Operational Influences Affecting Sawlog Weight and Volume Relationships in the Intermountain West

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AUTHORIZATION TO SUBMIT THESIS

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ABSTRACT

Weight sampling has been used as an efficient measurement method to estimate log scale volume and assess mill inventory. In this thesis, I review past North American weight scaling research and identify areas for subsequent scientific investigation. In chapter three, I describe a field study designed to model sawlog moisture loss in Douglas-fir sawlogs on the University of Idaho Experimental Forest. Of variables considered, days since harvest, sawlog size, and vapor pressure deficit were the best predictors of stem moisture content. These results supported my hypothesis that sawlog moisture content affect weight scaled volume and value estimates. In the fourth chapter, net truckload weight, log small-end diameter, length, piece count, percent defect, and seasonal quarter were identified as significant influences on weight and volume relationships statewide. Species-level linear mixed-effects models were developed to predict net sawlog volume per truck based on a stratified random sample of 7929 loaded trucks sampled across Idaho.

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Chapter 1

Operational Influences Affecting Sawlog Weight and Volume Relationships in the Intermountain West

Introduction

Assessment of sawlog scaling volume through systematic weight scaling procedures in the western United States has expanded since the early 1990s due to increases in product utilization at sawmills, and decreases in mean sawlog diameter. Sample weight scaling practices involve developing weight-to-volume (W:V) relationships to reduce scaling costs and increase efficiency while maintaining accuracy (Donnelly and Barger, 1977; Dicke and Parker, 1999; Fonseca, 2005). These conversions are derived from conventional stick scaling of delivered sawlog loads in combination with measuring load net weight, in order to establish W:V relationships employed on future loads that are only weighed. Traditional scaling methods require each delivered sawlog to be measured using established methods (Freese, 1973), in order to determine gross and net volume for inventory purposes. The Scribner Decimal C short-log scaling rule is the most commonly applied log rule in the Intermountain West, USA. The application of systematic weight scaling has been used widely in the southern USA pine market (Dicke and Parker, 1999). However, distinct regional variations in seasonal precipitation and temperature, elevation, harvest region, and species composition have slowed the integration of weight scaling in Northern Rocky Mountains (Fonseca, 2005). Benefits of weight scaling, particularly for sawlogs, are reduced truck turn-time at mills, and reduced scaling costs associated with conventional scaling methods which requires 100% scaling of delivered product. Also, the process of weight scaling accounts for the entirety of the delivered product. This adjustment occurs in a market where product utilization is maximized to include wood chips and sawdust (unaccounted for in conventional scaling, which only assesses the board foot volume within logs).

Because much of the research associated with weight scaling and establishing weight to volume relationships in sawlogs has been limited to the southeastern United States, or has occurred in proprietary industry studies (Kia and Shupe, 2005), more research is needed to better identify and characterize the factors affecting weight and volume relationships. These benefits may include production of more accurate inventory and log supply assessments (Page and Bois, 1961; Dicke, 1999; Fonseca, 2005). Since the initiation of weight scaling, multiple methods, procedures, and variations have been developed to establish regional relationships for specific wood markets. Investigation into the significant weight scaling factors including species, harvest region, climate, and scaling data could help to generate more reliable assessments of sawlog volume purchases or sales.

Although research has highlighted many factors affecting the W:V relationships developed, few studies have moved beyond analysis of operational scaling data as a means of analyzing these relationships (Taras, 1956; Donnelly and Barger, 1977; Van Deusen et al., 1981; Markstrom and King, 1993). Seasonal climate variation can also affect stem moisture content and drying rates after harvest (Page and Bois, 1961). A challenge for the implementing the operational use of weight scaling in mountainous regions is the proper identification of variables that are directly connected to the environmental variation associated with forestlands (Guttenberg et al., 1960). Increased emphasis on weight scaling methods for volume exchange and inventory purposes could help to better quantify these conversion relationships, their sensitivity, and the potential effects of climate on W:V. Quantifying weight to volume relationships at statewide spatial scales will provide new information to help managers.

