentage of the circumference affected was recorded. The length of sapwood affected was also recorded.

Pocket rot was identified by the presence of stained or decayed wood in a region outside of the central core and not limited to a series of growth rings. If the pocket rot was square or triangular in shape, the maximum height and width was recorded. If it was circular or oval in shape, the maximum diameter was recorded. Where multiple occurrences of pocket rot were observed within 5 cm of one another, the rot was amalgamated and considered one defect.

Where separation between and across annual rings, also known as shake and check, was observed, the outside and inside diameters of the separated rings were recorded. If it did not form a full circle, the percentage of a projected full circle was recorded. When check was observed, its height and maximum width was recorded. If the fibre was also separated on the outside of the log, its length was also recorded.

Voids are a group of defects used to describe missing portions of wood fibre in a log. Voids may develop as a result of wounding of the live tree, limb loss and damage during falling. Trees that become wounded by fire, lightning, mechanical damage or other reasons may develop scars, creating a void in the perimeter of the log. These types of defects are known as catface. When observed, the length of log affected was recorded to the nearest 0.1 m. If the catface extended to a cut end of the log, the height and maximum width was recorded. If the catface did not advance to the end of the log, the width at its widest point was recorded.

Scars that become overgrown and healed create a patch of bark which may be wholly or partially enclosed in the wood. This type of defect is known as a bark seam. Bark seams may also develop at the base of trees with excessive fluting and in the crotch of forks. When observed, the height and maximum width at the end of the log and the length of the bark seam was recorded.

Missing, broken or damaged wood may be caused by wood being ripped away from the centre (stump pull) or edge (slabbing) of the tree as it falls, trees shattering on impact, gouging of the stem by falling limbs or mechanical damage during handling. When missing, broken or damaged wood was observed, the length of the segment and the percentage of the log circumference affected at its widest point were recorded. When stump pull was observed, the height, width and estimated length of the missing piece was recorded.

Goitre, galls and burls are swelling or abnormal growth on a tree which may be associated with internal rot. When observed, the length and width at their widest point were recorded.

Sweep, crook and pistol grip are defects that describe a lateral movement along the length of a log. Sweep is a bow-like bend in the trunk of a tree, crook is a pronounced kink at one point of a tree, usually caused by the loss of a leader, while pistol grip is a pronounced bend at the butt of a tree. Where sweep, crook or pistol grip was observed, the length of the log affected was recorded to the nearest 0.1 m and maximum distance of movement from the central axis of the log was recorded to the nearest centimetre.

Knots affect both the quantity and quality of recoverable wood. Knots are recognized as either sound or rotten and tight or loose. Sound knots have no observable decay or discoloration from rot. Rotten knots have evidence of decay or discoloration from rot. Tight knots are formed by living branches at the time of harvest while loose knots are formed by dead branches. The dimension and type of knots observed along the length of the log were recorded. Knot size was measured perpendicular to the length of the log. Knots of greater than 1 cm in size were recorded and classed into discrete size classes. Knots between 1 and 3 cm were classed as 2 cm knots while all other knots were rounded to the nearest 5 cm category (5 cm, 10 cm, 15 cm etc.). The distance from the knot to the large end of the log was recorded to the nearest 0.1 m. Where knots of the same diameter class and type occurred less than 1 m apart, the knots were measured as a section with the length of the section and the distance from the first knot to the large end recorded.

High resolution photographs (3072 x 2304 pixels) were taken of the large end of each log and used to classify the stage of decay evident: none; incipient; developing; or advanced. Incipient decay described the early stages of rot, characterised by a discolouration of the wood (Figure 2-3). The wood retained its strength and could not be dislodged by a fingernail or other small, sharp object. Developing decay described intermediary stages of rot, where discolouration was more pronounced and the rot was creating small cavities in the wood (Figure 2-4). The wood still retained most of its strength and could not be dislodged by hand. Advanced decay described the final stages of rot. Large cavities had developed and the wood had lost its strength, with pieces able to be dislodged by hand (Figure 2-5).

Figure 2-3 Large end of log showing incipient stage of decay.

Figure 2-4 Large end of log showing developing stage of decay.

Figure 2-5 Large end of log with advanced stage of decay.

2.2.3 Log bucking

After measurement, the logs were bucked into shorter mill-lengths by the managers of each sawmill. At Revelstoke, logs were bucked to minimum lengths of 3.1 m to enable rejected sections to be on-sold as pulp logs. The exception was for logs with damaged ends, which were bucked at the first point free of the damage. The length of each bucked log was measured to the nearest 0.1 m. Log numbers were painted onto the cut faces of each end using pink or red spray paint to enable identification during sawmilling. Bucked logs were visually assessed by the sawyer at each location. Logs that were deemed to have no potential for lumber recovery were rejected from milling and were recorded as yielding zero lumber.

2.3 Lumber measurement procedures

All bucked logs that were deemed to have potential for lumber recovery were milled. Logs from the interior region were sawn at Joe Kozek Sawmill, situated in the township of Revelstoke. Logs from the coastal region were milled at the MKRF Sawmill, situated within the research forest in Maple Ridge. The objective of data collection at both mills was to record the grade, dimension and length of each recovered piece and to attribute each to a specific log.

2.3.1 Layout of Joe Kozek Sawmill

Joe Kozek Sawmill specializes in custom cutting a variety of species including western red cedar, western hemlock and Douglas fir. The sawmill consists of nine machine centers connected by conveyors (Figure 2-6).

Logs are first run through a de-barker before proceeding along two conveyors to a bandsaw carriage headrig. After primary breakdown, sawn pieces travel to a trim saw where they are trimmed if required. The exception is cants of 6 x 6 inches or greater, which travel via a separate conveyor to a cant trim saw. Non-cant pieces then travel to a quad gang saw where they are edged and sawn into multiple pieces if necessary. They then travel to two trim saws where they are trimmed to their final length if necessary and graded. Pieces with excessive wane or defects causing a grade reduction are transferred onto a re-saw conveyor where they are ripped and/or re-edged. Rough-green lumber then exits the mill to the green chain, where it is stacked into various dimension and grade piles. All slabs, edgings and other residual pieces are chipped.

Logs were sawn to produce the mill's normal product line; consisting of 25 x 102 mm (1 x 4 inch), 25 x 152 mm (1 x 6 inch), 25 x 203 mm (1 x 8 inch), 51 x 102 mm (2 x 4 inch), 51 x 152 mm (2 x 6 inch), 51 x 203 mm (2 x 8 inch), 51 x 254 mm (2 x 10 inch), 51 x 305 mm (2 x 12

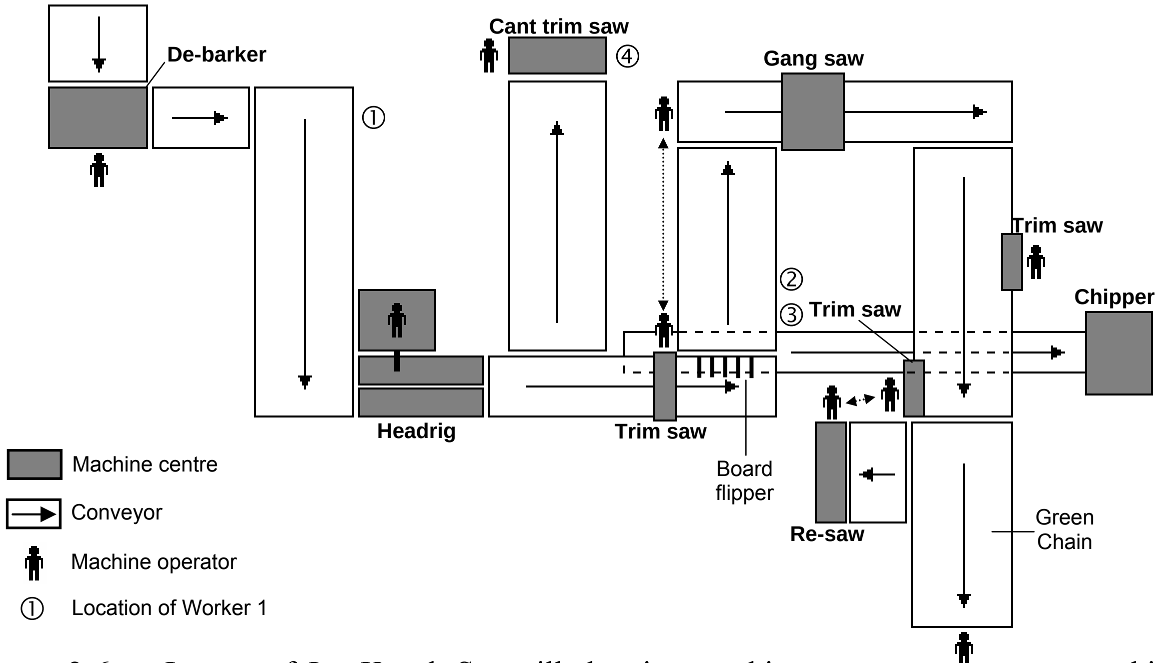

Figure 2-6 Layout of Joe Kozek Sawmill showing machine centers, conveyors, machine operators and location of data collection workers.

inch), 76 x 102 mm (3 x 4 inch), 76 x 152 mm (3 x 6 inch), 76 x 203 mm (3 x 8 inch), 76 x 254 mm (3 x 10 inch), 76 x 305 mm (3 x 12 inch), 152 x 152 mm (6 x 6 inch), 152 x 203 mm (6 x 8 inch), 152 x 254 mm (6 x 10 inch), 152 x 305 mm (6 x 12 inch), 178 x 254 mm (7 x 10 inch), 254 x 254 mm (10 x 10 inch) and 305 x 305 mm (12 x 12 inch) of even lengths in feet of between 1.83 m (6 feet) and 6.1 m (20 feet). Two lumber grades were recognized in this trial: Clear, and Standard & Better. The Clear grade used most closely matched the “C Industrial” grade for industrial clears as outlined in the Standard Grading Rules for Canadian Lumber (Table 2-3) (National Lumber Grades Authority (NLGA) 2007). Pieces that did not achieve the criteria for this grade were considered Standard & Better. The sawmilling objective was to maximize the total value of lumber recovered.

2.3.2 Lumber measurement procedures at Joe Kozek Sawmill

Four workers were responsible for recording the lumber recovered at Joe Kozek Sawmill and were stationed at key locations within the mill. Worker 1 was responsible for recording the

Table 2-3 Lumber grading provisions for "C" Industrial grade of 57 mm ($2^1/_4$") and thicker, 76 mm (3") and wider. Specifications are based on a piece 203 mm (8") wide and 3.6 m (12') long.
Source: NLGA 2007.

Characteristic	Limiting Provision
Checks	4, small - no limit if surface is rough
Heart Stain	firm
Sap Stain	medium; 25% of face or equivalent greater area of lighter stain
Skips	occasional, very light on face; light on edges and reverse side
Slope of Grain	1 in 6
Splits	short, in 5% of the pieces
Torn or Raised Grain	light
Warp	light in occasional pieces
Knots	4 sound tight 1" or 5 equivalent smaller in $2^1/_4$" thicknesses to 4, 2" or 5 equivalent smaller in 12" thicknesses or Pitch Streak - 1 medium, or Pockets - 4, 6"

log sequence into the headrig and transferring this information to Worker 2 prior to the log being cut. Worker 1 was stationed between the debarker and headrig.

Workers 2 and 3 were stationed on an elevated walkway between the first trim saw and the gang saw. Worker 2 identified the log number being cut at all times. As each log entered the headrig, its number was recorded and checked against the prior log sequence provided by Worker 1. When the first cut piece from a new log reached the end of the headrig to gang saw conveyor, the new log number was supplied to Worker 3. Each subsequent piece of solid wood entering the gang saw was attributed to this log until the next log number was given.

Worker 3 was responsible for recording the dimension, length and grade of each piece of solid wood recovered. As each piece exited the gang saw, its nominal dimensions were recorded. The final length and grade of each piece was estimated. Estimates of length and grade were necessary as a bottleneck prior to the final trim saws caused pieces to lose sequence. Determining the exact output for each log would therefore require enough spacing between logs to allow all pieces from one log to clear the bottleneck prior to the first piece of the following log arriving. This would slow production at the mill and was not allowed by sawmill management.

When each piece was flipped prior to the gang saw, defects requiring trimming or a grade reduction on both sides were observed by Worker 3. His estimates of the final length and grade were based on these observations. As he was also a grader and an experienced trim saw operator, the length and grade estimates could be considered the best approximations of actual lengths and grades had he been responsible for trimming.

Worker 4 was responsible for determining the final length of each cant, as the cant trim saw was not visible from the elevated walkway used by Worker 3. After trimming Worker 4 recorded their length and conveyed this information to Worker 3.

2.3.3 Layout of MKRF Sawmill

The MKRF sawmill specializes in custom cutting specialty timbers. For this study, the sawing objective was to maximize the recovery of Clear 25 x 152 mm (1 x 6 inch) boards to be used for wainscoting. Four machine centres were used in this study: a Wood-Mizer™, a Peterson flip saw, a re-saw and a trim saw (Figure 2-7). Most of the machine centres were connected by conveyors, although only the trim saw to green chain conveyor was motorized.

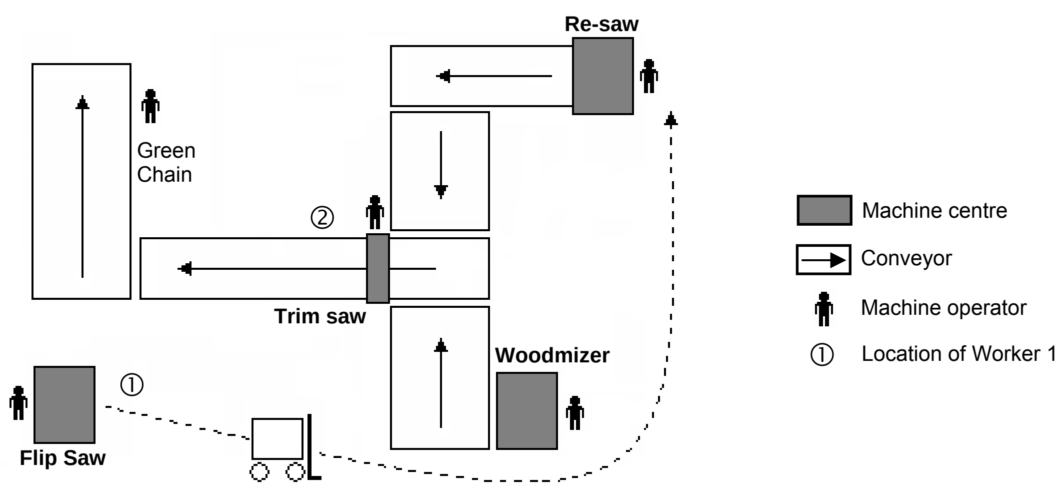

Figure 2-7 Layout of MKRF Sawmill showing machine centers, conveyors, machine operators and location of data collection workers.

Primary log breakdown and edging occurred at both the Peterson flip saw and the Wood-Mizer™ (Figure 2-8). During primary log breakdown, mostly 102 x 152 mm (4 x 6 inch) and 51

Figure 2-8 Primary log breakdown and edging for the majority of logs at the MKRF Sawmill was achieved using a Peterson flip saw.

x 152 mm (2 x 6 inch) pieces were recovered. These were then stacked and transported to the re-saw using a forklift. Pieces were ripped into predominantly 25 x 152 mm (1 x 6 inch) boards at the re-saw and then travelled via a conveyor to a trim saw, where they were trimmed to their final length and graded. All pieces then proceeded to the green chain to be stacked.

Two lumber grades were recognized for the trial: Clear and Standard & Better. The Clear grade most closely resembled the "D Select" grade for boards as outlined in the Standard Grading Rules for Canadian Lumber (Table 2-4) (NLGA 2007). As the majority of pieces were to be trimmed to 1.22 m (4 feet) lengths after drying, the tolerances for the Clear grade were relaxed if oversized defects could be trimmed without reducing the number of 1.22 m (4 feet) Clear pieces. Pieces that did not achieve the criteria for this Clear grade were considered Standard & Better.

2.3.4 Lumber measurement procedures at MKRF Sawmill

Two workers were responsible for recording lumber recovery at the MKRF mill. After bucking, the length of each log was measured to the nearest 0.1 m. Both ends of the log were painted with one of six colours of paint with successive logs given different colours. This

Table 2-4 Lumber grading provisions for D Select grade for Boards, Selects and Commons. Specifications are based on a piece that is surfaced on four sides and 25 x 203 mm (1” x 8”) wide and 3.6 m (12’) long.
Source: NLGA 2007.

Characteristic	Limiting Provision
Checks	seasoning - small, scattered; medium on back
Cup	very light
Skip	1 very light on face; hit and miss on back; one edge may be 1/16" scant for 1/2 the length in an occasional piece
Split	short on one end or equivalent
Stained Wood	medium, over entire face if otherwise high quality
Torn or Raised Grain	light in scattered spots
Twist	7/4 and thinner, very light. 8/4 and thicker, 1/2 of very light
Wane	on reverse side, 3/4 of thickness, 1/4 of width and 1/4 of length
With the above, only one of the following characteristics:	
Knots	4 small, fixed
Pitch	medium, over not more that 2/3 of face, less if heavy
Pitch Streak	1 medium
Pockets	4 small

enabled of all of the pieces from each log to be clearly identified throughout the sawing process. After initial log breakdown, pieces with the potential for lumber recovery were stacked and the log number was written onto the cut face at both ends using a lumber crayon to enable identification through the mill.

After initial breakdown, the lumber stacks were transported to either the re-saw or Wood-Mizer™ and ripped into predominantly 25 x 152 mm (1 x 6 inch) inch boards. At each saw, all of the pieces from a single bucked log were sawn successively. The coloured ends made this possible (Figure 2-9). Pieces then travelled to the trim saw, where they were trimmed to their final length and graded. As each piece exited the trim saw, its nominal dimension, length and grade were recorded alongside the appropriate log number.

3. Data analysis procedures

The log and lumber data were used to conduct an economic analysis of sawing pulp quality logs into solid wood products. The analysis was conducted from the sawyer’s perspective, considering log and operating costs and lumber and chip revenues to determine profitability.

Figure 2-9 Pieces ready for trimming at the MKRF Sawmill.