The earliest application of weight scaling focused on measuring water displacement due to loaded logs on cargo ships traveling between the eastern and western US coasts (Brereton, 1925). The total volume of loaded logs was closely and positively correlated to the changes in buoyancy because the draft of more heavily loaded ships was lower. However, with limited access to accurate log truck sized weighing scales, the process of weight scaling truckloads remained a scarce process until the late 1940s. With a relatively high initial financial investment for the construction of weighing stations, many sawmills used portable systems that assessed truck weight on log landings prior to on-board truck scales (Lange, 1962). The first use of W:V factors for converting between the weight of green wood with bark and its volume applied cords as the unit of measure (Schumacher, 1946). Later studies identified log length, diameter, and moisture content as factors affecting pulpwood weight (Taras, 1956, 1967; Swan, 1959; Page and Bois, 1961; Yerkes 1966, 1967). The relationship between board foot volume and sawlog weight using traditional log scaling rules can be quantified through regression analysis to determine the variation among multiple truckloads

(Guttenberg et al., 1960; Bower, 1962; Row and Guttenberg, 1966; Donnelly and Barger, 1977).

The first accurate and consistent use of weight scaling outside of the southeastern United States included both net load weight and log count as components in determining volume for ponderosa pine (*Pinus ponderosa*) (Donnelly and Barger, 1977). Stratifying truckloads by species, region of origin, and site characteristics have been shown to improve consistency in weight scaling procedures (Schumacher, 1946). Conversion factors for specific log rules, such as Doyle and International ¼" have been constructed based on average small-end diameter (SED) (Van Deusen et al., 1981). Additional factors for improved regression models include logs per load, average log length, and moisture loss (Markstrom and King, 1993). While use of weight scaling as a method to assess log volume is increasing, application to certain forest product markets remains limited (Timson, 1974; Adams, 1976). High value products, including certain species of hardwoods, utility poles, and western redcedar (*Thuja plicata*) products remain too valuable and subject to stringent guidelines to be measured through weight scaling.

Research Objectives

The research objectives of this research were to: (1) improve our understanding and application of weight scaling practices in commercial softwood markets of the western United States; (2) determine the effects of harvesting systems, stem size, and bole moisture content on weight scaling practices; (3) improve our understanding of how species, region, and environment influence the fine scale accuracy of weight scaling practices in Idaho, and (4) assess the potential impacts that weight scaling systems may have on different valued forest products. In the following section, each thesis chapter is described in detail, including the experiments and modeling used to evaluate each objective.

Chapter Summaries

The primary research focus involved characterizing W:V relationships of sawlogs in Idaho, through advancing our understanding of factors influencing weight scaling practices, and applying that knowledge to quantify approaches for increasing accuracy of the resulting products. Furthermore, the research presented develops, tests, and evaluates mixed-effects regression models for characterizing W:V relationships in sawlogs affecting weight scaling practices in the state of Idaho.

Chapter two is a literature review of the historical development and application of weight scaling. This review covers the successful introduction of weight scaling practices into the forest products industry, relative to traditional log scaling practices. While the focus is derived from past research, the chapter identifies knowledge gaps and develops future research needs to continue the growth and accuracy of weight scaling.

Chapter three describes a designed, factorial field experiment to evaluate the effects of harvesting method, environmental conditions, and stem size on the moisture content of felled Douglas-fir (*Pseudotsuga menziesii*) sawlogs. The study was located on the University of Idaho Experimental Forest in northcentral Idaho **(**46° 50’05.15” N / 116° 50’25.19” W)**.** The selected stand consisted of a mature, closed canopy Douglas-fir (*Pseudotsuga menziesii*) stand in the West Hatter Creek Unit (WHC), 15 km northeast of Moscow, Idaho. The southern aspect study site lies near the western edge of the Palouse Range. The Palouse Range contains a mixture of second-growth conifers. The forest stands in the range are distributed across a topographically complex landscape and, consequently, a diverse range of habitat types (Cooper et al., 1991). On this study, tree coring data was collected during July, 2013 to observe changes in moisture content from felled sample trees. The site allowed for the investigation of how stem size, harvest method, and environmental factors affect bole moisture content after felling and subsequently affect weight scaling conversion factors.

The secondary objective of Chapter three was to determine the influence of stem moisture content on weight scaling conversion relationships. The moisture content of heartwood and sapwood in the felled stems of 30 Douglas-fir trees was sampled on alternate days over a four-week period, in order to model total saw log weight change associated with moisture loss.

Chapter four describes a large, statewide experiment evaluating the relative importance of region, species, log small end diameter (SED), truck load piece count, and season on the weight to volume relationship of Idaho sawlogs, using data collected from 7929 truckloads of sawlogs sampled from 2011-2013.

The study area for the analysis conducted in Chapter four was comprised of the entirety of the Idaho Department of Lands ownership, specifically timber harvest units active from 2011-2013. State owned lands are divided into 11 supervisory areas which were included with the exception of the Eastern supervisory area. This land compilation contains many softwood sawlog species including Douglas-fir *(Pseudotsuga menziesii),* western larch *(Larix occidentallis)*, western hemlock *(Tsuga heterophylla),* grand fir *(Abies grandis),* western redcedar *(Thuja plicata)*, ponderosa pine *(Pinus ponderosa),* and lodgepole pine *(Pinus contorta).* The harvest units ranged from 400-2100 m in elevation. Monthly average temperature ranged from -8.7°C in January to 24.7°C in August with yearly precipitation variations of 0-312 mm across the state. The sample loads collected were representative in size to the annual harvest volumes of each supervisory district.

Mixed-effects regression models were used to model truck volume as a function of weight and other predictors. While the project data was obtained from the Idaho Department of Lands scaling offices, an original data collection method was created to continue specialized data collection over time, in order to ensure long-term updates and improvements of weight scaling conversion factors.

Each thesis chapter has been formatted for journal submission. Chapter two is in preparation for submission to *The Journal of Extension* with Dr. Robert F. Keefe, Dr. Randall H. Brooks, and Dr. Leonard R. Johnson as co-authors. Chapter three has been submitted to *Forests* with Dr. Robert F. Keefe, Dr. Randall H. Brooks, Dr. Leonard R. Johnson, Dr. Wade T. Tinkham, and Dr. Alistair M.S. Smith as co-authors. Chapter four is in preparation for submission to *The Forest Products Journal* with Dr. Robert F. Keefe, Dr. Randall H. Brooks, and Dr. Leonard R. Johnson as co-authors.

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Chapter 2

Development and application of commercial weight scaling in western North America

Abstract

Log scaling is a necessary and prevalent part of the forest products industry. Used to quantify production, assess inventory, and quantify the output of finished products as the basis for financial transactions, log scaling practices can have a large effect on the profitability of transactions among landowners, logging contractors, and mills. Decreases in average log size and increases in the volumes of wood scaled at mills in recent decades in western North America have led to a transition toward faster and more efficient methods for assessing log volume than conventional scaling that is both accurate and consistent. The practice of weight scaling logs, coupled with sample scaling methods that establish loaded truck weight to volume relationships, has grown beyond its original roots in pulpwood production and is quickly becoming a common method of sawlog volume determination at mills across the North America. Using weight scaling in connection with a sample scaling process or establishment of regionalized conversion factors can reduce use of board foot log rules that are known to have bias, as well as providing greater accuracy and consistency in predicting volume estimates of forest products.

Introduction

The trade of commodities is dependent on sellers and buyers agreeing on mutually acceptable units of measurement for quantities of purchased goods. In forestry, this exchange has traditionally been based primarily on the volume of the product in question. In order to ensure the equity of volumes and values associated with purchasing and selling of sawlogs, common systems of product evaluation have been adopted. Log scaling is the process through which quantity and quality of various forest products are estimated and recorded (Bauer and Hogan 2006). Typically expressed as cubic or board foot volume, log scaling is not a new process. However, scaling methods have become more refined as values associated with sawlogs have risen. Over the past 200 years, traditional volume scaling in North America has evolved with regional variations associated with three predominant methods, or *log rules*. These rules were developed to predict product output from various combinations of length and diameter of logs delivered to mill facilities. Log scaling provides a method for applying consistent rules to the many potential combinations of log size, taper, and defect. In spite of its importance and financial implications for forestry and forest products industries, current scaling procedures are subject to a variety of environmental (e.g., regional growth forms, fungal pathogens, etc.), managerial (e.g., size distributions, species mixtures, etc.), and human-induced errors in the measurement process (Fonseca 2005). While each scaling rule provides accurate estimates for log volumes within specified diameter ranges, each also operates under a system of limitations. Changes in the average sizes of harvested sawlogs over the past century have diverged from the log sizes that many scaling rules were designed to accommodate. In an attempt to fill the voids associated with traditional board foot volume scaling, the method of weight scaling logs through establishment of weight to volume conversion factors specific to species, region, diameter, length, and other variables has shown the potential to provide an efficient and consistent prediction of volume output (Fonseca 2005; BC Ministry of Forests, Lands, and Natural Resource Operations 2011). Weight scaling is based, in part, on current stick scaling procedures. However, when deployed as part of a process that includes sample and check scaling of truckloads of sawlogs, increased efficiency gains are possible. Through the identification and accounting of a combination of environmental and procedural factors, weight scaling provides an opportunity to establish a clearer concept of product exchange in less time, thus improving the overall efficiency the timber supply chain.