Measurements of diameter, bark thickness and length were used to determine the gross under-bark volume of each log. As mid-section diameter measurements were made over bark, a model was developed to predict bark thickness using the under bark diameter and bark thickness measurements from the log ends. The model was developed using SAS Version 9.1.3. Preliminary analyses of the data indicated that a linear function was suitable to model the relationship between bark thickness and over-bark diameter. Partial F-tests found that parameters accounting for region and intercept were not significant using an α-level of 0.05. The final model contained a single parameter to predict bark thickness from measurements of over-bark diameter. Tests found that the assumptions of linearity, normality and equal variance were met. The model explained 62.9% of the variability in the data set and the sole parameter was significant at the α-level of 0.05 (Equation 2-1, Figure 2-10).

$$BT = 0.0250\,Dob \qquad \text{(Equation 2-1)}$$

Where:

BT = single bark thickness (cm)

Dob = diameter over bark (cm)

The bark thickness model was used to estimate under-bark diameters from the mid-section diameter measurements of each log. These were used to calculate the gross under-bark volume of

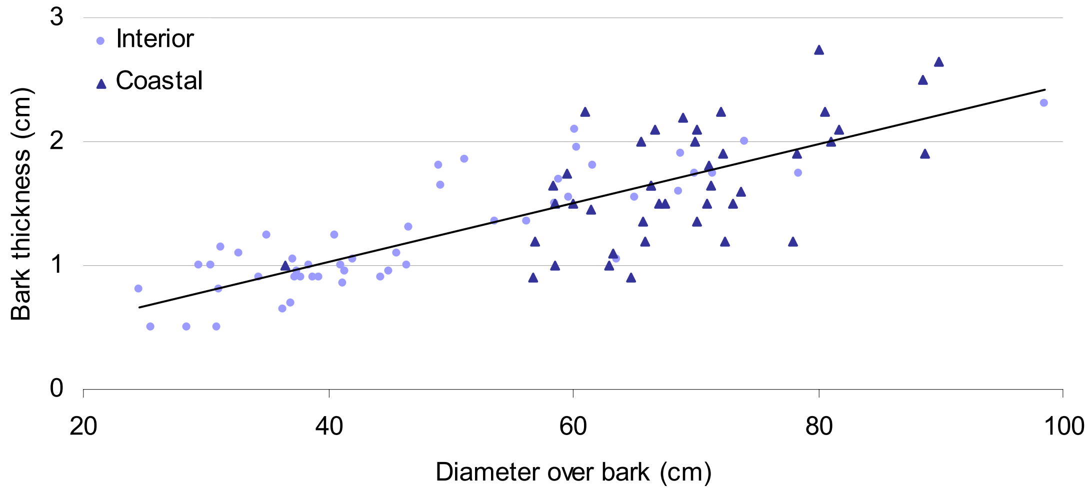

Figure 2-10 Relationship between diameter over bark and bark thickness.

each 3 m section between diameter measurements using Smalian's formula (Equation 2-2). Total log volume was considered the sum of volumes of all sections in a log.

$$g_i = \frac{\frac{\pi b_i^2}{10000} + \frac{\pi s_i^2}{10000}}{2} len_i \qquad \text{(Equation 2-2)}$$

Where:

g_i = gross volume (m^3) of section i;

b_i = radius under bark (cm) at the large end of section i;

s_i = radius under bark (cm) at the small end of section i;

len_i = length (m) of section i.

The volume of sound wood fibre, also known as firmwood volume, was estimated for each log. Deductions to the gross volume to account for rot, hole, char and missing wood were carried out in accordance with the procedures outlined in the B.C. Log Scaling Manual (MoFR 2007). For the interior sample, no defect measurements were made for 15 logs that were deemed to have no potential for lumber recovery. For these logs, an estimate of the firmwood volume was made by subtracting the average deduction (%) for all other interior logs from which no lumber was recovered from the gross volume.

Rough-green lumber volumes were calculated using the nominal dimension and length for each piece recovered. Losses due to drying and planing were not considered in this study. Volume recovery was calculated as both a percentage and lumber recovery factor (LRF) and was considered the volume of rough-green lumber divided by the firmwood volume of each log.

The volume of wood available for chips was estimated as the volume of firmwood that was not recovered as lumber minus a 7.3% sawdust allowance (Fahey 1983). As chips are traded in bone dry units (1 BDU = 1.2 tons (2400 lbs) oven dry), a weight to volume conversion for green western hemlock was required. The average of two published figures was used, with a cubic metre of green western hemlock minus bark estimated to weigh 0.89 tons (1782.5 lbs) (Smith 1986, Widmann 1990). This was converted to an oven dry weight by assuming a moisture content of 54% for green western hemlock (Celgar Pulp Company pers. comm. 2007).

To calculate the lumber revenue obtained from each log, confidential lumber prices were provided by Joe Kozek. Celgar Pulp Company provided prices for both Standard and Premium grade chips which were used to estimate the potential chip revenue from each log. As the percentage of Premium grade chips was not known, two scenarios were considered where the entire chip sample was assumed to be either Standard or Premium grade.

Delivered log prices were determined from the MoFR Revenue Branch Log Market Reports (MoFR 2008b). At Revelstoke, the average price for hembal logs of Lumber Reject Grade from the interior region for the three months ending May 31st, 2007 was used. At Maple Ridge, the average price for the corresponding grade for hembal logs from the coastal region for the three months ending Dec 31st, 2007 was used. These dates were chosen as they corresponded most closely to the dates which the logs were milled.

Operating costs for sawmills in the B.C. coastal and interior regions were determined using a report that benchmarked sawnwood costs in 2004 (International Wood Markets Research Inc. *et al.* 2005). These were converted to Canadian currency using the 2004 USD-CAD average exchange rate (Canada Revenue Agency, 2005) and adjusted for consumer price index to generate average operating costs at May 31st, 2007 for an interior sawmill ($81.60/m^3) and at Dec 31st, 2007 at a coastal sawmill ($109.3/m^3). Given that sawmills which maximize grade recovery generally have higher labour and capital costs than dimension mills, the operating costs used likely underestimated the true cost of sawmilling.

These cost and revenue estimates were used to determine the profitability of recovering solid wood and chips from the log samples. Log and operating costs and lumber and chip revenues were then individually adjusted to find the point at which the mill would have broken even.

Models were developed to predict the volume of lumber recovered and the proportion of Clear grade lumber using the measured log attributes. All measured log attributes were considered as candidate variables. Additional candidate variables were developed that combined other attributes, such as the sound collar width. This attribute described the minimum radius of wood at either end that was unaffected by butt rot, heart rot, ring rot or shake. For logs with none of these defects, the sound collar width equalled the log radius. Models were developed using SAS Version 9.1.3, using the PROC GLM and PROC LOGISTIC procedures.

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CHAPTER 3. ECONOMIC EVALUATION OF LUMBER RECOVERY FROM WESTERN HEMLOCK LOGS INTENDED FOR PULP PRODUCTION[2]

1. Introduction

Western hemlock is a major commercial species in British Columbia. It is the most prevalent species on the western side of the Coastal Mountain Range (BC Forestry Innovation Investment 2008) and is also found in the interior wet belt, west of the Rocky Mountains. Its light, even textured wood and ease of machining make it suitable for dimension and shop lumber, moulding and panelling. The wood has relatively low levels of extractives (Keays and Hatton 1971) and good fibre qualities, making it a preferred species for market kraft pulp and newsprint production (King *et al.*1998).

Western hemlock is one of the most abundant species in British Columbia, yet compared with other commercial species it contributes less value relative to the volume harvested. This is partially due to its susceptibility to a range of defects. Low levels of fungitoxic extractive compounds make western hemlock one of the least resistant species to stem decay in the world (Clark 1957, Scheffer and Morrell 1998). It is also prone to forming wetwood, where the heartwood becomes internally infused with water. In logs with wetwood, extreme moisture differentials lead to fibre separation (shake and check). Wetwood also leads to increased lumber downgrades and drying costs. Lumber with variable moisture content is prone to warping, shrinkage and collapse, particularly after kiln drying (Hartley *et al.* 1961, Ward 1972, Josza *et al.* 1998). Kiln drying wetwood takes two to six times longer than sapwood to reach acceptable moisture levels, increasing production costs (Sachs *et al.* 1974).

Its susceptibility to decay and wetwood make the profitable recovery of solid wood from western hemlock more difficult than for other commercial species. Log grading rules tend to be more stringent than for other species which results in greater volumes of low value log grades. In

[2] A version of this chapter will be submitted for publication. Mortyn, J. and T. Maness. *Economic evaluation of lumber recovery from western hemlock logs intended for pulp production*. 32 pp.

conjunction with its good pulping attributes, a large percentage of western hemlock logs are used for pulp production in the province.

As western hemlock is estimated to account for 60% of the mature forests in the coastal region (Coast Forest Products Association 2003), increasing its value recovery would have enormous benefits to the forest industry. Improving the margins for logs being used to produce pulp would help to achieve this goal. This could be accomplished by identifying which logs could achieve higher margins with different manufacturing outcomes. A study of western hemlock pulp logs at Alaskan sawmills found that 60% (stud mill) and 53.2% (dimension mill) of log volume was recovered as rough-green lumber (Fahey 1983). While the pulp classification was based on size rather than log quality, this shows that high volumes of lumber can be recovered from western hemlock logs that would have otherwise been used for pulp. This study aims to determine the economic feasibility of recovering solid wood products from old-growth western hemlock logs that are presently used to produce pulp in British Columbia.

2. Data collection and analysis procedures

A total of 116 old-growth western hemlock logs that were intended for pulp production were sampled for this study: 45 from the Malcolm Knapp Research Forest (MKRF) in the Coastal Mountain Ranges; and 71 from the Columbia Mountains north of Revelstoke. The logs were numbered and measured to enable accurate estimates of gross volume according to the procedures outlined in the Ministry of Forests and Range (MoFR) Scaling Manual (MoFR 2007). Log defect measurements were made for a subsample of 102 logs that were deemed to have the potential for economic lumber recovery to enable accurate estimates of firmwood volume (MoFR 2007). This subsample of logs were bucked to mill lengths and transported to local sawmills in each region where they were sawn with the aim of maximizing value recovery. The interior log sample was sawn at Joe Kozek Sawmills in the township of Revelstoke and the coastal sample was sawn at the MKRF sawmill. The nominal dimension and grade of all rough-green lumber recovered from each log was recorded. The remaining log volume minus a 7.3% sawdust allowance was used to estimate the volume available for chips (Fahey 1983).

Economic analyses were conducted to determine the profitability of milling both log samples. The analyses were conducted from the sawyer's perspective, considering log and operating costs and lumber and chip revenues. Confidential lumber prices were provided by Joe Kozek, General Manager of Joe Kozek Sawmills and used to calculate the recovered lumber revenue for both log samples. Two lumber grades were recognized: Standard & Better and Clear. For an equivalent dimension, Clear grade lumber generated approximately four times the value of Standard & Better lumber (Figure 3-1).

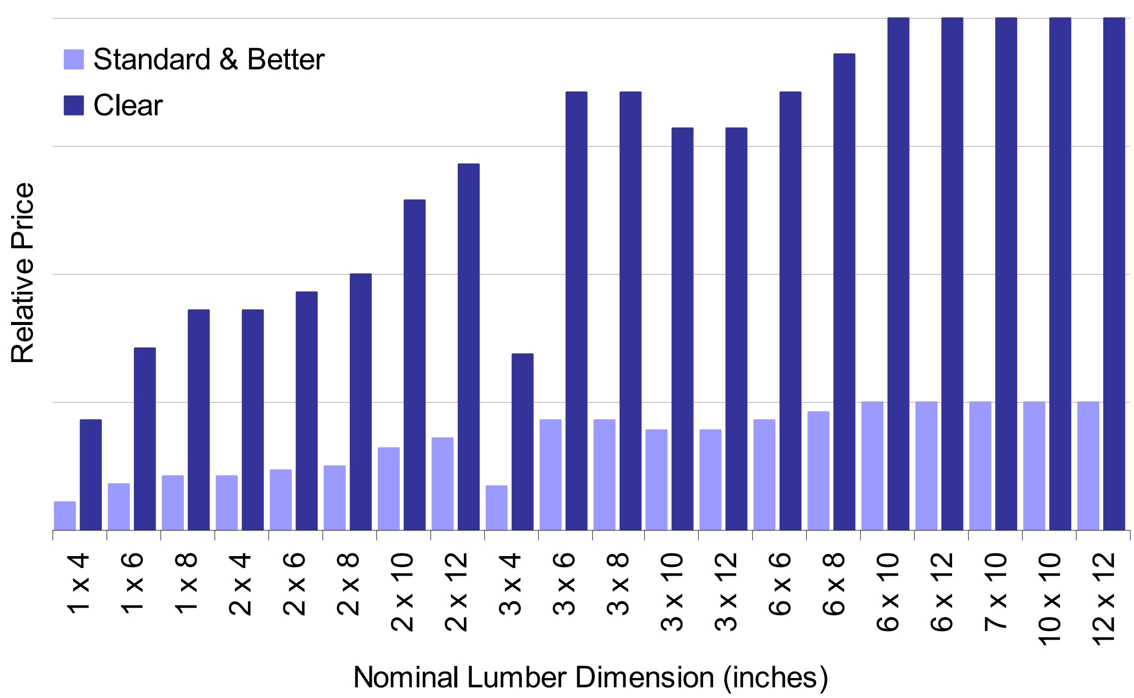

Figure 3-1 Relative lumber prices by grade and dimension used to estimate lumber revenues.

Prices for Standard and Premium grade chips were provided by Celgar Pulp Company and used to calculate the potential chip revenue from each log. Raw log prices were determined from the MoFR Revenue Branch Log Market Reports (MoFR 2008). The grades for the interior sample were not known and logs were assumed to be Lumber Reject Grade (Code 4) with a log price of \$29.50/m^3. This corresponds to the average price for this log grade for the 3 months ending May 31st, 2007. For the coastal sample, the price for each log grade was used and based on the average sales price for hembal logs from the coastal region for the 3 months ending Dec 31st, 2007 (Table 3-1). These dates corresponded most closely to the dates which the logs were milled.

Table 3-1 Average sales price for hembal logs from the coastal region for the 3-month period ending December 31st, 2007.
Source: MoFR Revenue Brach Log Market Reports 2007.

Log Grade	H	I	J	U	X	Y
Purchase Price (\$/m^3)	76.74	60.09	50.66	47.72	45.97	45.31

Average operating costs for sawmills in the B.C. coastal and interior regions were based on benchmarked sawnwood costs from 2004 (International Wood Markets Research Inc. *et al.* 2005). These were adjusted to account for consumer price index between 2004 and the time of milling.

These costs and revenues were used to calculate the margins of cutting the logs depending on the mix of products produced: lumber only; lumber and Standard grade chips; lumber and Premium grade chips. The costs and prices were then adjusted to determine the critical breakpoints at which sawing the log samples became profitable.

3. Log recovery analysis

The gross volume of logs sampled was similar between sites (116.87 m^3 interior, 106.53 m^3 coastal) (Table 3-2), although coastal logs were larger in diameter (66.56 cm versus 45.54 cm) and gross volume (2.37 m^3 versus 1.65 m^3). The logs from the interior were, on average, 4.2 m longer than those sampled from the coast. The shorter lengths were likely related to the increased weight of these logs and greater log handling required at the MKRF mill. T-tests assuming unequal variance were conducted to determine whether significant differences existed between the populations. Measurements of large and small end diameter, length and gross volume were found to be significantly different between study sites at an α-level of 0.05.

Table 3-2 Summary statistics for logs measured to estimate gross volume.
* indicates significant difference between populations using α-level of 0.05

	Interior			Coastal			Overall		
	n	Mean	St. Dev.	*n*	Mean	St. Dev.	*n*	Mean	St. Dev.
Logs	71			45			116		
LEDUB† (cm)		45.54	14.54		66.56*	8.82		53.71	16.27
SEDUB‡ (cm)		27.73	13.25		51.27*	9.16		36.92	16.54
Length (m)		13.21	2.07		9.01*	2.80		11.75	3.01
Gross Volume (m^3)		1.65	1.23		2.37*	0.74		1.93	1.12

† large end diameter under bark
‡ small end diameter under bark

Fourteen logs from the interior sample were deemed to have no potential for lumber recovery by Joe Kozek, General Manager of Joe Kozek Sawmills and were not measured for defects. For the remaining 102 logs, butt/heart rot was present in 59.8% of logs, making it the most common defect other than knots (Table 3-3). It was more prevalent in the coastal sample (64.4% of logs) than the interior sample (56.1%). Shake and check were the next most common defects (36.6% of logs) and were also found to be more prevalent in the coastal sample than the interior sample.

For both samples, the average firmwood volume was 0.25 m^3 less than the average gross volume. As the logs from the interior were smaller, this represented a greater percentage of gross volume (15.7%) compared with the logs from the coast (10.4%). The major cause of firmwood deduction at both locations was butt and heart rot (0.22 m^3). Although defects were more prevalent in the logs from the coastal region, their extent was greater in the interior logs due to the smaller log size. The sound collar represents the width of wood around the perimeter of the log that is unaffected by butt rot, heart rot, ring rot or shake. For the interior logs, the average sound collar at the large end was 8.32 cm less than the logs from the coast, while at the small end, it was 10.18 cm less. The average knot size of the interior sample was almost half that of the

Table 3-3 Summary statistics for logs measured to estimate firmwood volume.
* Significant difference between populations using α-level of 0.05.
† Stage of decay recorded at large end only

	Interior			Coastal			Overall		
	n	Mean	St. Dev.	*n*	Mean	St. Dev.	*n*	Mean	St. Dev.
Logs	57			45			102		
LEDUB (cm)		45.17	14.32		66.56*	8.82		54.62	16.19
SEDUB (cm)		27.31	13.33		51.27*	9.16		37.95	16.73
Length (m)		13.14	2.13		9.01*	2.80		11.51	3.06
Taper (cm/m)		1.37	0.40		1.67*	0.60		1.50	0.52
Gross Volume (m^3)		1.59	1.18		2.37*	0.74		1.94	1.08
Firmwood Volume (m^3)		1.34	0.84		2.12*	0.78		1.69	0.90
Cause of firmwood loss									
Butt/Heart Rot (m^3)		0.22	0.63		0.22	0.32		0.22	0.51
Ring Rot (m^3)		0.01	0.02		0.02	0.07		0.01	0.05
Pocket Rot (m^3)		0.01	0.04		0.00	0.01		0.01	0.03
Sap Rot (m^3)		0.01	0.03		0.00	0.00		0.00	0.02
Missing, Broken & Damaged Wood (m^3)		0.01	0.02		0.01	0.03		0.01	0.02
Number of logs with									
Butt/Heart Rot	32			29			61		
- incipient†	6			5			11		
- developing†	6			5			11		
- advanced†	12			14			26		
RingRot	5			4			9		
Pocket Rot	1			3			4		
Sap Rot	5			1			6		
Shake	18			19			37		
Check	19			18			37		
Length with knots (%)		72%	0.44		18%*	0.21		48%	0.45
Knot Size (cm)		8.35	4.12		15.74*	13.45		11.61	10.1
Width of sound collar:									
Large end (cm)		12.83	5.82		21.15*	7.36		16.54	7.73
Small end (cm)		10.06	5.88		20.23*	6.80		14.59	8.07

coastal sample although knot frequency was four times greater. T-tests (α=0.05) found that large and small end diameter, length, taper, gross volume, firmwood volume, the percentage of length containing knots, the knot size and the average collar thickness at both the large and small ends were significantly different between the two study sites.