Scaling History

The origins of log scaling stem from the 19th century, when traveling scalers would migrate between U.S. logging camps measuring and assessing values and volumes of decked logs prior to transport to mill facilities (Hopkins 1982; Bell and Dilworth 2002). These scalers largely went unchecked and utilized only partially similar techniques to predict expected outputs from felled timber. With advances in technology in the 20th century, greater quantities of logs were transported farther distances, leading to a need for more widely accepted methods of determining log volumes (Daniels 2005). Thus regional log rules were established to help log scaling systems meet the desired level of accuracy and consistency. The adoption of scaling in mill yards and other centralized locations was followed by the formation of check scaling boards and log rule advisory groups in the early

20th century (Freese 1973). These organizations, while responsible for constructing and recording regional log scaling rules and regulations, became involved with the process of check scaling to ensure consistency for all logs scaled regionally at the close of the 19th century and forward through the 20th century. Log scaling rules fall into two categories, diagram rules and mathematical rules. Both rule types are predicated on producing board foot volume predictions from measured logs. However, board foot rules that estimate only the lumber contained within a log overlook the potential use of waste sawdust and chips, which are important by-products in today’s forest economy (Briggs 1994). The most common and widely used log rules today in the United States and Canada are the diagram-based Scribner log rule, the mathematically based Doyle and International ¼ log rules, and the cubic log rule.

Developed by J.M. Scribner, the fourth edition of the Scribner log rule was published in 1846, although the original date of its first publication is unknown. The Scribner rule is predominantly used in the western United States (Bell and Dilworth 2002) and is based upon predicting the number of one inch boards that can be cut from a circle of a given diameter. The boards are separated by an assumed ¼ inch (.63 cm) saw kerf, and the rule is based on the small end diameter of each scaled log. In turn, the Doyle and International ¼ log rules, used in southeast and northeast United States were developed from mathematical formulas using volumetric equations of a cylinder. From the calculated cylinder, deductions are made for defect, kerf, and slabs to derive a usable volume. Issues arise with the Scribner method because of its inconsistency for predicting volume output across diameter classes, as well as poorly accounting for taper. Several regional taper rules were later built into the log rule; however assessing log volume from the small-end diameter (SED) does not overcome the issue (Bauer and Hogan, 2006). Log segments under 16 feet (4.9 m) in length and 28 inches (71.1 cm) in diameter scale consistently. However, as log segments increase, the rule produces estimates with increasingly larger over-runs (Belyea 1931; Freese 1973). Log over-run occurs when the amount of lumber recovered is greater than the predicted volume from scaling (Bauer and Hogan 2006). A modification of the Scribner rule which rounds all final values to the nearest 10 board feet, originally designed in 1900 by the Lufkin Rule Company, has become the most commonly used form of the rule today. The rounding rule is referred to as the Scribner Decimal C system. This modification can also be applied to other rules. While individual rounding of log segments introduces minor errors, the potential for inaccurate inventory figures becomes prominent over large volumes of logs (Freese 1973). Distinct from other current rules, the Scribner log rule is separated into two rules based on location. Scribner Short Log is used in the interior western United States and contains a maximum scaling unit length of 20 feet (6 m), while Scribner Long Log which is used in the coastal western United States allows a maximum 40 (12.2 m) foot scaling unit. The adjustments to the Scribner Log Rule are designed to better account for regional taper characteristics (Fonseca 2005).

To account for inconsistencies in diagram methods, mathematical log rules were developed to control bias and better account for variability within individual logs. The results included the International ¼ rule, Doyle log rule, and more recently the cubic log scale. The Doyle rule has grown to be one of the most widely used and criticized log rules still used today (Dicke and Parker 1999). The first published edition of Doyle's rule (Equation 1) was in 1825, but was not adopted into common practice until roughly 1870 (Freese 1973; Bell and Dilworth 2002).

$$\text{[Equ. 1] } bf = (SED - 4)^2 \times length \div 16$$

The Doyle log rule was initially accepted due to its easy application and basic formula (Husch et al. 2003). The rule produces estimates of log volume in board feet (bf), where SED is the log's small-end diameter in inches and length is measured in feet, with no common procedures for determining the log's diameter, length, and taper (Fonseca 2005). To account for kerf and shrinkage, the Doyle rule reduces the volume of each scaled cant by 25 percent to achieve the gross scale volume (Husch et al. 2003). While Scribner loses accuracy as diameter and length increase, Doyle produces its largest over-run on small logs (Briggs 1994; Bell and Dilworth 2002; Fonseca 2005). In a study investigating the scaled volumes of 10 inch (25.4 cm) diameter, 16 foot (4,8 m) long log segments, the Doyle estimate under predicted the International ¼ rule by 40%. Producing far higher levels of over-run in smaller diameters however is offset by Doyle's constant under-run in estimates as log diameters increase beyond 25 inches (63.5 cm) (Freese 1973).

To counter complaints and discrepancies with Scribner's inconsistency and concerns with the Doyle rule, the International ¼ rule was developed in 1906 by Judson Clark (Avery and Burkhart 2002). The International rule was the first widely used rule to attempt to account for log taper, applying a fixed standard of 1/2 inch (1.3 cm) deduction in diameter per 4 foot (1.2 m) log section. The rule also allowed for pre-determined kerf and slab widths. Originally devised for 1/8 inch (.3 cm) kerf allowance, the adjustment to 1/4 inch (.63 cm) was made due to a lack of mills being able to meet the 1/8 inch requirement with saws of the time. Additionally, the rule accounts for potential product loss in shrinkage, trimming, and edging through pre-determined and assumed reductions (Bell and Dilworth 2002). The volume reduced from each board sawn constitutes 15.8 percent of each 4 foot scaled cylinder (Husch et al. 2003). The combination of addressing taper, saw kerf, assumed product loss, and operating with cylindrical volume has made the International ¼ rule a widely used and prominent log rule in today's forest products industry in the central and eastern North America.

Building where the International ¼ rule left off, the cubic log scale was encouraged as early as the 1920s. Although the method was not formally encouraged until 1991 in the United States, scaling logs with the cubic log rule has been in use by land owners and mills across the United States and British Columbia for many years (Fonseca 2005). The rule in its various forms has gained in popularity, a response to its accurate results and detailed methods. Cubic log scaling produces volume outputs determined from predominantly Smalian's formula (Equation 2) and recorded in either ft.^{3} or 100 ft.^{3} referred to as a cunit. Additional cubic formulas include Huber and Newton's rules, but are only scarcely implemented. Cubic scaling is accurate because the method accounts for taper, defect, merchantability, and total log volume, a combination not found in other methods. The entire volume of a delivered sawlog is valued in cubic scaling, an important factor in the current forest products industry which focuses on multiple yields and products from a given sawlog resulting in no loss from kerf or slabs (Keegan et al. 2010). Other log rules only predict board foot volume output and do not assess the entirety of the log. In comparing the most common log rules, International ¼ shows the most consistency throughout increasing diameter classes, but ultimately failed to overtake regional favor of the Scribner or Doyle rules outside of the North and northeastern North America.