After measurement, the coastal logs were graded by a certified log grader according to the BC Ministry of Forests log grading rules for Coastal forests (MoFR 2007). The log sample, which was intended for pulp, consisted of all grades from No. 2 sawlog to No. 7 chipper. Twenty-six logs representing 63.9% of the firmwood in the entire sample were classified as a sawlog grade. Just six logs, representing 9.3% of the total firmwood, were classified as the grade intended for pulp logs, No. 7 chipper grade. Due to market conditions at the time of measurement, this cross section of grades were representative of the logs being used for pulp production (P. Lawson pers. comm. 2008). The individual log grades for the interior sample are not known.

After measurement the logs were bucked into 244 mill-length logs (Table 3-4). The bucked logs were assessed by the sawyers in each region and those deemed to have no potential for lumber recovery were left at the sort yard. For the interior sample, 52 mill-length logs representing 44% of the estimated firmwood volume were left at the sort yard. For the coastal sample, seven logs representing 8% of the estimated firmwood volume were not milled.

For the interior sample, 22.2 m^3 (9.4 mbf) of rough-green lumber was recovered. This equates to 40.8% of the firmwood sent to the mill and 22.9% of the original sample (Figure 3-2). The lumber recovery factor (LRF) of the milled component was 172.7 bf/m^3. Less than 3% of the

Table 3-4 Final destination by volume for the sample logs.

	Interior				Coastal			
	Full Length Logs	Mill Length Logs	Gross Volume (m^3)	Firmwood Volume (m^3)	Full Length Logs	Mill Length Logs	Gross Volume (m^3)	Firmwood Volume (m^3)
Original sample	71	144	116.9	97.0	45	100	106.5	95.3
Left at Sort Yard		52	53.5	42.6		7	53.9	7.4
Taken to Mill		92	63.3	54.4		93	52.6	87.9
Rough green lumber				22.2				45.3
- Clear grade				0.6				34.6
- Standard & better grade				21.5				10.7
Milling residue				32.2				42.6

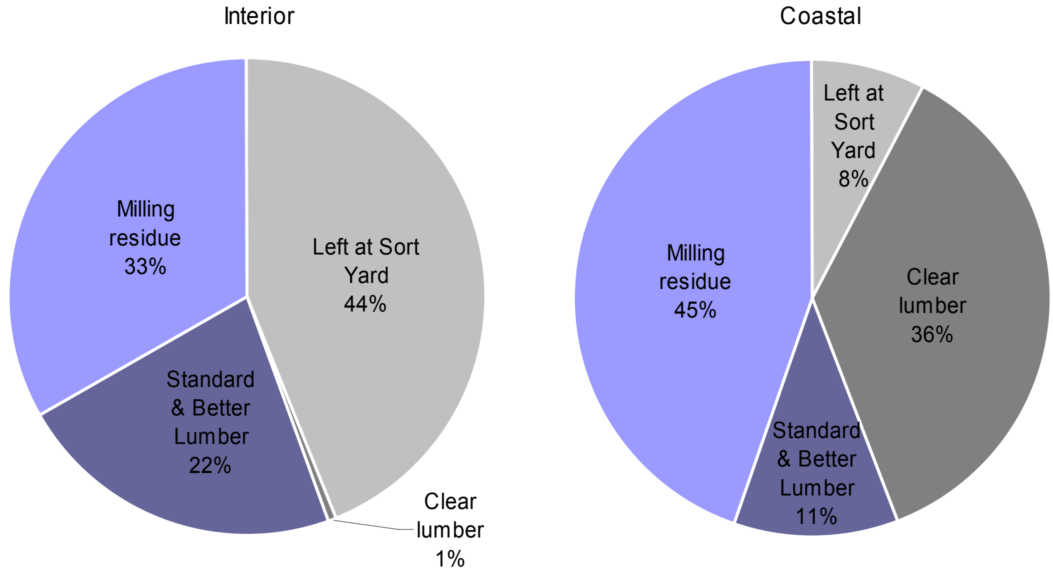

Figure 3-2 Percentage of the original firmwood volume by final destination at both study sites.

lumber recovered was classified as Clear grade. For the coastal sample, 45.3 m^3 (19.2 mbf) of rough-green lumber was recovered, representing 51.6% of the firmwood that was milled (218.6 bf/m^3 LRF) and 47.6% of the original sample. Over 76% of the lumber recovered was classified as Clear grade.

The number of rough-green lumber dimensions cut at the interior mill was considerably higher than at the coastal mill (Figure 3-3). The interior mill produced a lot of larger dimension timbers, which generate higher prices than structural dimensions. The highest volumes produced were 76 x 102 mm (3 x 4 inch), 76 x 305 mm (3 x 12 inch) and 51 x 152 mm (2 x 6 inch) pieces. In contrast, 60.3% of the volume produced at the coastal mill was 25 mm x 152 mm (1 x 6 inch) and most of the remaining volume was 51 x 152 mm (2 x 6 inch) (27.7%). This reflects the wainscoting cutting program used at the coastal mill.

Lumber at the coastal mill was cut to shorter lengths than at the interior mill (Figure 3-4). The number of pieces shorter than 3.05 m (10 feet) represented 46.0% of the total production at the coastal mill and just 9.2% at the interior mill. The number of pieces longer than 3.96 m (13 feet) represented 56.3% of production at the interior mill and just 14.6% at the coastal mill.

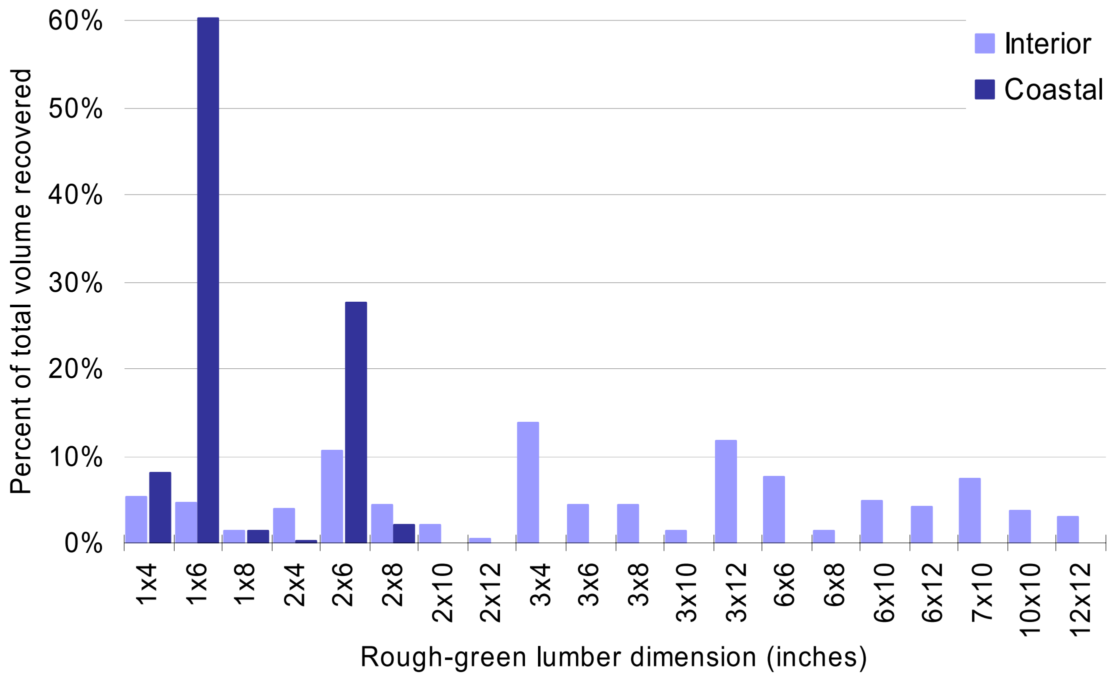

Figure 3-3 Percentage of total lumber volume by nominal rough-green dimension at both study sites.

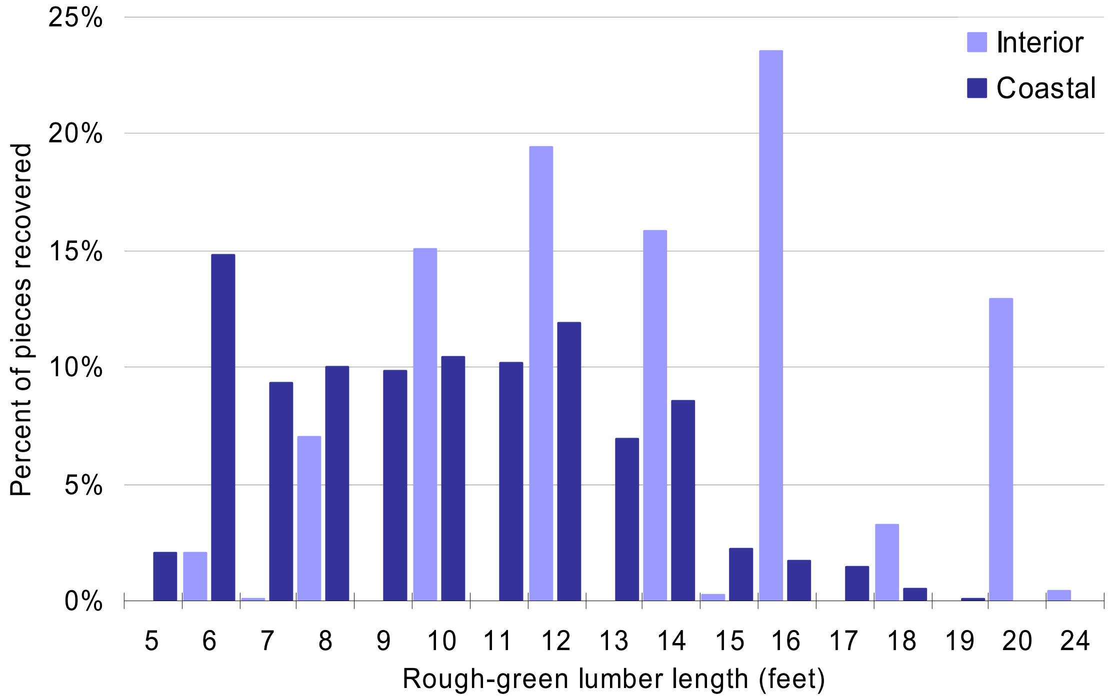

Figure 3-4 Percentage of total number of pieces recovered by length at both study sites.

For the coastal sample, the percentage of firmwood in the log and the percentage of lumber recovered were related to grade (Figure 3-5). Logs classified as a sawlog grade (H, I & J) had

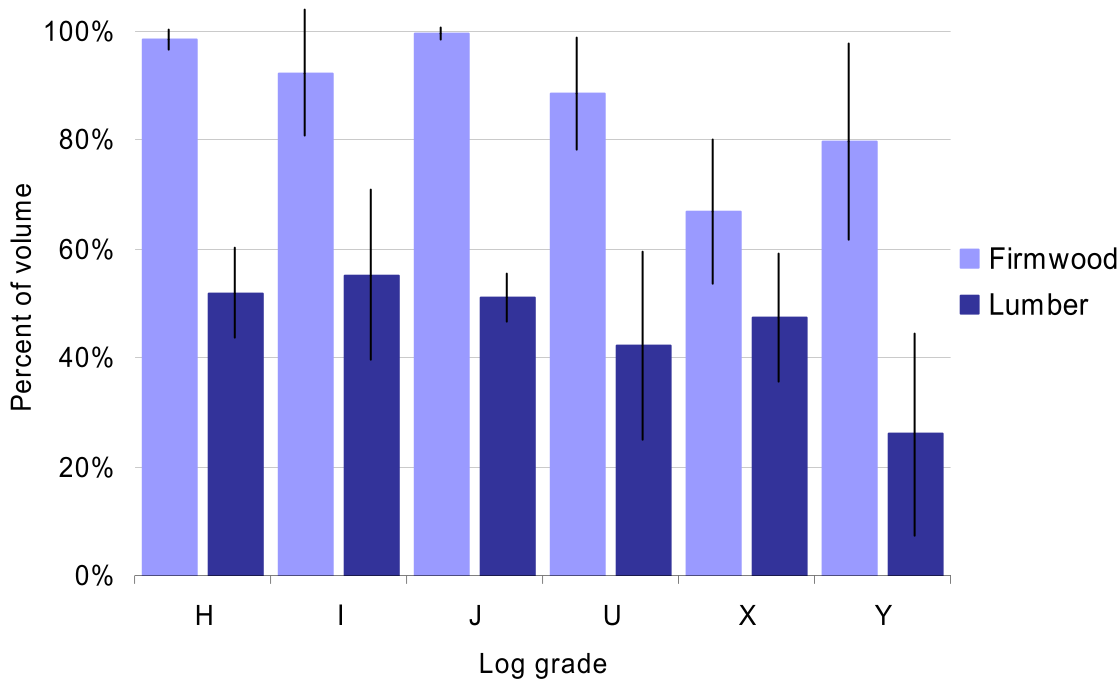

Figure 3-5 Mean and standard deviation of firmwood volume as a percent of gross log volume and mean and standard deviation of rough-green lumber volume as a percent of firmwood volume by grade for the coastal sample.

both the highest percentage of firmwood and the highest rough-green lumber recovery. No. 3 sawlogs (I) recorded the maximum lumber recovery, with 55.2% of the scaled volume recovered as rough-green lumber. No. 7 chipper (Y) logs had the lowest lumber recovery, with 25.9% of the scaled volume recovered. Statistical tests were conducted to determine whether significant differences existed in lumber recovery between log grades. Pairwise t-tests were conducted between all log grades using the two-tailed alternate hypothesis $\mu_1 \neq \mu_2$ and a corrected α-level of 0.05 overall. No significant differences were detected.

Using the combined data from both regions, simple correlation coefficients were used to determine which log attributes were related to both the volume and value of lumber recovered. The attributes that were most closely correlated with the percentage of volume and value recovery included measurements of log size, defect size, defect stage, knot frequency and knot size (Table 3-5). The log diameter at both ends showed moderate and weak positive relationships with the value and volume of lumber recovered respectively. Log length was negatively

Table 3-5 Simple correlation coefficients relating various log attributes with the percentage lumber recovery and the value of lumber recovered. Percentage lumber recovery is calculated as the volume of lumber recovered as a percent of the firmwood volume of the log.

Log Attribute	Log End	Lumber Recovery		Lumber Value	
		Ranking	Correlation	Ranking	Correlation
Diameter under bark (cm)	Small	1	0.3596	2	0.6908
Log Length (m)		2	-0.3441	6	-0.3835
Sound collar width (cm)	Small	3	0.3166	3	0.6427
Diameter under bark (cm)	Large	4	0.3116	1	0.6930
Sound collar width (cm)	Large	5	0.2608	4	0.5036
Shake (% of end)	Large	7	-0.2054	32	-0.0875
Pocket rot (area)	Small	8	-0.1812	34	-0.0821
Butt rot/heart rot (area)	Large	9	0.1785	24	0.1023
Check (% of end)	Large	10	-0.1778	39	-0.0378
Knots (% of length)	Large	14	-0.1615	5	-0.4450
Check (area)	Large	41	-0.0250	7	0.3090
Maximum knot size (cm)		22	0.1155	8	0.2962
Taper (cm/m)		27	0.0997	9	0.2621
Shake (area)	Small	21	0.1173	10	0.2311

correlated with the volume percentage (ranked 2nd) and value (6th) of lumber recovered. The width of the sound collar at both ends was positively correlated to both the volume percentage and the value of lumber recovered. Defects that showed weak negative relationships with lumber recovery included shake and check at the large end and pocket rot at the small end. Lumber value recovery was found to decrease as the length affected by knots increased. Stem taper showed a weak positive relationship with both the value and volume of lumber recovered.

4. Economic analyses

4.1 Scenario 1 – Sawmilling residue treated as waste

This scenario considers a situation where both a coastal and interior sawmill purchases the entire sample of logs from their region. After bucking the logs into mill-lengths, rejected roundwood would then be sold to a pulp mill at the purchase price. As the rejected roundwood is revenue neutral, the outcome is identical to a situation where the mill purchases only the mill-length logs that are sawn.

Under this scenario, the interior sample would have been milled for a loss of $1,373, while the coastal sample would have generated a $1,289 profit (Table 3-6). At the interior mill, the lumber revenue of $4,669 would barely cover the operating costs of $4,438. In contrast, lumber revenue at the coastal mill would be $16,080, offsetting the higher operating expenses and log costs. The additional revenue was driven by Clear grade lumber, which generated 91.3% of lumber revenue at the coastal mill and only 7.5% of lumber revenue at the interior mill. The six logs that were graded as No. 7 Chipper (Y) grade from the coastal sample were milled at a $17 loss under this scenario.

If operating costs and lumber revenues were unchanged, log costs would have needed to be less than $\$4.2/m^3$ for the interior mill to have generated a profit (Table 3-7). The coastal mill

Table 3-6 Costs and revenues associated with sawmilling the interior and coastal log samples using the assumptions of scenario 1.

	Interior		Coastal		
	Mean Unit Cost/Revenue	Total Cost/Revenue	Mean Unit Cost/Revenue	Total Cost/Revenue	
				Y Grade	All logs
Log Costs	$\$29.50/m^3$	$2,861	$\$58.44/m^3$	$400	$5,543
Operating Costs	$\$81.60/m^3$	$4,438	$\$109.30/m^3$	$509	$9,600
Roundwood Revenue	$\$29.50/m^3$	$1,256	$\$58.44/m^3$	$188	$351
Lumber Revenue:	$452.69/mbf	$4,669	$838.72/mbf	$703	$16,080
- clear		$350		$651	$14,687
- standard & better		$4,319		$52	$1,393
Profit/Loss		-$1,373		-$17	$1,289

would have made at a loss if average log costs were more than $72.0/m^3$. If log costs were unchanged, operating costs would have needed to be 31% less or lumber revenues 29% more for the interior mill to have broken even. For the coastal mill, operating costs could have been up to 13% higher and lumber revenues 8% cheaper and the logs still would have generated a profit.

Table 3-7 Unit costs and revenues required to break even if remaining costs and revenues remain unchanged under the assumption of scenario 1.

	Interior		Coastal	
	Mean Unit Cost/Revenue	Change	Mean Unit Cost/Revenue	Change
Log Costs	$4.2/m^3$	-86%	$72.0/m^3$	23%
Operating Costs	$56.4/m^3$	-31%	$123.9/m^3$	13%
Lumber Revenue	$585.8/mbf	29%	$771.0/mbf	-8%

If costs and revenues had remained unchanged, the interior sample would have been milled at a profit had it been limited to logs which yielded greater than 37% lumber (Figure 3-6). As would be expected, the average margin increased with the minimum recovery of the sample at both locations.

Only nine of the 71 logs (12.7%) from the interior returned a profit under this scenario while for the coastal sample, 27 of 45 logs (60%) returned a profit (Figure 3-7). A relationship was found between the margin and the percent of firmwood recovered as rough-green lumber. For the interior sample, all logs with greater than 50% firmwood recovery produced a profit, while only one log with less than 50% recovery returned a profit. For the coastal sample, 18 out of 21 logs that yielded over 50% lumber recovery returned a profit, while only two of the eight logs with less than 40% recovery did so. The original firmwood volume of the log did not appear to be related to the return-to-log at either location.