Growth of Weight Scaling

As technology improved the industry's ability to mill ever smaller diameter logs and harvest volume increased during the 1920s, the volume scaled at mills increased (Daniels 2005). This change led to the need for more accurate and consistent practices became apparent weight scaling emerged as a potential alternative to traditional labor intensive methods (Briggs 1994). Weight to volume relationships were developed to provide quick estimates of products, offering comparable accuracy with greater efficiency. The concept of buying and selling forest products by weight is not a new idea (Avery and Burkhart 2002). Bernard John Stephen Brereton is credited with the first conceptual application of weight scaling in his 1921 edition of *The Practical Lumberman* (Fonseca 2011). The increase of accuracy and consistency combined with creating a safer working environment by removing scalers from busy log landings and mill yards offered a quality alternative (Muller 1958; Guttenberg 1967). In addition, comparisons between Doyle, International ¼, and Scribner were difficult to make. Their different formulas and methods of accounting for taper and kerf result in predicted outputs that are individually unique. The most consistent volume to weight relationships were formed from estimates of cubic foot volume derived from Smalian's formula (Equation 2) (Spelter 2004). However, cubic foot scaling was slow to catch on, producing a need for a way of universally determining log volume across regions from weight.

$$\text{[Equ. 2] } V_c = [(B_s+B_l)/2](L)$$

V_c= predicted cubic volume

B_s= Cross-sectional area of small-end of log

B_l= Cross-sectional area of large-end of log

L= Length of log

The first use of weight scaling was the displacement method to determine log volumes onboard ships traveling between the eastern and western American seaboards (Brereton 1925). Developed initially for log rafts, the method was later applied to measuring the change in water level against a ship's hull as logs were loaded for transport. The volume of logs could be directly and positively correlated with the change in the water level as the ship became heavier and sat lower. However, without access to large weight scales, commercial weight scaling remained scarce until the late 1940s. While mills with weight scales were initially limited, portable platform scales were developed to weight trucks in the woods prior to on-board truck scales (Lange 1962). Eventually factors were produced for converting between the weight of green wood with bark and its volume in cords (Schumacher 1946). Later studies demonstrated the influence that log length, diameter, and moisture content had on weight when buying pulpwood (Taras 1956; Swan 1959). Further investigations analyzed the close connection between board foot volumes and the weight of sawlogs (Guttenberg et al. 1960). Through regression comparisons of truckload data, Bower (1962) observed positive, high correlation between weight and volume and the homogeneity of measured logs. Extending the measured variables of weight to volume conversions, heartwood to sapwood ratios and wood density were included to improve regression analysis results (Yerkes 1966). The first computer program formulas used to collect and process weight factor information used a geometric formula to determine total log weight in relationship to common log rules such as Doyle's (Row and Guttenberg 1966). Similar computer program manuals were developed and conversion tables distributed, with each offering slightly adjusted figures (Tyre et al. 1973). These advancements helped weight scaling spread quickly throughout the south in the 1960s due to its accuracy and convenience. The accuracy and equations predicting volume from weight and other factors are shown in Table 1. The culmination of early weight scaling studies occurred when computer programs were developed, fitting sample loads into a formula including pieces per load, to develop consistent weight conversion factors (Guttenberg and Fasick 1973). This advance allowed mixed-species loads to be weight scaled as two factor levels that could be applied to the species-specific piece counts within a given load. With the evolution of scale accuracy and sample scaling protocols, weight scaling became favored for its elimination of scaler bias, efficiency, and encouragement of prompt delivery to the mill (Taras 1967).

The first accurate and consistent use of weight scaling outside of the southeastern United States included both net load weight and load log count as components in determining volume for southwestern ponderosa pine (*Pinus ponderosa)* (Donnelly and Barger 1977). Donnelly and Barger (1977) noted that while each weight scaling occasion was unique, there were guidelines that could reduce the overall error involved in the process (Donnelly and