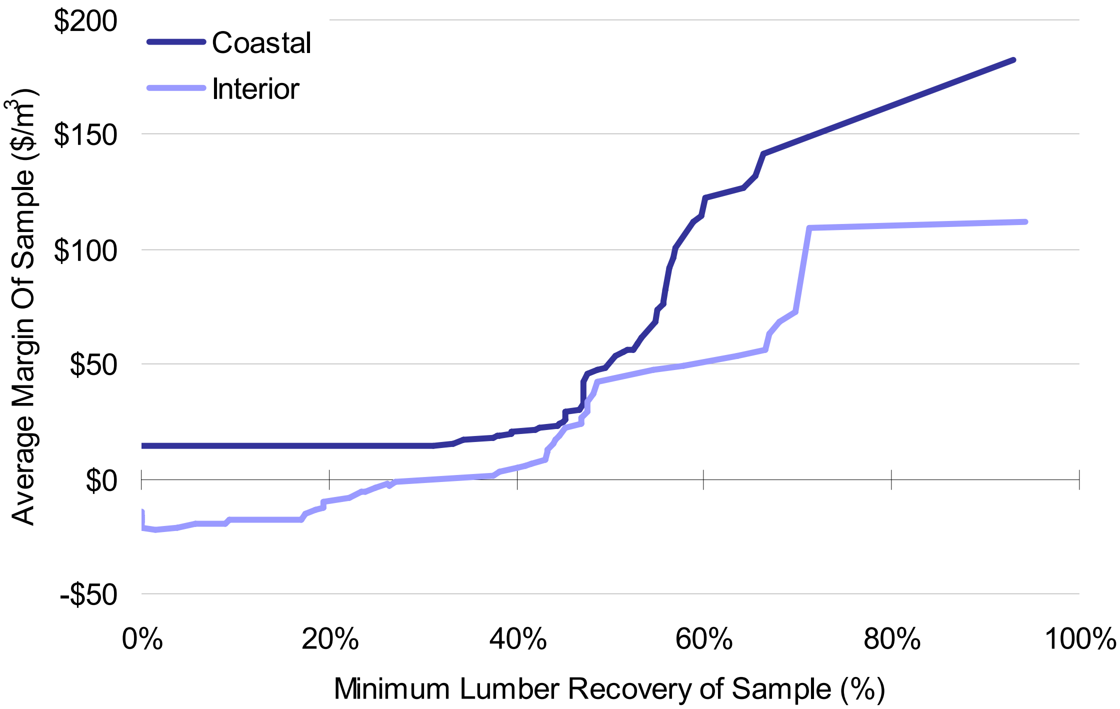

Figure 3-6 Average margin ($\$/m^3$) generated at coastal and interior mills if the logs below a minimum lumber recovery were not included in the sample under scenario 1.

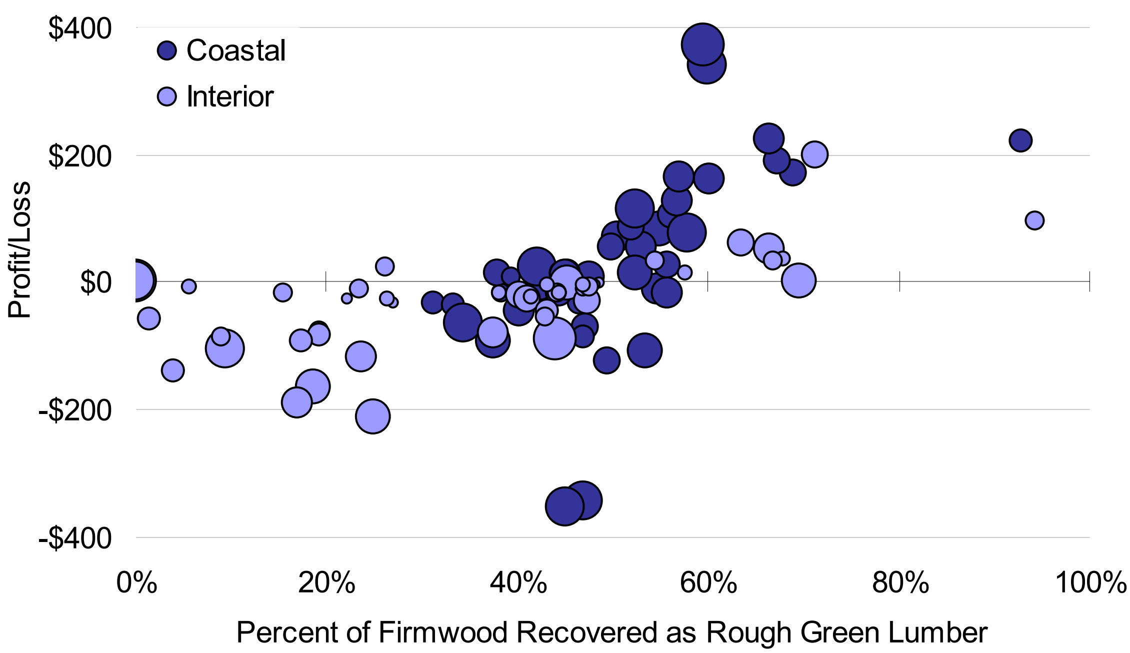

Figure 3-7 Percentage of firmwood volume recovered as rough-green lumber by profit/loss for each log under scenario 1.
Bubble size represents firmwood volume.

4.2 Scenario 2 – Sawmilling residue converted to Standard grade chips

The aim of this scenario was to determine how the economics of sawing the samples would change if additional revenue was generated by converting the sawmilling residue into chips. It was assumed that 7.3% of the sawmilling residue would consist of sawdust (Fahey 1983), while the remaining firmwood component could be converted to Standard grade chips. An additional operating cost of $\$5/m^3$ of firmwood was imposed to account for costs associated with operating a chipper.

Under this scenario, the interior mill would have made an overall loss of $626, while the coastal mill would have generated a $1,866 profit (Table 3-8). Chips generated over $1,000 additional revenue at both mills, while operating costs increased by $272 at the interior mill and $440 at the coastal mill to cover the cost of running the chipper. The six logs that were graded as No. 7 Chipper (Y) grade generated a profit of $23, or $2.62 per cubic metre of firmwood under this scenario.

Table 3-8 Costs and revenues associated with sawmilling the interior and coastal log samples using the assumptions of scenario 2.

	Interior		Coastal		
	Mean Unit Cost/Revenue	Total Cost/Revenue	Mean Unit Cost/Revenue	Total Cost/Revenue: Y Grade	Total Cost/Revenue: All logs
Log Costs	$\$29.50/m^3$	$2,861	$\$58.44/m^3$	$400	$5,543
Operating Costs	$\$86.60/m^3$	$4,710	$\$114.30/m^3$	$532	$10,039
Roundwood Revenue	$\$29.50/m^3$	$1,256	$\$58.44/m^3$	$188	$351
Chip Revenue	$81.60/bdu	$1,019	$81.60/bdu	$64	$1,008
Lumber Revenue:	$452.69/mbf	$4,669	$838.72/mbf	$703	$16,080
- clear		$350		$651	$14,687
- standard & better		$4,319		$52	$1,393
Profit/Loss		-$626		$23	$1,866

In order to break even, log costs would have needed to have been 39% less in the interior, assuming all other costs and revenues remained the same (Table 3-9). In contrast, for the coastal mill, log costs could have been up to 34% higher and the sample still would have generated a profit. The interior mill would have made a profit if either: operating costs were less than $70.1/m^3$; chip revenues were greater than $131.7/bdu; or average lumber revenues were greater than $513.4/mbf. The coastal mill would have made a loss if either: operating costs were greater than $130.4/m^3$; or average lumber revenues were less than $745.0/mbf. As chip revenues were less than total profit for the coastal mill, chips would need to be sold at a loss for the mill to make a loss, assuming all other costs and revenues remained unchanged.

Table 3-9 Unit costs and revenues required to break even if remaining costs and revenues remain unchanged under the assumptions of scenario 2.

	Interior		Coastal	
	Mean Unit Cost/Revenue	Change	Mean Unit Cost/Revenue	Change
Log Costs	$18.0/m^3$	-39%	$78.1/m^3$	34%
Operating Costs	$70.1/m^3$	-19%	$130.4/m^3$	14%
Chip Revenue	$131.7/bdu	61%	-$61.2/bdu	-175%
Lumber Revenue	$513.4/mbf	13%	$745.0/mbf	-11%

If costs and revenues had remained unchanged, the interior sample would have been milled at a profit had it been limited to logs which yielded greater than 19.3% lumber under this scenario (Figure 3-8).

Under this scenario, 13 of the 71 logs (18.3%) from the interior and 29 of the 45 logs (64.4%) from the coast generated a profit (Figure 3-9). Profitability was again related to the percentage of firmwood volume that was recovered as rough-green lumber. For the interior sample, all nine logs with greater than 50% recovery returned a profit while only one of the 55 logs with less than 45% recovery returned a profit. For the coastal sample, 19 of the 21 logs with greater than 50% recovery returned a profit while six of the eight logs with less than 40% recovery returned a loss.

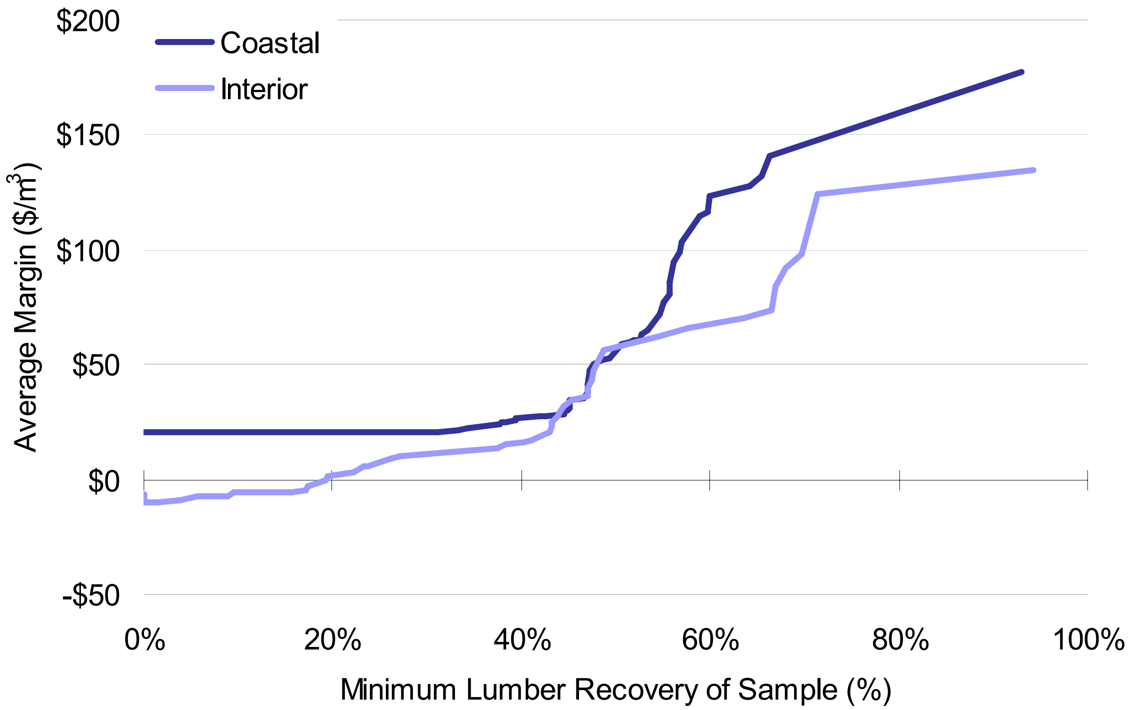

Figure 3-8 Average margin ($\$/m^3$) generated at coastal and interior mills if the logs below a minimum lumber recovery were not included in the sample under scenario 2.

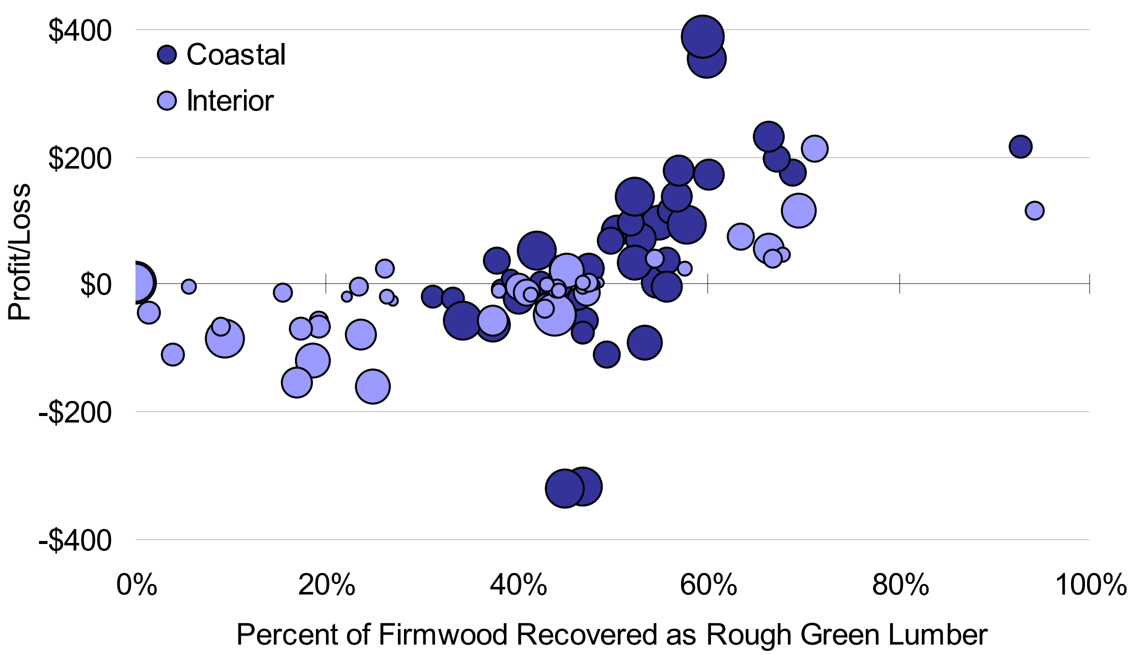

Figure 3-9 Percentage of firmwood volume recovered as rough-green lumber by profit/loss for each log under scenario 2.
Bubble size represents firmwood volume.

4.3 Scenario 3 – Sawmilling residue converted to Premium grade chips

The aim of this scenario was to determine how the economics of milling the two samples would change if sawmilling residue was converted into Premium grade chips. Celgar Pulp Company Ltd. pays an $8/bdu bonus for chips that are less than 9 mm in thickness with less than 5% oversize, less than 3% fines and less than 0.5% bark. The remaining assumptions were the same as scenario 2.

Under this scenario, the interior mill would have made a $526 loss, while the coastal mill would have generated a $1,966 profit (Table 3-10). The $8 higher chip price generated $100 additional revenue both mills. The six logs that were graded as No. 7 Chipper (Y) grade generated a profit of $29, or $3.33 per cubic metre of firmwood under this scenario.

Table 3-10 Costs and revenues associated with sawmilling the interior and coastal log samples using the assumptions of scenario 3.

	Interior		Coastal		
	Mean Unit Cost/Revenue	Total Cost/Revenue	Mean Unit Cost/Revenue	Total Cost/Revenue	
				Y Grade	All logs
Log Costs	$29.50/m^3	$2,861	$58.44/m^3	$400	$5,543
Operating Costs	$86.60/m^3	$4,710	$114.30/m^3	$532	$10,039
Roundwood Revenue	$29.50/m^3	$1,256	$58.44/m^3	$188	$351
Chip Revenue	$89.60/bdu	$1,119	$89.60/bdu	$70	$1,107
Lumber Revenue:	$452.69/mbf	$4,669	$838.72/mbf	$703	$16,080
- clear		$350		$651	$14,687
- standard & better		$4,319		$52	$1,393
Profit/Loss		-$526		$29	$1,966

Under this scenario, the interior sample would have returned a profit if either: log costs were less than $19.8/m^3; operating costs were less than $71.9/m^3; chip prices were greater than $131.7/bdu; or the average lumber revenue was more than $503.8/mbf (Table 3-11). For the coastal sample to have returned a loss, either: average log costs would have needed to have been more than $79.2/m^3; operating costs more than $131.6/m^3; or average lumber prices less than

$735.8/mbf. As total profit exceeded chip revenues, chips would have needed to have generated a loss of greater than $68.2 per bone dry unit for the mill to have made a loss.

Table 3-11 Unit costs and revenues required to break even if remaining costs and revenues remain unchanged under the assumptions of scenario 3.

	Interior		Coastal	
	Mean Unit Cost/Revenue	Change	Mean Unit Cost/Revenue	Change
Log Costs	$19.8/m^3	-33%	$79.2/m^3	36%
Operating Costs	$71.9/m^3	-17%	$131.6/m^3	15%
Chip Revenue	$131.7/bdu	61%	-$68.2/bdu	-184%
Lumber Revenue	$503.8/mbf	11%	$735.8/mbf	-12%

If costs and revenues had remained unchanged, the interior sample would have been milled at a profit had it been limited to logs which yielded greater than 18.5% lumber under this scenario (Figure 3-10).

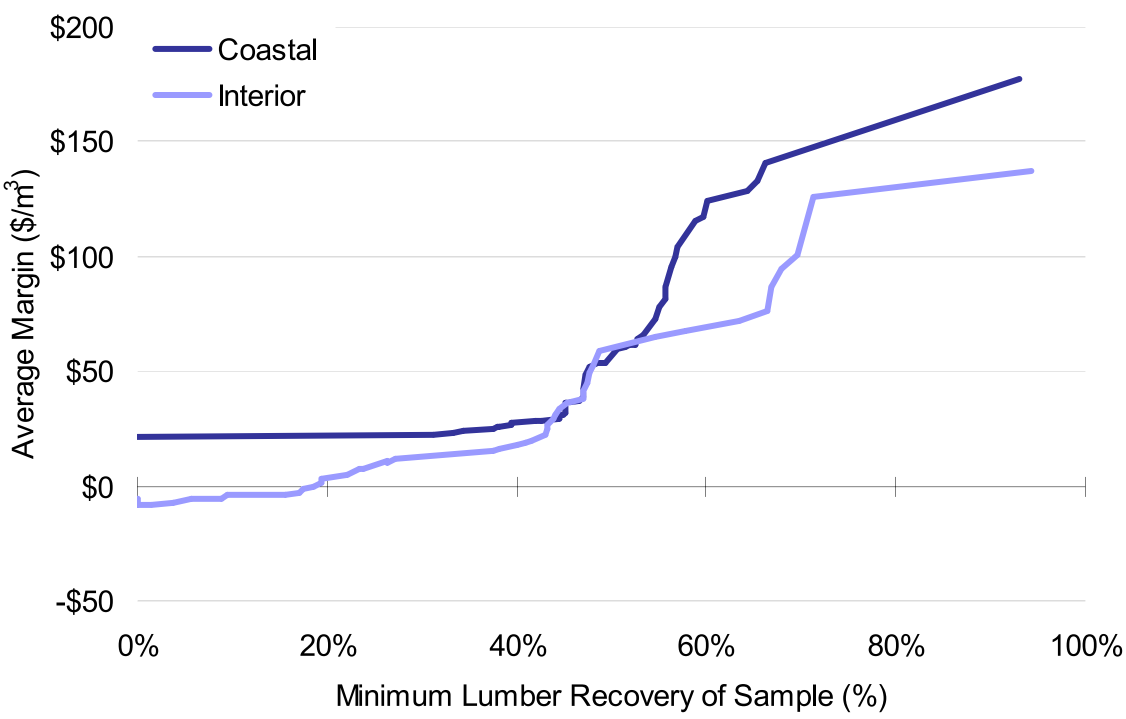

Figure 3-10 Average margin ($/m^3) generated at coastal and interior mills if the logs below a minimum lumber recovery were not included in the sample under scenario 3.

At the interior sawmill, 15 of the 71 logs (21.1%) would have generated a profit under this scenario while at the coastal sawmill, 30 of the 45 logs (66.7%) would have been milled at a profit (Figure 3-11) The percentage of lumber recovery was again an important factor in profitability. For the interior sample, all nine logs with greater than 50% recovery returned a profit while only two of the 55 logs with less than 45% firmwood recovery returned a profit. For the coastal sample, 19 of the 21 logs with greater than 50% lumber recovery returned a profit.

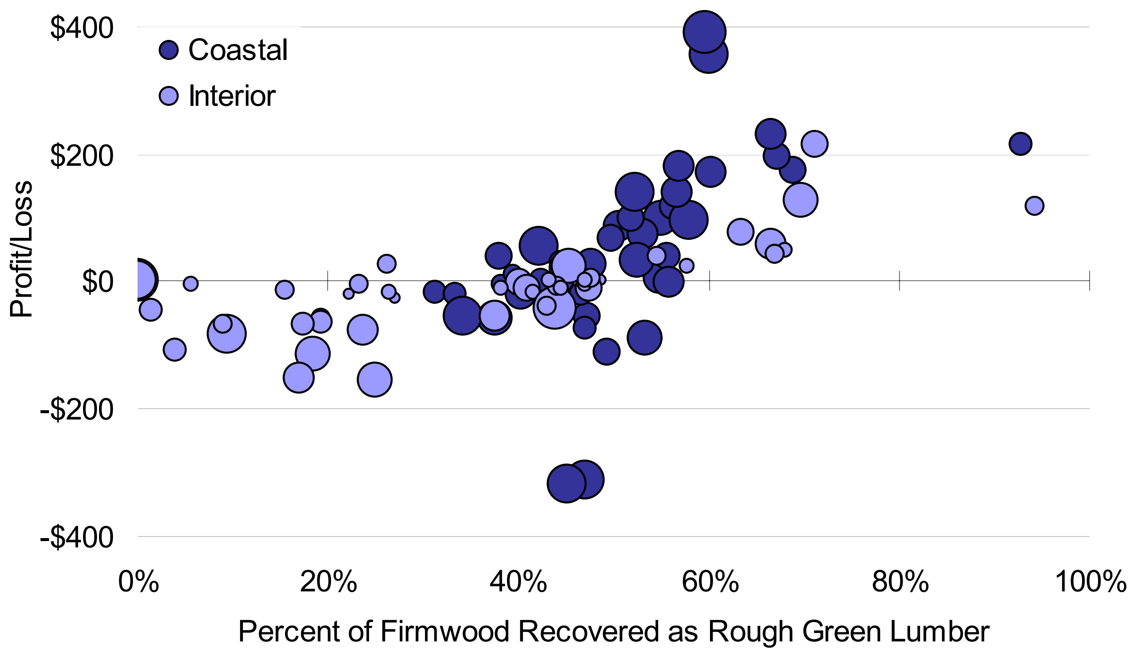

Figure 3-11 Percentage of firmwood volume recovered as rough-green lumber by profit/loss for each log under scenario 3.
Bubble size represents firmwood volume.

5. Discussion

The economic results were remarkably different between the two locations considered in this study. At current market prices, milling the coastal sample of logs would have generated a profit regardless of whether or not chips were produced from the sawmilling residue (Tables 3-6, 3-8 and 3-10). In contrast, milling the interior logs would have resulted in a loss regardless of whether chips were produced.

The increased profitability of the coastal sample was primarily a result of two factors: greater total lumber recovery; and a significantly greater recovery of the higher value Clear grade lumber (Table 3-4). For the coastal logs, 47.6% of the original firmwood volume was recovered as rough-green lumber compared with just 22.9% from the interior sample (Figure 3-2). Over 36% of the original volume of the coastal logs was recovered as Clear grade lumber compared with less than 1% for the interior logs. These two factors resulted in the coastal mill generating over three times more revenue from lumber than the interior mill, offsetting the additional log and operating costs. There are a number of reasons that likely resulted in the increased recovery of total lumber and Clear grade lumber from the coastal sample.

A greater proportion of the interior log sample was rejected from milling, as it was deemed to have no potential for lumber recovery. This was a major reason for the increased lumber and Clear grade recoveries at the coastal mill, as these volumes were considered in the recovery calculations. In the interior, 52 mill-length logs representing 44% of the firmwood volume were left at the sort yard (Figure 3-2). On the coast, just seven mill-length logs representing 8% of the original sample were not milled. As the sawyers determined which logs were rejected at each location, it is difficult to determine whether this discrepancy was caused by significantly different log samples or different judgments by the sawyers. Both factors likely played a role.

In addition, the logs sampled from the interior were clearly of poorer quality than the coastal sample and one would expect a greater proportion of logs to be rejected from milling. While the estimated volume affected by decay was similar between samples, the interior logs were significantly smaller, meaning a greater proportion of volume would have been decayed (Tables 3-2, 3-3). This is demonstrated by the average thickness of the collar of sound wood at both ends. For logs that were milled, the average thickness of the sound collar was significantly less for the interior sample. At the large end of the log, the average collar thickness of the interior logs was just 60% of that of the coastal logs, while at the small end it was less than half that of the coastal logs (Table 3-3). Unfortunately, the characteristics of the rejected logs from the interior were not measured. Based on the logs that were milled, we can conclude that the interior logs had a lower proportion of sound wood at both ends and we would therefore expect the number of rejected logs to be greater.

Varying motivations of the sawyers' also likely played a role in the greater volume of rejected wood from the interior sample. One of the mandates of the coastal mill is to support research, while the interior mill operates solely as a private enterprise. The operator of the coastal mill would therefore have had more incentive to include logs that might have seemed unlikely to return a profit. It is impossible to determine how big a role this played in the observed differences between the coastal and interior samples. These two mills provide an important contrast, as the coastal mill demonstrates what is possible where as the interior study shows what is commonly done in practice.

When only the logs that were milled are considered, both lumber recovery and Clear grade recovery remained higher for the coastal sample. For the coastal logs, 51.6% of the milled firmwood volume was recovered as lumber compared with 40.8% at the interior mill (Table 3-4). Over 76% of the lumber recovered at the coastal mill was Clear grade compared with less than 3% at the interior mill (Table 3-4). Some of this discrepancy is also likely due to the differences between logs at the two study sites. Defects represented a greater proportion of the interior log volume and we would therefore expect lumber recovery to be lower.

To be classified as Clear grade lumber, the size and frequency of defects such as shake and knots must fall below critical values. The coastal logs contained a significantly lower frequency of knots than the interior sample and we would therefore expect them to produce greater volumes of Clear grade lumber. On average, 72% of the length of interior logs contained at least one knot of more than 25 mm in diameter within a 1 m section compared with just 18% of length for the coastal logs (Table 3-3). The frequency of knots showed a moderate negative relationship with value recovery and only a weak relationship with volume recovery (Table 3-5).

For the coastal log sample, just six of the 45 logs sampled were No. 7 chipper grade, the grade intended for logs of pulp quality. Due to low demand for lower grade sawlogs/utility logs and high prices for pulp logs, grades from No. 2 sawlog to No. 7 chipper were being used for pulp production at the time of this study. Although no significant differences were detected, the percentage of lumber recovery generally decreased with grade, with the lowest recovery (25.9% of firmwood volume) recorded for No. 7 chipper grade logs (Figure 3-5). Individual log grades were not provided for the interior logs; so, it is not possible to determine whether the differences in lumber recovery were due to a greater proportion of lower quality log grades in that sample. The smaller sizes and greater defect proportion of the log ends suggest that this is likely.

Difference in log dimensions may have also been responsible for the contrasting lumber recovery between samples. Lumber recovery is known to increase with log diameter (Steele 1984). This was supported by the positive correlations between lumber recovery and the diameters at both ends of the logs (Table 3-5). The diameters of the milled logs from the coast were larger than those from the interior (Table 3-3), suggesting that diameter likely played a role in the increased lumber recovery in the coastal sample.

Both the volume and value of lumber recovered was negatively correlated with log length (Table 3-5). On average, the milled logs from the interior were 45% longer than those from the coast, while lumber recovery was 10.8% less (Table 3-3). The shorter lengths were likely related to the increased weight of the coastal logs and greater log handling required at the MKRF mill. Log lengths can reduce volume and value recovery if they are not closely matched to the desired lumber lengths (Steele 1984). The wide range of lumber lengths utilized at the interior sawmill suggests that this was likely not a contributing factor (Figure 3-4). Rather, the negative correlations between log length and volume recovery was likely due to longer logs masking additional internal defect that was not visible at the cut ends. The shorter a log is cut, the more likely that internal defect will be visible at either end. A better understanding of the internal state of the log enables more accurate grading, bucking and sawing decisions, likely leading to improved recoveries. The method of infection of the two major causes of heart rot in western hemlock likely accentuated the effect of log length.

Indian paint fungus and Annosus root and butt rot are the major causes of heart rot in mature western hemlock in British Columbia, which has been attributed to the loss of one quarter of gross volume (Kimmey 1964, Allen *et al.* 1996, Holsten *et al.* 2001). Unusually for heart rots, neither gains entry to the heartwood through scars or dead branches. Indian paint fungus infects trees through the living stubs of exceptionally small branches (<1 mm) (Etheridge *et al.* 1972). Annosus root and butt rot gains entry to living trees via surrounding stumps. Typical indicators of rot, such as dead branches, rotten knots and scars don't exist. For longer logs, the lack of external indicators makes it increasingly likely that internal heart rot would remain undetected until initial log breakdown. Indian paint fungus is also much more prevalent in the interior regions (Kimmey 1964). Combined with the longer average length of the interior logs, this likely contributed to the lower lumber recovery, as the likelihood that logs contained internal defect that remained undetected until the sawmill would be increased.

To sawyers, western hemlock is often considered a demanding species due to the difficulty in predicting its internal properties. Much of this can likely be attributed to the methods of infection of Indian paint fungus and Annosus root and butt rot. This would support greater merchandizing of western hemlock logs. Bucking longer logs into mill-lengths prior to grading and allocation would reduce the likelihood of the log containing internal defect that was not visible at the ends. As this study shows, many of these logs contain profitable volumes of recoverable lumber. Increased log merchandizing would improve the ability to direct logs to manufacturing facilities that could recover the highest margin.

Other than the logs, sawmills were the other major source of variation in this study. Differences between mills, including the equipment and cutting patterns would have had an important effect on the recoveries at the two study sites. The method of log breakdown at the two sawmills varied considerably and was likely a major reason for differences in lumber and grade recovery. At the interior sawmill, primary breakdown occurred at a headrig with no scanning or optimization technology. Only the leading end and the open face were visible to the headrig operator. At the coastal sawmill, primary log breakdown was achieved using a Peterson flip saw. The saw's orientation is easily adjusted between vertical and horizontal and is manually adjusted for height and depth. This allows infinite flexibility in the cutting pattern. The increased proximity and time taken to cut the log means the operator is very familiar with the log prior to and during cutting. These differences likely affected the lumber and grade recoveries of the two samples. The sawyer at the MKRF sawmill could measure the log and defect dimensions prior to each cut and determine the best combination of pieces to maximize value recovery. This opportunity was not available to the headrig operator at Joe Kozek Sawmill and recoveries would be expected to be lower.

Differences in the definitions of Clear grade lumber would have been responsible for some of the increased volumes from the coastal sample. Although the grade specifications for Clear grade were similar at both mills, the application was more lenient at the coastal mill. As most pieces were to be trimmed for wainscoting, the tolerances for knots were relaxed if defects permitted the recovery of clear sections in 1.22 m (4 feet) multiples. Thus, a 3.96 m (13 foot) board with a large unsound knot at 1.27 m (4'2") would still be classified as Clear if the remaining length met specifications. This was not the case at the interior mill. The volume of Clear grade lumber recovered at the interior mill would be expected to have been greater had the same grading rules been applied.

The mix of products cut is known to affect lumber recovery. As the number of saw lines increases, more sawdust is produced and recovery should generally decrease (Steele 1984). However, considerably more saw lines were made in the coastal logs, which generated higher recoveries than the interior sample. The majority of lumber cut at the coastal mill was 25 mm (1 inch) thick and no pieces had a thickness of greater than 2 inches (Figure 3-2). In contrast, 67.5% of the volume cut at the interior mill was more than 51 mm (2 inch) thick. With so many small dimension pieces, more sawdust would have been produced at the coastal mill and recoveries would be expected to be lower. The use of nominal rather than actual dimensions to calculate recovery likely mitigated the affect of kerf. It is also possible that cutting for smaller product dimensions and lengths allowed more recovery from the slab and edge pieces at the coastal mill, offsetting the greater number of saw lines.

In order to determine the impact of the variability between logs and sawmills on the results, the experimental design should have allowed logs from each location to be sawn at either mill. Unfortunately, this was not the case as only one replicate was planned at the time of the interior sample collection and mill trial. When the second replicate was measured, the high costs and limited funds prevented the transportation of logs to the interior mill. It is not possible to directly determine whether the observed differences were caused primarily by differences between the log samples or the sawmills. This is a weakness of this study.

Lumber recoveries obtained in this study were within the range of other published figures for western hemlock. Recorded recoveries of rough-green lumber from western hemlock have ranged from 26% to 60% of the original log volume (Woodfin and Snellgrove 1976, Fahey 1983, Milota 2004). In the only known study that considered pulp logs exclusively, 60% and 53.2% of the original volume was recovered as rough-green lumber at a stud mill and dimension mill respectively, although the pulp classification was based primarily on size (13–36 cm large end diameter) rather than log defects (Fahey 1983). In contrast, just 25.9% of lumber was recovered from logs graded as No. 7 Chipper Grade in this study. In a study of western hemlock logs classified as poorer than pulp quality, just 26% of the original volume was recovered as rough-green lumber (Woodfin and Snellgrove 1976).

The recovery of planed and dried lumber would have been less than the recoveries of rough-green lumber reported. Western hemlock is highly prone to forming wetwood, where heartwood becomes internally infused with water (Ward and Pong 1980). In logs containing wetwood, moisture content varies considerably between the heartwood and sapwood. This makes it extremely difficult to dry the lumber to a uniform moisture content (Kozlik 1970). As the lumber dries, the differences in moisture content cause it to split, warp and collapse (Ward 1972). This leads to downgrading or trimming of the affected portion and in the worst cases can make the lumber worthless. A study of 51 mm (2 inch) western hemlock lumber found that 9.7% of volume was lost due to shake, check and warp after drying and planing (Salamon and McBride 1965).

The recovery of finished products at the coastal mill would have been lower due to the cutting program used. After planing and drying, most lumber was to be trimmed to 1.22 m (4 foot) lengths for wainscoting. Not all rough-green lumber was cut in 1.22 m multiples and trimming would have resulted in additional lost volume (Figure 3-3). Volumes of rough-green lumber were used in this report rather planed and dried volumes as the results are intended to be applicable to other sawmills. This likely overestimated the volume of Clear grade lumber produced.

Given current market values for sawn wood and chips, the coastal mill would have generated a profit from the logs that were graded as pulp logs (Y Grade) if it chipped the sawmilling residue. If the residue was converted into Standard grade chips, the six logs would gave generated a $23 profit. If the residue was converted into Standard grade chips, the six logs would gave generated a $29 profit. Generating no chip revenue from the pulp grade logs would have resulted in a \$17 loss. This demonstrates that it can be marginally profitable to recover lumber from the logs which the grading rules designate for pulp production.

As costs and prices are dynamic, the key breakpoints at which it would have been profitable for each mill to recover lumber from the samples were determined. If lumber prices and operating costs remained unchanged, average log costs would have needed to have been less than \$4.20/m^3 for the interior sawmill to have made a profit when not producing chips (Table 3-7). When producing chips, log costs would need to be less than \$18/m^3 (Standard grade chips) or \$19.80/m^3 (Premium grade chips). Based on historic log prices, \$4.20/m^3 for western hemlock pulp logs from the interior region is highly unlikely. Since 2003, the lowest average monthly price for pulp logs listed on the MoFR Log Market Reports was \$6.87/m^3 while the average monthly price was \$23.65/m^3 (MoFR 2008). The price breakpoints for mills producing chips would seem more possible though. Twice in 2003, the average monthly price for western hemlock pulp logs was less than \$18/m^3. While it has consistently been above that price since that point, they represent only a 4% and 13% decline respectively from July 2007 log price.

The results were quite different at the coastal sawmill, where a substantial rise in log prices would be required before the mill made a loss. If the sawmill did not produce chips and lumber prices and operating costs remained unchanged, log costs would need to be more than \$72/m^3 for the mill to have begun making a loss (Table 3-7). When producing chips, log costs would need to be more than \$78.10/m^3 (Standard grade chips) or \$79.20/m^3 (Premium grade chips). Based on historic price fluctuations, such high log prices would seem unlikely. Since 2003, the highest monthly price for western hemlock pulp logs from the coast was \$50.41/m^3. Recent price declines would make such a rise seem unlikely in the short-term.

If all other costs and revenues remained the same, operating costs would have needed to be 12-31% lower at the interior sawmill for it to have made a profit milling the logs sampled in this study. The operating costs used in this study represent the average costs for BC interior mills in

2004 pro-rated to 2007 dollars (International Wood Markets Research Inc. *et al.* 2005). The operating costs of mills designed to capture value rather than volume recovery would likely be higher. It is considered unlikely that mills would have been able to profitably recover sawn wood from the interior sample without either a significant increase in lumber prices or a significant decrease in log costs.

If logs, lumber and chip prices remained unchanged, coastal sawmills with operating costs greater than 20% above the average used in this study would have made a loss. Mills designed to capture value recovery generally have higher operating costs than most sawmills. It is therefore likely that not all sawmills would have made a profit from these logs.