Barger 1977). Stratifying truckloads, by species, region of origin, and site characteristics has been shown to improve consistency in weight scaling procedures (Schumacher 1946). Specific conversion factors concerning notable log rules like Doyle and International ¼ were constructed at Mississippi State University where it was found that average small-end diameter (SED) was the most significant factor for predicting volume using weight to volume conversion factors (Van Deusen et al. 1981). Additional factors found to improve the regression models included logs per load, average log length, and moisture loss (Markstrom and King 1993). By accounting for species, defect percentage, scaling rule, and wood storage time they were able to increase the strength of the weight to volume predictive relationship (Markstrom and King 1993). While use of weight scaling as a method to assess log volume is increasing, application to certain forest product markets remains elusive. High value products, including certain species of hardwoods, telephone poles, and cedar products remain too valuable and subject to stringent guidelines to be measured through weight scaling. In addition, extensive load variation in hardwoods due to stem characteristics requires more loads to be sample scaled in order to establish weight to volume conversion factors with narrow confidence intervals (Timson 1974; Adams 1976). Today, however, over 97% of interior British Columbia, Canada’s sawlogs are weight scaled on a sample basis, with comparable statistics in the southern U.S. pine regions (BC Ministry of Forests, Lands, and Natural Resource Operations 2011).

The pulp and paper industry in southern Georgia made the first concerted move toward the use of weight scaling during the 1960s (Daniels 2005). Due to the homogeneity of softwood sawlogs in the southeastern United States, this region was the primary source of published weight scaling research over the 20th century (Table. 2). The uniformity of pulpwood made it an ideal product for weight scaling. Greater variability in sawlog volumes resulted in a slower adoption of weight scaling by sawmills. Variations in species, season, moisture content, ratio of heartwood to sapwood, and taper made it difficult to establish consistent weight to volume relationships. Regional variability of factors like specific gravity of wood affects log weight. For example, specific gravity of coastal Douglas-fir (*Psuedotsuga menziesii)* varies from .36 to .54 and Western Hemlock (*Tsuga Heterophylla)* varies from .34 to .50 (Hoadley 1990; Bowyer et al. 2007). Variation in seasonal moisture content can also affect weight to volume relationships as much as 32 percent in some species

(Marden et al. 1975). The combination of log moisture loss and subsequent changes to specific gravity has a significant effect on weight to volume relationships (Page and Bois 1961). The most accurate and consistent method for estimating weight factors and their fluctuations due to the environment is to weigh representative samples (Briggs 1994). The ability to understand and properly apply a system for determining specific gravity of wood from varying moisture contents is important for gauging the effect of water on weight to volume relationships (Simpson 1993). Changes to wood composition and structure dramatically affect final weight to volume relationships, including the presence of defected or damaged wood within a log segment. Where traditional scaling procedures make a diameter, length, pie, or squared volumetric deduction resulting in gross and net volume board foot tallies to account for defect, the reduced weight of defected wood is harder to account for in weight scaling (Fonseca 2005).

Factors Affecting Scaling

Water is present in most living organisms, including trees. In the xylem tissue of the bole of live or recently harvested trees, water commonly makes up over half the total green weight (Bowyer et al. 2007). Water in recently felled trees is located in both the cell wall and the cell lumen. Changes in moisture content of sawlogs of 5 percent in green wood decrease wood weight by 1 to 2 pounds per cubic foot (Page and Bois 1961). This variation in weight from moisture content is most evident in standing dead or beetle kill harvested trees in the Rocky Mountain region. The lighter dead wood requires greater volumes to obtain weight capacity on trucks and can lead to situations of inefficiency for contractors paid by weight when fully loaded trucks remain below legal weight limits. Seasonally, the quantity of moisture within the cell wall essentially remains constant; however, the portion of water within the cell lumen may vary (Lothner et al. 1974). Alternative studies have shown that moisture percentages in standing trees can also vary with location (Besley 1967; Nylinder 1967; Husch et al. 2003). The loss of water from trees is one of the most important processes influencing variability in conversion factors in weight scaling that may result from the season of harvest or the time logs remain on the ground or in decks prior to scaling (Yerkes 1967; Lothner et al. 1974).