Some logs from both samples were milled at a profit. At the coastal sawmill, between 60% and 67% of logs were milled at a profit, depending on whether chips were also produced. At the interior mill, between 13% and 21% of logs were milled at a profit. If the interior only produced lumber and Standard grade chips from the logs, the mill would have made a profit had the sample been limited to logs that yielded more than 19.3% lumber (Figure 3-8). An accurate method for predicting the lumber recovery of western hemlock pulp logs would better enable sawmills to identify profitable logs.

6. Conclusion

It can be profitable to cut solid wood products from western hemlock logs that are being used for pulp production. At the coastal sawmill, given historic operating costs and product prices, between 60% and 67% of logs were milled at a profit, depending on whether chips were also produced. At the interior mill, between 13% and 21% of logs were milled at a profit. Milling the coastal sample returned a profit regardless of whether chips were also produced. The additional revenue from chips easily offset the additional costs, making this the most promising approach. At the interior sawmill, the outcome was different with all three scenarios resulting in a loss. This was largely attributed to the logs sampled. On average, the interior logs had smaller diameters, longer lengths, a greater proportion of rot and approximately four times more knots than the coastal logs. The longer logs likely contained additional internal defect that remained undetected until the sawmill. Identifying internal defect in these logs would have been exacerbated by the lack of external indicators from the two main causes of heart rot in western hemlock. Differences in log breakdown and lumber grading between sawmills also likely contributed to the contrasting results. Knowing that it can be profitable to recover solid wood from some logs that are used for pulp production, the issue then becomes one of efficiency.

Old-growth western hemlock pulp logs are better suited to mills that focus on value rather than high volume production. Despite the prevalence of internal decay, large volumes of clear wood can be recovered from these logs as shown by at the coastal mill. Doing so requires high flexibility in the cutting pattern, which was exemplified by the Petersen flip saw. The cutting program used at the MKRF sawmill was also well suited to the logs. By predominantly cutting 25 mm (1 inch) boards, the mill was able to extract a lot of value from the clear collars of the logs. The choice of wainscoting also allowed greater recovery of Clear grade pieces, as the specifications were applied to 1.22 m (4 foot) sections rather than to the entire length.

Methods to better understand the internal quality of western hemlock logs would likely improve value recovery from lower quality logs. If internal defects could be more accurately identified, grading and allocation decisions could be made with greater certainty. Sawyers could then be more confident of making profitable returns from lower grade western hemlock logs. This would likely increase the demand for these logs, resulting in fewer grades being sent to pulp mills than at present. Methods to better understand the internal quality of logs include increased merchandizing, predictive models based on external features and internal log scanning.

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CHAPTER 4. METHOD OF ESTIMATING THE VOLUME OF LUMBER AND PROPORTION OF CLEAR GRADE LUMBER FROM WESTERN HEMLOCK LOGS INTENDED FOR PULP PRODUCTION[3]

1. Introduction

In British Columbia, western hemlock is an important commercial species to both the solid wood and pulp and paper industries. Its light, even textured wood and ease of machining make it suitable for dimension and shop lumber, moulding and panelling. The wood has relatively low levels of extractives (Keays and Hatton 1971) and good fibre qualities, making it a preferred species for market kraft pulp and newsprint production (King *et al.*1998).

Compared with other commercial species, western hemlock produces a higher proportion of pulp grade logs and subsequently contributes less value relative to the volume harvested. The increased proportion of pulp logs is a result of its susceptibility to a range of defects. It is one of the least resistant species to stem decay in the world (Clark 1957, Scheffer and Morrell 1998) and its heartwood commonly becomes infused with water, leading to fibre separation (shake and check), warping, shrinkage and collapse, particularly after kiln drying (Hartley *et al.* 1961, Ward 1972, Josza *et al.* 1998). Kiln drying wetwood takes two to six times longer than sapwood to reach acceptable moisture levels, increasing production costs (Sachs *et al.* 1974).

As it accounts for 60% of the mature forests in the coastal region (Coast Forest Products Association 2003), increasing the value recovery of western hemlock would have enormous benefit to the forest industry. A previous study found that 67% of logs sampled from a coastal forest that were intended for pulp production could have been profitably milled into solid wood products (Chapter 3). A method to accurately identify these logs in the woods or at a sort yard could add significant value to the resource by ensuring that the right log is sent to the right manufacturing facility.

[3] A version of this chapter will be submitted for publication. Mortyn J. and T. Maness. *Method of estimating the volume of lumber and proportion of clear grade lumber from western hemlock pulp logs.* 23 pp.

Various models have been developed to predict the total volume, grade volume and value of recoverable products for both trees (Ernst and Hann 1984, Kellogg and Warren 1984, Liu and Zhang 2005, Zhang and Tong 2005, Moberg and Nordmark 2006, Zhang and Liu 2006) and logs (Fahey and Woodfin 1982, Ernst *et al.* 1986, Willits and Fahey 1988, Howard and Gasson 1989, Beauregard *et al.* 2002). Most models have used combinations of diameter, length, height and taper to predict the volume of various products, while some models have also used log defects. A model for western hemlock trees found that diameter, height and taper were the most important attributes in predicting the value of lumber recovered (Kellogg and Warren 1984).

The objectives of this research were to develop models that reliably predict both: (1) the total volume of lumber recovered; and (2) the proportion of Clear grade lumber recovered from old-growth western hemlock logs intended for pulp production. These models were to be based on external characteristics to better enable logs with the potential for profitable lumber recovery to be identified during log grading.

2. Data collection and analysis procedures

A total of 102 old-growth western hemlock logs that were intended for pulp production were sampled in this study. The logs were sourced from two regions in British Columbia: 45 from the Malcolm Knapp Research Forest (MKRF) in the Coastal Mountain Ranges; and 57 from the Columbia Mountains north of Revelstoke. Detailed log dimension and defect measurements were made using procedures outlined in the Ministry of Forests and Range (MoFR) Scaling Manual (MoFR 2007). The logs were bucked into mill lengths and those deemed likely to yield lumber were transported to local sawmills in each region and sawn with the aim of maximizing value recovery. The interior log sample was sawn at Joe Kozek Sawmill in the township of Revelstoke and the coastal sample was sawn at the MKRF sawmill, north of Maple Ridge. The nominal dimension and grade of all rough-green lumber recovered from each log was recorded. Two lumber grades were recognized at each sawmill: Clear, and Standard and Better. At Joe Kozek Sawmill, the Clear grade most closely matched the “C Industrial” grade for industrial clears while at the MKRF mill, it most closely matched the “D Select” grade for boards (National Lumber Grades Authority 2007). The remaining log volume minus a 7.3% sawdust allowance was used to estimate the volume available for chips (Fahey 1983).

The data were used to develop models to predict the volume of lumber and the proportion of Clear grade lumber recovered. All measured log attributes were considered as candidate variables for the models, with log defects supplied in both absolute and relative terms. Additional candidate variables were created that considered combinations of attributes, such as the maximum knot size as a proportion of the log diameter and the average thickness of the sound collar at both ends of the log. Class variables such as the region, presence/absence of defects and the stage of decay were also considered (Appendix A). The regressions were fitted using SAS Version 9.1.3.

3. Model to predict lumber recovery

The total lumber volume (m^3) recovered from each log was used as the response variable (Y). A single dataset combining the data from the two regions was created and all 102 logs with defect measurements were included. Preliminary investigations indicated that a linear model best decribed the relationship within the range of the data. A linear model would likely not describe lumber recovery in small logs as well as a non-linear model, as no lumber can be recovered from logs below a certain diameter threshold. This would likely be exacerbated by the lack of small logs in the data set, and consequently the model should not be used outside of the range of log sizes measured.

A stepwise regression procedure was used to identify the continuous variables that explained the majority of variance in the volume of lumber recovered. A generalized linear modelling procedure (PROC GLM) was used to fit the model. Partial-F tests were used to determine whether the addition and subtraction of candidate variables were justified using an α-level of 0.05. An interaction between two variables describing: 1) the average thickness of the sound collar at both ends, and 2) gross volume minus the combined volume of broken wood, damaged wood, missing wood, pistol grip and crook was found to explain the majority of variance in recovered volume. This was included as the single continuous predictor variable. A class variable describing the stage of butt/heart rot at the large end was found to significantly improve the model. Partial F-tests showed that a model containing an interaction between the class and continuous predictor variable as well as the class variable as a y-intercept adjustment was significantly better than reduced models.

Due to the similarity between parameter estimates describing the stage of butt/heart rot, statistical tests were conducted to determine whether all four categories (none, incipient, developing, advanced) were needed. Partial F-tests confirmed that the full model containing all four categories was not significantly better than a reduced model with only three rot levels (none/incipient, developing, advanced). The final model explained 70.98% of the variance in the data set and was significant at an α-level of 0.05 (Table 4-1).

Table 4-1 Analysis of variance table for model to predict volume of rough-green lumber recovered.

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	23.0015	4.6003	46.96	<0.0001
Error	96	9.4038	0.0980		
Uncorrected Total	101	32.4053			

The model appears to satisfy the assumptions of linearity and equal variance, with an even spread of residuals around the *y*-axis across the range of predicted values (Figure 4-1). Four statistical tests found that the selected model did not violate the assumption of normality.

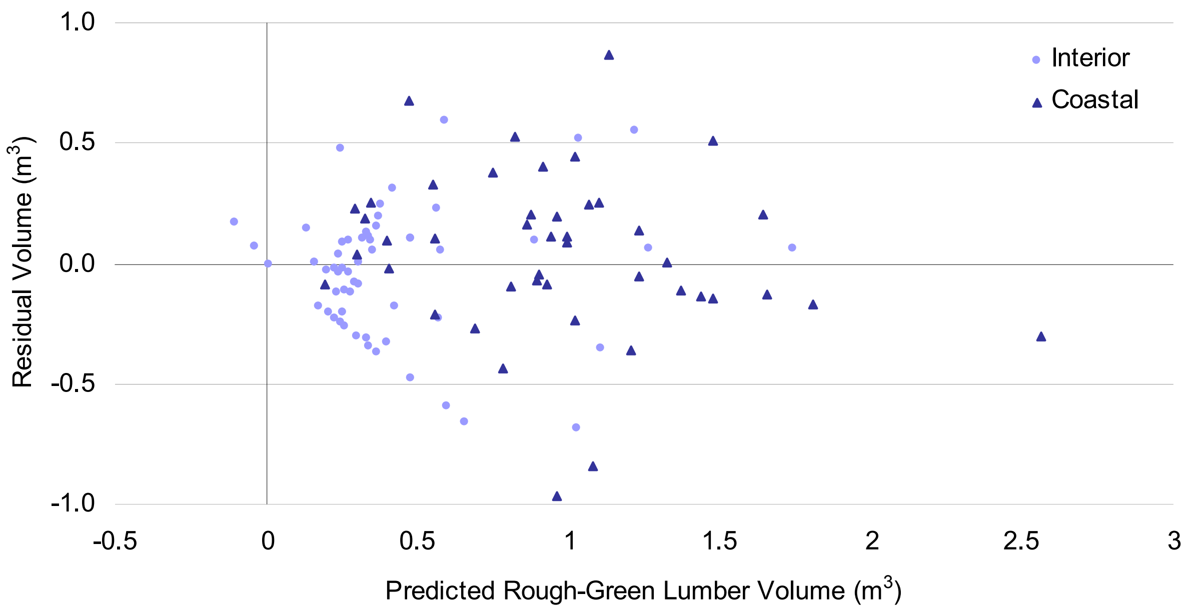

Figure 4-1 Plot of residuals for model to predict volume of rough-green lumber.

The selected model uses one continuous variable, one class variable and six parameters to predict the volume of lumber recovered (Equations 4-1, 4-2 and 4-3). The variables in the model describe the gross volume minus the combined volume of broken/damaged/missing wood, crook and pistol grip, the average radius of the collar of sound wood at both ends and the stage of butt/heart rot evident at the large end of the log.

For logs with none/incipient levels of butt/heart rot at the large end:

$$\hat{y}_i = 0.0153 + 0.1554(g_i - c_i - p_i)\left(\frac{cl_i + cs_i}{2}\right) \qquad \text{(Equation 4-1)}$$

For logs with developing levels of butt/heart rot at the large end:

$$\hat{y}_i = 0.0171 + 0.0355(g_i - c_i - p_i)\left(\frac{cl_i + cs_i}{2}\right) \qquad \text{(Equation 4-2)}$$

For logs with advanced levels of butt/heart rot at the large end:

$$\hat{y}_i = 0.0186 - 0.1299(g_i - c_i - p_i)\left(\frac{cl_i + cs_i}{2}\right) \qquad \text{(Equation 4-3)}$$

Where:

$\hat{y}_i$ = estimated volume (m^3) of rough-green lumber of log i;

g_i = gross volume (m^3) of log i calculated using Smalian's formula minus volume of broken, missing or damaged sections;

c_i = volume (m^3) of log i affected by crook calculated using Smalian's formula;

p_i = volume (m^3) of log i affected by pistol grip calculated using Smalian's formula;

cl_i = minimum radius of outermost collar (cm) at large end of log i unaffected by shake or rot (butt, heart or ring rot of developing or advanced stages only);

cs_i = minimum radius of outermost collar (cm) at small end of log i unaffected by shake or rot (butt, heart or ring rot of developing or advanced stages only).

In order to predict the volume of recoverable lumber, gross volume should be calculated using Smalian's formula from measurements of diameter under bark at both ends of the log. Voids created by broken, missing or damaged wood should be subtracted according to the rules outlined in the B.C. Log Scaling Manual (MoFR 2007). The volume affected by crook or pistol grip should be calculated using Smalian's formula from measurements of the length and the diameter at both ends of the affected section minus the estimated bark thickness. The collar at the large and small ends is the minimum radius of the outermost portion of the log end which is unaffected by either rot (butt, heart or ring rot of developing or advanced stages) or shake.

The model predicts that lumber will increase as log volume and average collar thickness increase and with decreasing stages of butt/heart rot at the large end (Figure 4-2). Due to the selection of a linear model, the model does not pass through the origin. This results in unrealistic predictions for small logs, such as positive lumber recovery from logs with zero volume. Predicting lumber recovery for small logs is commonly problematic as logs must be of a certain size before any lumber can be recovered. Consequently, the model should not be used for small logs.

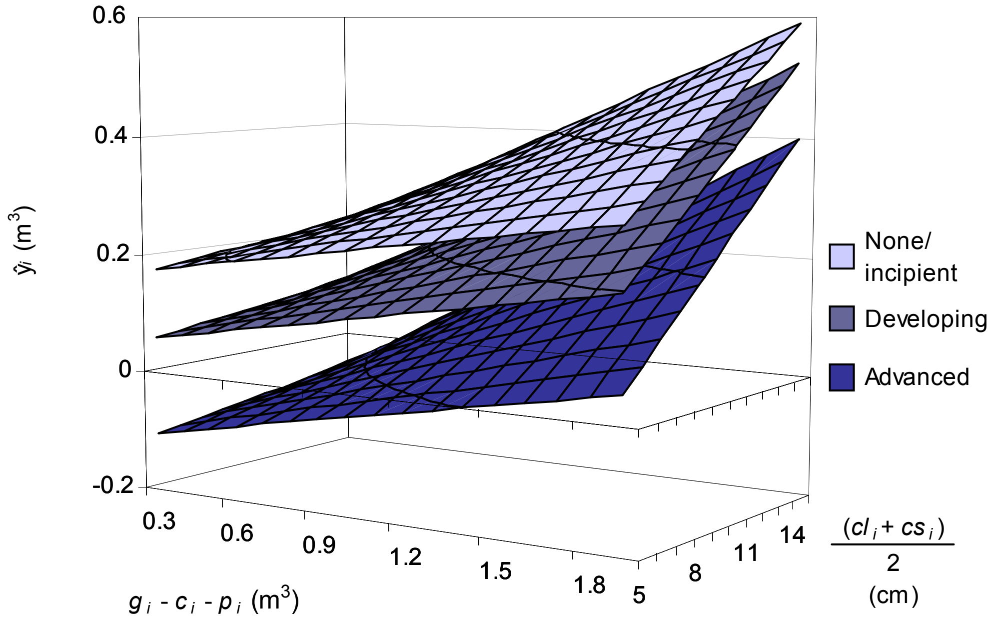

Figure 4-2 Predicted lumber volume ($\hat{y}_i$) by gross log volume minus the combined volume of broken/damaged/missing wood, crook and pistol grip ($g_i - c_i - p_i$), the average radius of the collar of sound wood at both ends ($(cl_i + cs_i)/2$) and the maximum stage of decay of butt/heart rot at the large end.

4. Model to predict the proportion of Clear lumber

A regression was developed to predict the proportion of Clear grade lumber from each log. Determining the proportion of Clear grade lumber allows a more accurate calculation of potential revenue, as prices can vary considerably by grade. A proportional approach ensured that predictions of Clear grade lumber were compatible with predictions of total lumber volume.

The Clear grades differed between mills, due to the difference in end products produced. Consequently, separate regressions were developed for the coastal and interior samples, as the dependent variable could not be considered equivalent. The models aimed to predict the proportion of recovered lumber that was Clear grade, so only logs that yielded lumber were used. The response variable was the volume of Clear grade lumber as a proportion of the total volume of lumber. The proportional response variable makes ordinary least squares regression unsuitable, as the predicted values would not be constrained between 0 and 1. Parameters were estimated using maximum likelihood estimation with a logistic model and a binomial probability distribution (Equation 4-4). This approach is commonly used in such circumstances (Demsetz and Lehn 1985, Kieschnick and McCullough 2003).

$$L = \prod_{i=1}^{n} \left(\frac{\exp(\mathrm{x_i}'\beta)}{(1+\exp(\mathrm{x_i}'\beta))} \right)^{y_i} \left(1 - \frac{\exp(\mathrm{x_i}'\beta)}{(1+\exp(\mathrm{x_i}'\beta))} \right)^{1-y_i} \qquad \text{(Equation 4-4)}$$

The model was developed using the LOGISTIC procedure. As this requires a discrete response variable, the proportions were multiplied by 100 and rounded to the nearest whole number, resulting in 100 potential discrete variables. The response variable was modelled as a count and expressed as the observed response over 100. To identify the explanatory variables to include, candidate variables were individually introduced and the resulting likelihood recorded. The variable returning the highest likelihood was then included in the preliminary model and the process was continued by re-introducing each variable. This process was repeated, with candidate variables both added and subtracted, similar to a stepwise procedure. Wald tests were used to determine the significance of each explanatory variable in the presence of the other explanatory variables in the model. Likelihood ratio tests were used to determine whether restrictions to nested models were significant. The chosen models were based on the -2 log likelihood, likelihood ratio, the significance of parameters and the number of variables required.

4.1 Model to predict the proportion of Clear lumber for coastal sample

For the coastal sample, the selected model uses four continuous variables to predict the volume of Clear grade lumber as a proportion of total lumber volume (Equation 4-5). The variables in the model describe log length (m), the proportion of length containing knots of at least 20 mm in diameter, the width of the collar of sound wood at the large end (cm) and the log taper (cm m^{-1}). All parameters were significantly different from zero at the 5% α-level. A Cox and Snell pseudo-R^2 statistic (0.1174) showed that the selected model was only marginally better than an intercept only model. This statistic can be used to measure the goodness of fit of models that are fitted using maximum likelihood estimation. It is calculated by comparing the likelihood of the selected model with an intercept only model, with values closer to zero indicating a poor fit. A residual plot shows an even spread of points around the y-axis and relatively equal variance for all predicted values (Figure 4-3). Equation 4-6 can be used to predict the proportion of Clear grade lumber ($\hat{y}_i$) from the coastal sample.

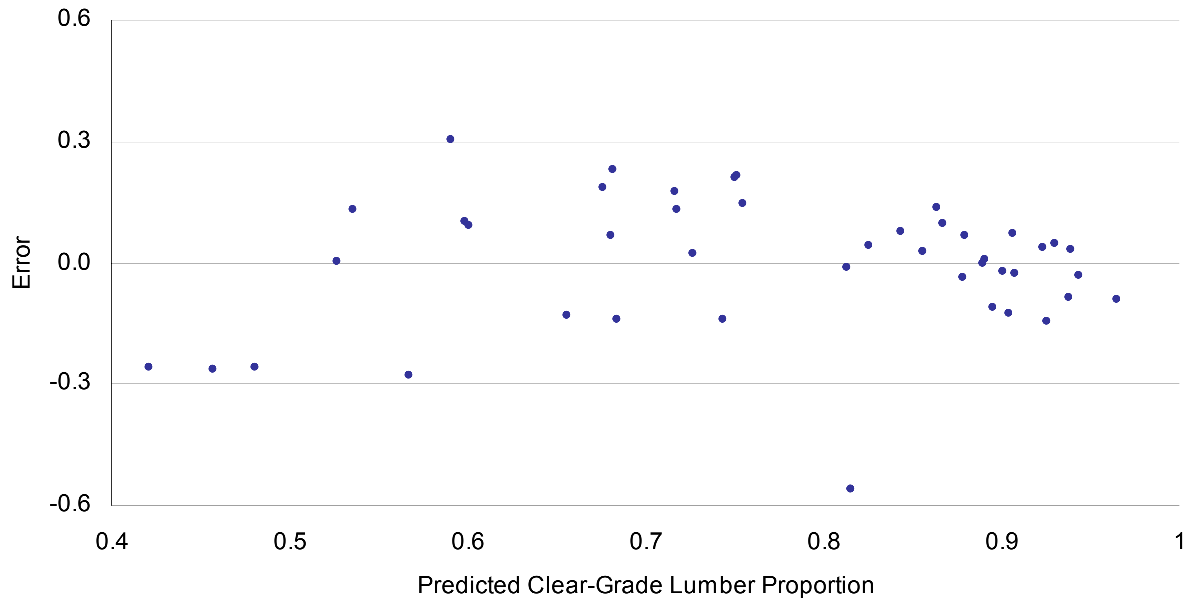

Figure 4-3 Plot of residuals for model to predict proportion of Clear grade lumber from coastal sample.

$$\mathbf{x_i}'\boldsymbol{\beta} = b_0 + b_1 len_i + b_2 k_i + b_3 cl_i + b_4 t_i \qquad \text{(Equation 4-5)}$$

$$\hat{y}_i = \frac{\exp(3.9098 - 1.7739 len_i - 0.2012 k_i - 0.0412 cl_i + 0.3598 t_i)}{(1 + \exp(3.9098 - 1.7739 len_i - 0.2012 k_i - 0.0412 cl_i + 0.3598 t_i))} \qquad \text{(Equation 4-6)}$$

Where:

len_i = length (m) of log i;

k_i = length of log i containing knots of at least 20 mm in diameter as a proportion of total log length (where knots that are less than 1m apart, the length from the first knot to the last knot before the first clear 1 m section is used);

cl_i = minimum radius of outermost collar (cm) at large end of log i unaffected by shake or rot;

t_i= taper (cm m^{-1}) of log *i*, difference between small and large end diameters (cm) divided by the log length (m).

The model predicts that Clear grade lumber proportions will increase as knot frequency, log length and the width of the sound collar at the large end decrease (Figure 4-4). As these log attributes are likely to be correlated, the effect of each attribute on model behaviour can not be considered in isolation.

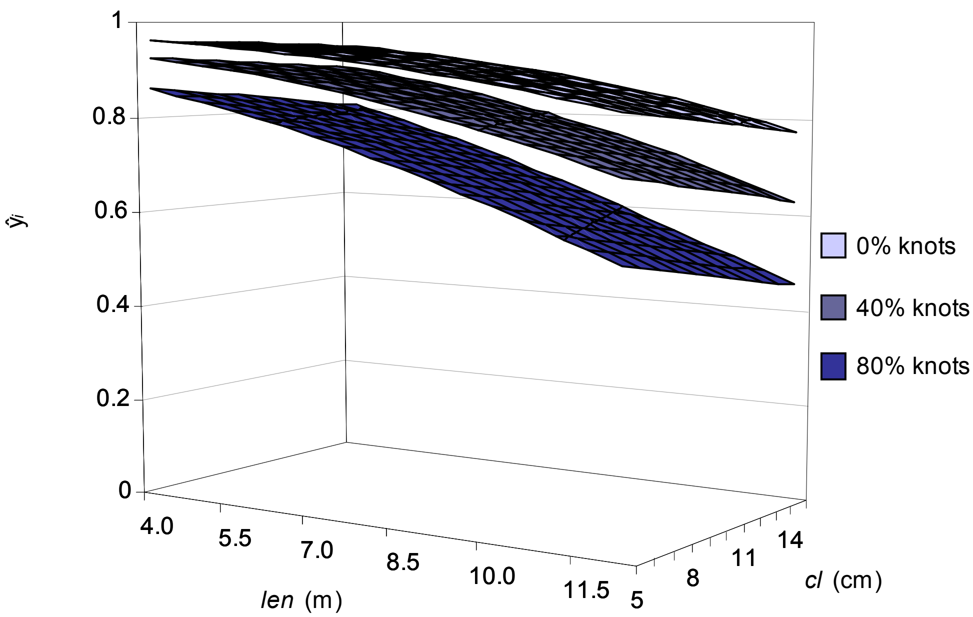

Figure 4-4 Predicted volume of Clear grade lumber as a proportion of total lumber volume ($\hat{y}_i$) for the coastal sample by log length (*len*), the average radius of the collar of sound wood at the large end (*cl*) and the frequency of knots (note: calculations assume a taper of 1 cm/m).

4.2 Model to predict the proportion of Clear lumber for interior sample

For the interior sample, the selected model uses three continuous variables to predict the proportion of Clear grade lumber (Equation 4-7). The variables in the model describe the proportion of length containing knots of at least 20 mm in diameter, the large end diameter under bark (cm) and the estimated gross volume (m^3). All parameters were significantly different from zero at the 5% α-level. A Cox and Snell pseudo-R^2 value (0.0943) showed that the selected model was only marginally better than an intercept only model. A plot of residuals showed that points were not evenly spread around the y-axis, with lower error for logs where the proportion

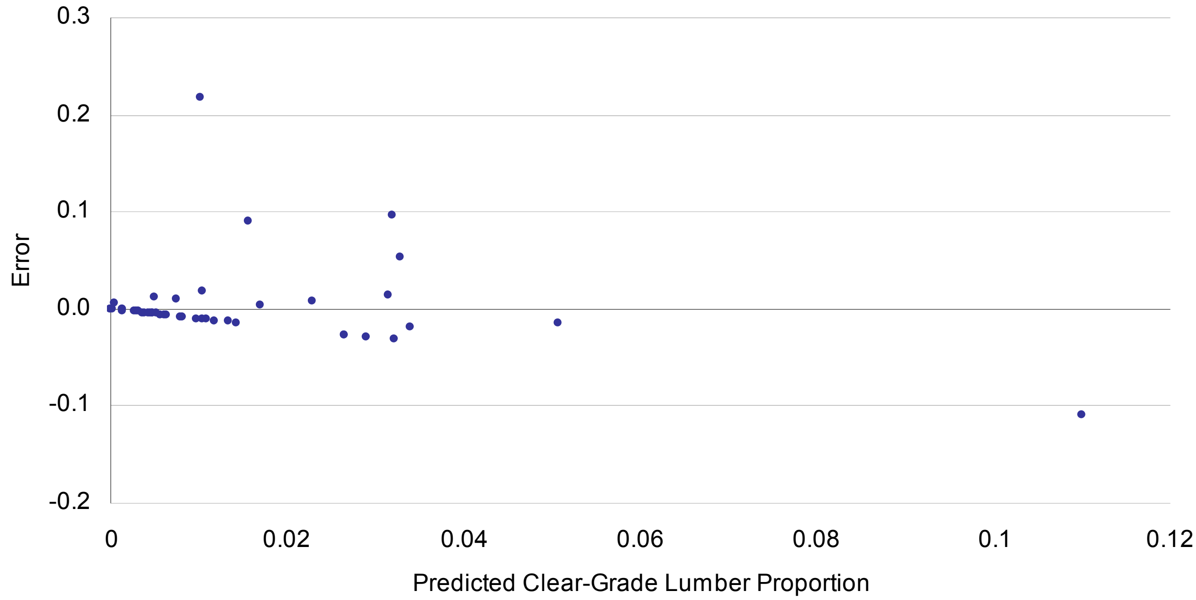

Figure 4-5 Plot of residuals for model to predict proportion of Clear grade lumber from interior sample.

of Clear grade lumber was over predicted compared with logs that were under predicted (Figure 4-5). This was due to the large number of logs that yielded no Clear grade lumber. The residual plot also showed that the error variance decreased with the predicted values. Equation 4-8 can be used to predict the proportion of Clear grade lumber ($\hat{y}_i$) from the interior sample.

$$\mathbf{x_i}'\boldsymbol{\beta} = b_0 + b_1 k_i + b_2 d_i + b_3 g_i \qquad \text{(Equation 4-7)}$$

$$\hat{y}_i = \frac{\exp(-4.7015 - 3.2823k_i + 0.0660d_i - 0.4976g_i)}{(1 + \exp(-4.7015 - 3.2823k_i + 0.0660d_i - 0.4976g_i))} \qquad \text{(Equation 4-8)}$$

Where:

k_i = Length of log i containing knots of at least 20 mm in diameter as a proportion of total log length (where knots that are less than 1 m apart, the length from the first knot to the last knot before the first clear 1 m section is used);

d_i = diameter under bark (cm) at the large end of log i;

g_i = gross volume (m^3) of log i

The model predicts that Clear grade lumber proportions will increase as knot frequency and gross volume decrease and as the diameter at the large end increases (Figure 4-6). As log

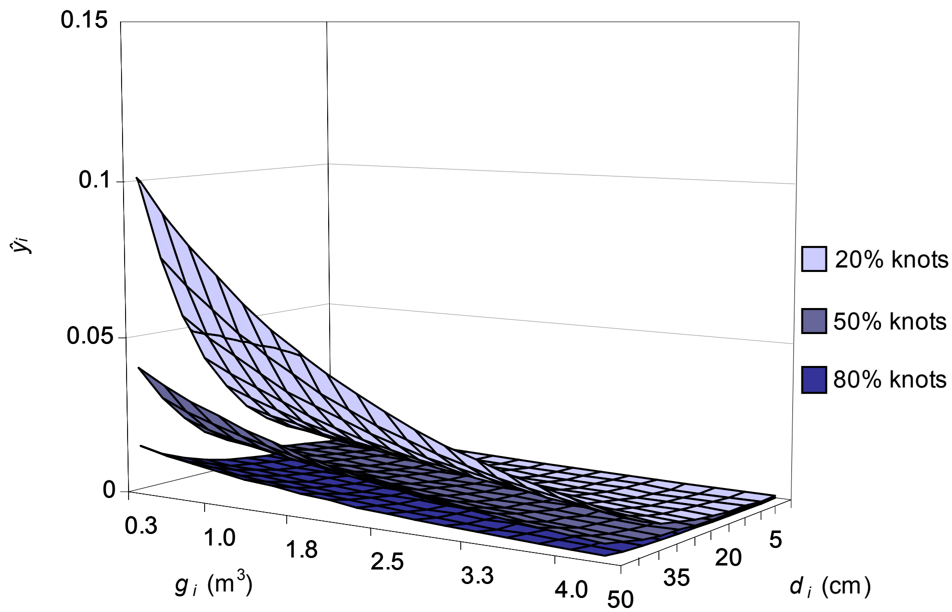

Figure 4-6 Predicted volume of Clear grade lumber for as a proportion of total lumber volume ($\hat{y}_i$) for the interior sample by gross log volume (g_i), the diameter under bark at the large end (d_i) and the frequency of knots.

diameter and volume are certain to be correlated, the effect of each attribute on model behaviour can not be considered in isolation.

5. Discussion

Models were developed to predict the total volume of lumber and the proportion of Clear grade lumber recovered from the sample logs using external log features. The most important attributes for predicting the volume of lumber recovered were: gross volume minus the combined volume of broken/damaged/missing wood, crook and pistol grip; the average width of the sound collars at both ends; and the maximum stage of decay of butt/heart rot at the large end. It is not surprising that lumber recovery was predicted to increase with log volume. The relationship between log size and lumber recovery is well established, with many other studies showing that log dimension attributes are positively correlated with lumber recovery (Fahey and Woodfin 1982, Steele 1984, Ernst *et al.* 1986, Willits and Fahey 1988, Howard and Gasson 1989). In larger logs, a lower proportion of volume tends to end up in slabs and edgings, as an increased number of potential cutting patterns allow greater utilization of the outer log. Gross log volume minus broken, damaged and missing sections and minus the volume affected by crook and pistol grip was a better predictor of lumber recovery than other volume measurements. Crook and pistol grip as well as damaged, broken and missing sections are generally unsuitable for lumber and would likely be bucked out. Volume estimates that account for these defects would be expected to be a more accurate representation of the merchantable volume than gross volume estimates alone.

Lumber recovery was predicted to increase as the average widths of the sound collars at both ends increased. For logs with heart rot, shake or check, the sound collar is the section of fibre that is structurally intact and suitable for lumber production. One would therefore expect it to be an important predictor of lumber recovery. Sawyers commonly use the collar width as a basic gauge to determine the suitability of a log for sawing. This study confirms that it is one of the most important predictors of lumber recovery.

The stage of butt and heart rot at the large end of the log was also significant in predicting lumber recovery. Decreasing lumber volumes were predicted from logs as the stage of butt/heart rot at the large end progressed from none/incipient to developing to advanced. This finding suggests that grading specifications that account for the stage of decay in the log are warranted.

All other candidate variables did not significantly improve lumber recovery predictions. Somewhat surprisingly, no significant differences were detected between regions, despite differences between the log samples, sawmills and the cutting programs used. This suggests that the log characteristics affecting the volume of lumber recovered from old-growth western hemlock logs may be similar in these two regions. It would be beneficial to test the model on logs from other geographic regions to determine whether a species-wide model is suitable.

In order to predict the proportion of Clear grade lumber, separate models were developed for the coastal and interior samples. The lumber grades and application of grading rules differed between sawmills, meaning that no consistent dependant variable existed. At the coastal mill, the rules for knots were more leniently applied than at the interior mill. As most pieces were to be later trimmed to 4 foot lengths, large knots were overlooked if they did could be trimmed without reducing the recovery of Clear grade 4 foot pieces. This was not the case at the interior mill.

For both models, the frequency of knots was found to be the most important predictor of the proportion of Clear grade lumber. As knottiness increased, the Clear grade lumber percentage was predicted to decrease. This is not surprising, as a low knot frequency is a primary determinant of Clear grade lumber.

Various log dimension measurements were important predictors of Clear grade recovery in both models. For the coastal sample, proportions of Clear grade lumber were predicted to decrease with log length. For the interior sample, Clear grade lumber proportions were predicted to increase with the large end diameter and taper. The significance of these variables is most likely related to the section of the tree from which the log originated. The majority of clear wood tends to occur at the base of trees, where knots tend to be smaller and the time since branches were shed is longer. Each of the significant dimension variables would seem to describe this difference. Butt logs have larger diameters, contain more taper than logs from the upper stem and consequently tend to be cut into shorter lengths. The proportion of Clear grade lumber would therefore be expected to increase with diameter, taper and with decreasing log length.

For the coastal model, the proportion of Clear grade lumber was predicted to decrease as the width of the sound collar at the large end increased. This is also considered most likely a *de-facto* indicator of the stem section. Butt logs more often contain decay and shake compared with logs from the upper stem. Despite larger diameters, they are more likely to contain smaller collars of sound wood, particularly for logs from old-growth stands. The significance of these variables would suggest that future models should consider including the portion of the stem from which the log originated as a candidate variable.

The models to predict the proportion of Clear grade lumber explained very little of the variance in the datasets. The pseudo-R^2 values for the coastal (0.1174) and interior (0.0943) regions were very close to zero, showing that the candidate variables were only marginally better than an intercept only model. The models are therefore most useful for identifying the external characteristics that are important for grade recovery rather than as a predictive tool. While the external log features measured in this study were comprehensive, other log characteristics may have explained more of the variability in the data set. In northern hardwood species, the height-to-width ratio of a defect in relation to the log diameter at that point was found to best predict the defect depth (Shigo and Larsen 1969). Other measurements which may have explained more of the variability in the data include twist, out-of-roundness and spiral grain.

In reality, it is the internal log features that truly determine the potential lumber and grade recovery. Using external features assumes a correlation between the external and internal characteristics of logs. For other species, external features have been shown to be imperfect predictors of internal log characteristics. In yellow poplar (*Liriodendron tulipifera* L.), the correlation between external and internal defect characteristics was found to be related to the time since defect formation, with the relationship weakening as time increased (Thomas 2008). This would be expected, as a lack of surface knots in larger logs would not necessarily indicate a lack of internal knots. Due to the relative size and age of the logs used in this study, the external features would have likely only been weakly correlated with the internal properties. This likely explains the low pseudo-R^2 values obtained in the models to predict the proportion of Clear grade lumber. Models developed for logs from younger stands would be expected to explain more of the variability in the dataset.

There are often no external features to identify heart rot in western hemlock. Indian paint fungus and Annosus root and butt rot are responsible for the majority of heart rot in western hemlock (Allen *et al.* 1996, Kimmey 1964, Holsten *et al.* 2001). The point of infection of Indian paint fungus is through the living stubs of exceptionally small branches (Etheridge *et al.* 1972), while Annosus root and butt rot enters living trees via the roots of surrounding stumps. Typical features that identify decay, such as dead branches, rotten knots and scars are not present. Due to the age and lengths of logs sampled in this study, it is likely that some contained internal decay that was not visible at the ends, making it impossible to predict from the measurements made.

Due to the difficulty of predicting the internal characteristics of western hemlock logs, technologies that measure internal log properties may be the most promising approach to improve value recovery. Various technologies such as x-rays (Lindgren 1991), nuclear magnetic resonance (Chang *et al.* 1989), ultrasound (Sandoz 1996) and longitudinal stress waves (Ross *et al.* 1997) can measure internal log features including density, knot size and the stiffness of centre boards (Oja *et al.* 2001). In recent years, x-ray scanning has received much attention in the forest industry (eg. Lundgren and Jäppinen 1998, Oja *et al.* 2000, Oja *et al.* 2004, Nordmark and Oja 2004, Alkan *et al.* 2005, Froome 2007, Pirouz 2008). In the 1970's, computed tomography (CT) technology enabled three-dimensional images of the internal structure of objects to be created from a series of two-dimensional images. This led to vastly improved images and allowed the exact positioning of internal objects to be determined. Advances in computing and digital radiography technologies enabled the processing of x-ray images to occur in real-time, widening the applicability of x-ray technologies.

X-ray scanning has enormous potential to increase margins by identifying the best manufacturing facility for western hemlock logs. If up to 67% of the logs that are being used for pulp production can be milled at a profit (Chapter 3), accurately identifying these logs in the sort yard or woods would greatly improve the value recovery from the resource. X-ray scanning is widely used in European sawmills, where it has been found to improve the accuracy of log sorting, predictions of board grade and predictions of the total value of boards (Grace 1994, Lundgren and Jäppinen 1998, Oja *et al.* 2000, Oja *et al.* 2004, Nordmark and Oja 2004). For western hemlock logs, it would likely improve grading, merchandizing and log allocation decisions. It is yet to be widely used for optimal log breakdown decisions due to the high cost and slow processing speed of the multi-axis (3+) scanners required (Pirouz 2008). It also can not reliably detect defects such as rot, wet pockets and check with the accuracy required for optimal sawing pattern decisions (Pirouz 2008). In a simulated setting, it was found to improve the value recovery of sawing decisions by 17.8% for red oak (*Quercus rubra* L.) (Chang *et al.* 1999) and 6.2% for lodgepole pine and Sitka spruce (Orbay 2001). Due to the difficulty of predicting the internal properties of western hemlock logs, the benefits of x-ray scanning would likely be greater than found for other species. Further studies are needed to determine the potential benefits of using x-ray technology for western hemlock logs.

A simpler approach to lift value recovery from lower quality western hemlock logs would be increased log merchandizing. Shorter log lengths would increase the likelihood that internal decay was exposed at the cut ends, allowing grading and allocation decisions to be made with more certainty. Sawyers could be more confident in the quality of logs they were receiving and the demand for lower grade western hemlock logs would likely increase.

6. Conclusion

Models to predict the total volume of lumber and the proportion of Clear grade lumber were developed from the two log samples. Together, the models enable the prediction of potential lumber revenue. They identify the critical log features that are most related to lumber and grade recovery and provide a method to better sort logs based on expected value recovery.

The model to predict the volume of lumber recovery found that variables describing the solid wood volume, the thickness of the sound collar and the stage of decay of butt/heart rot at large end were significant. These variables support intuitive and previously demonstrated understanding of lumber recovery principles. Other variables tested, including region, did not to significantly improve the model predictions. While this may imply that regional differences of western hemlock are not significant, it more likely suggests that other sources of variability prevented the detection of more subtle effects on lumber recovery.

The lumber volume model gave nonsensical predictions for small logs, such as positive lumber recovery from logs with zero volume. This was a function of the linear model selected, which provided a good fit of the predominantly large logs sampled. The model should not be used for small logs.

Definitions of Clear grade lumber differed between mills, so regional models to predict the proportion of Clear grade lumber were developed. As the dependent variable was proportional, a logistic regression was used with a binomial probability distribution. For both regions, the frequency of knots was found to be an important predictor of the proportion of Clear grade lumber. Other variables describing log dimension, including length, diameter and taper were also found to be significant. These were considered most likely related to the portion of the tree from which the log originated. Butt logs would be expected to contain more clear wood than logs from the upper stem. Attributes more likely to describe a butt log, including larger diameter, more taper and a shorter length were found to increase the proportion of Clear grade lumber recovered.

The models to predict the proportion of Clear grade lumber explained little of the variance in the dataset. This was considered due a low correlation between external and internal log features which would have been exacerbated by the age and size of the logs used and the method of infection of the two main causes of heart rot in western hemlock. Techniques that better identify the internal properties of western hemlock logs will likely increase value recovery by improving grading, merchandizing and log allocation decisions. These include technologies that measure internal log properties, such as x-ray scanning and nuclear magnetic resonance, and increased log merchandizing.

The models developed will potentially enable some mills to better select logs that are likely to return a profit. The Kozek Sawmill buys some of its logs from a centralized sort yard in Revelstoke, which enables it to inspect logs prior to purchasing them. Tools that better identify which logs are likely to return a profit would enable such mills to make better informed purchasing decisions. Many mills in BC do not have this luxury and rely on the accuracy of log grading. The fact that in some parts of BC, many sawlog grades are being used for pulp production indicates that the existing log grading rules may no longer accurately reflect the needs of industry. A review of the economics of different manufacturing outcomes for all log grades and the key log characteristics relating to value recovery would be beneficial.

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CHAPTER 5. SUMMARY

1. Western hemlock's role in British Columbia's forest industry

Western hemlock is important to the future of British Columbia's forest industry. It is one of the most common species in the province, predominantly occurring on the western side of the Coastal Ranges where it is the single most plentiful tree species (BC Forestry Innovation Investment (FII) 2008). Log sales in British Columbia combine western hemlock with other species with similar attributes such as amabilis fir into the market group hembal, which is also known as hem-fir. Compared to its volume abundance, hembal generates a smaller proportion of value from log sales in British Columbia. From 2004 to 2008, hembal represented 11.0% of total volume of logs sold, but generated only 9.6% of total value (Figure 1-2) (Ministry of Forests and Range (MoFR) 2008). In the coastal region, hembal accounted for 44.4% of the volume sold but comprised just 27.8% of the overall value. This is a consequence of more logs being classified into lower quality grades (Figure 1-1), and equivalent grades commanding lower prices than other species such as western red cedar and Douglas fir.

A susceptibility to a range of defects results in a greater proportion of western hemlock logs being classified into lower quality grades than other species in British Columbia. Western hemlock is one of the least resistant species to stem decay in the world (Clark 1957, Scheffer and Morrell 1998). It is also common for the heartwood to become internally infused with water, leading to fibre separation (shake and check), warping, shrinkage and collapse, particularly after kiln drying (Hartley *et al.* 1961, Ward 1972, Josza *et al.* 1998). Hembal logs of equivalent grades generally command lower prices than other species. The increased costs associated with longer drying times and lower recoveries due to drying downgrades, as well as the increased likelihood of undetected internal defects are likely contributing factors (U.S. Department of Agriculture 2007, FII 2008).

Many hembal finished products also command lower prices than competing species in North American markets. A large proportion of hembal is used in the structural framing market, where it is commonly priced below competing species such as Douglas fir, spruce-pine-fir and southern yellow pine (*Pinus palustris* P. Mill.). This is most likely due to some of the adverse wood properties of western hemlock, such as a tendency to split after screwing, a variable sawing performance, a low decay resistance and a low treatability, making it a non-preferred species among North American builders (Kennedy 1995, FII 2008). In contrast, western hemlock has an even density, which gives it excellent turning, shaping, planing and sanding properties (Kennedy 1995, FII 2008), which would seem to make it better suited to shop and moulding lumber than structural framing.

Due to its abundance, improving margins for western hemlock will be important to the long-term success of British Columbia's forest industry. This will require a greater focus on value recovery, in particular identifying the highest potential economic return from logs. This potential would seem to exist for logs that are presently used to produce pulp. These logs generate little revenue and many of the log grades currently being used for pulp production were created for higher value products. By measuring lumber and grade recovery from these logs, we can determine the economic breakpoints at which the production of solid wood products becomes profitable and identify which logs are most likely to yield profitable returns.

2. Study overview

A total of 116 old-growth western hemlock logs were sampled from the interior and coastal regions of British Columbia. Detailed measurements of dimension and quality attributes were made, which enabled estimates of the volume of sound fibre in each log. The logs were then sawn at one of two sawmills with the aim of maximizing value recovery. The nominal dimension and grade of every piece of rough-green lumber recovered from each log was recorded. The remaining log volume minus a sawdust allowance was used to estimate the volume available for chips. Product prices were applied giving the estimated revenue for each log.

The margin of sawing each log was calculated. Assumptions about log and operating costs were based on relevant published information. Margins were calculated based on the range of products made: lumber only; lumber and Standard grade chips; and lumber and Premium grade chips. The cost and price breakpoints at which it became profitable to recover solid wood were calculated. The minimum lumber recovery threshold at which it became profitable to cut solid wood products was also determined.

The data were then used to develop models to predict the volume of recoverable lumber and the proportion of Clear grade lumber based on the measured log attributes.

3. Key findings

Considerably more lumber was recovered from the coastal logs, with 47.6% of the original firmwood volume recovered as rough-green lumber, compared with just 22.2% for the interior sample (Table 3-4). Variability between the logs sampled at the two locations was likely an important factor. The interior logs were significantly smaller and the effects of diameter on lumber recovery are well established (Steele 1984). The interior logs contained more defective wood as a proportion of total volume and the width of the collar of sound wood at each end was significantly less (Table 3-3). The logs were also significantly longer than those from the coastal region. Longer logs are more likely to contain additional defects that are not visible at the ends. This was likely exacerbated by Indian paint fungus, which is the most prevalent form of heart rot in the interior regions but is virtually nonexistent on the coast (Kimmey 1964). It is characterised by a lack of external indicators, making it practically impossible to detect without internal scanning devices. In the interior logs, this would have likely lead to a greater volume of undetected heart rot.

It can be profitable to recover solid wood products from western hemlock logs that are used for pulp production in British Columbia. For the coastal logs, producing lumber and Premium grade chips resulted in a $20.63 profit for each cubic metre of wood input (Table 3-10). Sawing these logs can also result in considerable losses. The interior sample would have been milled a loss regardless of whether chips were produced. These differences were primarily driven by a three-fold increase in lumber revenue from the coastal logs, due to a significantly higher recovery of Clear grade lumber.

At the coastal sawmill, between 60% and 67% of logs were milled at a profit, depending on whether chips were also produced. At the interior mill, between 13% and 21% of logs were milled at a profit. If a similar range of log grades are being used for pulp production in other coastal areas, there is likely a lot of additional added-value in the western hemlock resource that is not being captured. Accurately identifying these logs prior to grading, bucking and allocation decisions could significantly increase the value recovered from the resource.

To better identify logs which may be milled at a profit, models were developed to predict the total volume of lumber and the proportion of Clear grade lumber. Lumber volume was predicted to increase as gross volume and the width of the sound collar increased, and as the stage of butt/heart rot at the large end decreased. These results suggest that additional grading rules that account for the stage of rot at the large end are warranted. Regional models were developed to predict the proportion of Clear grade lumber. In both models, the frequency of knots was significant. The Clear grade lumber models explained relatively little of the variance in the dataset which was attributed to the difficulty of predicting the internal properties of western hemlock and the ages of the logs sampled. Techniques that increase the understanding of internal log properties, such as x-ray scanning and log merchandizing are considered the best way to identify the best manufacturing outcome for logs.

4. Contribution to the field of study

This research is a valuable addition to the western hemlock literature. While other studies have examined lumber recovery from western hemlock pulp logs in Alaska (Fahey 1983), this is the first known study of its kind in British Columbia. This is also the first known study that has considered western hemlock logs where defects rather than size were the primary cause of the pulp classification. The models to predict the volume of lumber and proportion of Clear grade lumber provide insight into the most important attributes for old-growth western hemlock logs.

5. Potential applications of research

It is hoped this work will enable more value to be captured from the western hemlock resource in British Columbia. The findings demonstrate that it can be profitable to recover solid wood products from some of the logs that are currently being used for pulp production. The models and the economic breakpoint analysis enable mills to identify logs with the potential for profitable lumber recovery. The lumber volume prediction model also suggests that additional grading specifications to account for the stage of butt/heart rot at the large end may be warranted.

The results are most applicable to sawmills that are suited towards value rather than volume recovery. The profits at the coastal mill were largely from the production of a high value product, in this case Clear grade wainscoting. Had the mill produced a lower priced commodity product, the results would have likely been different.

6. Potential for future research

While this study considered old-growth western hemlock logs, an increasing proportion of British Columbia's forest resource consists of second-growth stands. Due to shorter rotations, it is expected that decay, shake and check will be less prevalent in logs from these forests. Pulp logs from second-growth stands are more likely to exhibit defects such as sweep or to be below minimum size requirements. The challenges of profitably recovering solid wood products and the attributes related to volume and grade recovery will likely be very different to old-growth logs. A similar study focussing on second-growth pulp logs would be of value to the industry.

Considerable research has been conducted on x-ray technology for scanning internal log characteristics (Grace 1994, Lundgren and Jäppinen 1998, Oja et al. 2000, Oja et al. 2004, Nordmark and Oja 2004). Due to the size of the resource and the difficulty in predicting its internal properties, research that measures the benefits of x-ray scanning in western hemlock is needed. In the next decade, it is likely that this technology will be applied at different stages of the forest value chain. It represents one of the best methods to increase value recovery by improving the information available for grading, bucking and allocation decisions.

British Columbia's log grades were first established in the 1970's, and while they have been updated since, the advent of new products and markets for wood means that they may no longer satisfy the needs of industry. The log characteristics and grading criteria may not be best suited to maximizing the value recovery from the resource. An economic evaluation of all log grades and the key log characteristics relating to value recovery would be beneficial. Such a study should consider the potential margins from alternative manufacturing outcomes such as biofuel production.

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CHAPTER 6. APPENDICES

Appendix A – Candidate variables considered for regressions

Candidate Variable	Units	Variable Type
Large end diameter under bark	(cm)	Continuous
Small end diameter under bark	(cm)	Continuous
Length	(m)	Continuous
Taper	(cm/m)	Continuous
Gross Volume	(m^3)	Continuous
Estimated firmwood volume	(m^3)	Continuous
Volume of broken, damaged and missing wood	(m^3)	Continuous
Gross volume minus broken, damaged and missing wood	(m^3)	Continuous
Gross Volume minus broken, damaged, missing wood and minus sections affected by sweep, crook and pistol grip	(m^3)	Continuous
Area at large end containing butt/heart rot	(%)	Continuous
Area at large end containing ring rot	(%)	Continuous
Area at large end containing pocket rot	(%)	Continuous
Area at large end containing sap rot	(%)	Continuous
Area at large end containing shake	(%)	Continuous
Area at large end containing check	(%)	Continuous
Area at large end containing catface/bark seams	(%)	Continuous
Area at large end containing rot	(%)	Continuous
Area at large end containing butt/heart rot, shake and check	(%)	Continuous
Area at large end containing shake and check	(%)	Continuous
Area at large end containing check and catface	(%)	Continuous
Area at large end containing shake, check and catface	(%)	Continuous
Area at large end containing butt/heart rot, shake, check and catface	(%)	Continuous
Width of the sound collar at the large end	(cm)	Continuous
Maximum stage of butt/heart rot at the large end		Class
Maximum stage of ring rot at the large end		Class
Maximum stage of pocket rot at the large end		Class
Maximum stage of sap rot at the large end		Class
Maximum stage of decay at the large end		Class
Area at small end containing heart rot	(%)	Continuous
Area at small end containing ring rot	(%)	Continuous
Area at small end containing pocket rot	(%)	Continuous
Area at small end containing shake	(%)	Continuous
Area at small end containing check	(%)	Continuous
Area at small end containing catface/bark seams	(%)	Continuous
Area at small end containing shake, check and catface	(%)	Continuous
Area at small end containing heart rot, shake, check and catface	(%)	Continuous
Area at small end containing rot	(%)	Continuous
Area at small end containing shake and check	(%)	Continuous
Area at small end containing check and catface	(%)	Continuous
Width of the sound collar at the small end	(%)	Continuous
Total length containing knots	(m)	Continuous
Total length containing rotten knots	(m)	Continuous
Presence/absence of rotten knots		Class
Maximum knot size as a proportion of small end diameter		Continuous
Maximum knot size as a proportion of large end diameter		Continuous
Maximum knot size	(cm)	Continuous
Average area at both ends containing shake and check	(%)	Continuous

Candidate Variable	Units	Variable Type
Average area at both ends containing butt/heart/heart rot	(%)	Continuous
Region	(%)	Class
Area affected by butt/heart/heart rot at both ends	(%)	Continuous
Area affected by ring rot at both ends	(%)	Continuous
Area affected by pocket rot at both ends	(%)	Continuous
Area affected by shake at both ends	(%)	Continuous
Area affected by check at both ends	(%)	Continuous
Area affected by catface at both ends	(%)	Continuous
Area affected by rot at both ends	(%)	Continuous
Area affected by shake and check at both ends	(%)	Continuous
Area affected by shake, check and catface at both ends	(%)	Continuous
Area affected by defects at both ends	(%)	Continuous
Average width of the sound collar at both ends	(cm)	Continuous
Area at large end containing butt/heart rot	(cm^2)	Continuous
Area at large end containing ring rot	(cm^2)	Continuous
Area at large end containing pocket rot	(cm^2)	Continuous
Area at large end containing sap rot	(cm^2)	Continuous
Area at large end containing shake	(cm^2)	Continuous
Area at large end containing check	(cm^2)	Continuous
Area at large end containing catface/bark seams	(cm^2)	Continuous
Area at large end containing rot	(cm^2)	Continuous
Area at large end containing butt/heart rot, shake and check	(cm^2)	Continuous
Area at large end containing shake and check	(cm^2)	Continuous
Area at large end containing check and catface	(cm^2)	Continuous
Area at large end containing shake, check and catface	(cm^2)	Continuous
Area at large end containing butt/heart rot, shake, check and catface	(cm^2)	Continuous
Area at small end containing heart rot	(cm^2)	Continuous
Area at small end containing ring rot	(cm^2)	Continuous
Area at small end containing pocket rot	(cm^2)	Continuous
Area at small end containing shake	(cm^2)	Continuous
Area at small end containing check	(cm^2)	Continuous
Area at small end containing catface/bark seams	(cm^2)	Continuous
Area at small end containing shake, check and catface	(cm^2)	Continuous
Area at small end containing heart rot, shake, check and catface	(cm^2)	Continuous
Area at small end containing rot	(cm^2)	Continuous
Area at small end containing shake and check	(cm^2)	Continuous
Area at small end containing check and catface	(cm^2)	Continuous
Area affected by butt/heart/heart rot at both ends	(cm^2)	Continuous
Area affected by ring rot at both ends	(cm^2)	Continuous
Area affected by pocket rot at both ends	(cm^2)	Continuous
Area affected by shake at both ends	(cm^2)	Continuous
Area affected by check at both ends	(cm^2)	Continuous
Area affected by catface at both ends	(cm^2)	Continuous
Area affected by rot at both ends	(cm^2)	Continuous
Area affected by shake and check at both ends	(cm^2)	Continuous
Area affected by shake, check and catface at both ends	(cm^2)	Continuous