Issues associated with traditional volume scaling methods such as Scribner, cubic foot, Doyle, or International ¼ originate from tendencies of these methods to over- or under-estimate volume in either the low or high tail of the log diameter range, and varying human error between scaling locations. The majority of the smaller diameter logs harvested today do not reflect the log sizes that the U.S. regional scaling rules were originally designed around. In addition, most traditional scaling practices are based upon estimating board foot volume, and either disregard the slab and kerf portions of log volume, or account for slab and kerf volume in ways that are inconsistent with modern mill equipment. Slabs and saw kerfs, which formerly served little purpose, are now chipped and utilized as a secondary product. The use of weight scaling accounts for the entirety of each log, reflecting the amount that is now used. Diagram-based methods such as Scribner's log rule also increase in discrete increments, whereas weight and cubic scaling methods result in smooth, continuous response functions. The process of weight scaling also promotes safety in the workplace by reducing the amount of scalers needed in the scaling yard to scale incoming loads (Guttenberg 1967). While incorporating a more accurate stick scaling method will greatly improve weight scaling conversions, the traditional practices currently installed will grow increasingly inefficient in handling the growing volumes of harvested sawlogs delivered daily. Weight scaling fulfills all objectives of log scaling beyond those of traditional stick scaling in part due to its consistency, efficiency, and relative to volume scaling, comparatively low cost.

Disadvantages with weight scaling and use of weight to volume conversion relationships exist, but can be accounted for statistically. Whereas a predetermined formula of volume assessment is applied to a large number of combinations of log shapes and sizes, each variable used to determine predictive weight to volume relationships can be accounted for at regional levels to help increase the accuracy of prediction. Weight to volume relationships can vary greatly by species, specific gravity, seasonality, heartwood to sapwood ratios, weather conditions, and time between harvest and weighing, which ultimately affects moisture content (Briggs 1994; Avery and Burkhart 2002; Fonseca 2005; BC Ministry of Forests, Lands, and Natural Resource Operations 2011). Prior literature suggests that log moisture content is a significant predictor of log weight (Yerkes 1966). Comparing the amount of time after cutting to moisture content identified the rate of moisture loss in ponderosa pine (*Pinus ponderosa*) sawlogs (Yerkes 1967). Decreasing the amount of time between cutting and weighing will limit the variability in moisture content of sawlogs and increase the correlation between weight and volume (Martin and Simard 1959; Besley 1967; Nylinder 1967). Accounting for sawlog defect and residual weight, such as bark and external debris (e.g. soil) is also important when scaling by weight. While log defect has been shown to not be a statistically significant factor when predicting volume from weight, the effects of bark and foreign material may be more variable (Yerkes 1966). In contrast, bark has been found to consist of between 9 and 19 percent of pulpwood logs after processing in the forest (Hardy and Weiland 1964). While the effects remain minimal in the U.S. southern pine region, seasonal and monthly changes in log moisture content have been identified as significant factors affecting weight to volume relationships in the aspen forests of Minnesota and northwest forests of Washington (Marden et al. 1975; Briggs 1994).

Local to regional variability in weight to volume relationships due to terrain topography, aspect, and species variation requires sampling to develop predictive regression equations. However, through the correct application of measurements and monitoring, robust conversion methods can be developed. To provide consistency throughout the weight scaling process, a system of sample scaling can be employed to account for the regional, species, and seasonal characteristics that affect weight factors. Determined prior to harvest operations and adjusted according to stand homogeneity among other specifications, sample scaling consists of stick scaling a set ratio of loads delivered in order to personalize weight to volume conversions. Common ratios of 1:5 or 1:10, allow weight conversions to be continuously updated through scaling 1 in every 5 or 10 delivered truckloads. This continual updating process helps limit variations encountered from defected logs as well as regional and seasonal variations. Harvest stand inventory data can also determine whether multiple conversions are needed to account for species variation within a stand. Dealing with issues of salvaged or highly defected timber, which go undetected in pure weight scaling are factored in sample scaling the same way. Identification of unique stand characteristics can affect the sample ratio and alter the weight to volume relationship to directly reflect the quality of the delivered product. Additionally, the practice of delivering sorted truckloads can also help to refine weight to volume relationships. The relationship between Scribner Decimal C and weight has a large amount of variation in all species, ranging as much as

5,200 to 13,500 lb. per thousand board feet (mbf) for Douglas-fir *Psuedotsuga menziesii* in western Oregon (Paxson 1944). Beyond sample scaling, the accuracy of weight to volume conversions equations also depends on the volumetric standard used. There are many advantages to weight scaling, but overcoming the inherent biases and inconsistencies in log rules is not one of them. For example, due to its consistent increase and volume determination based on the entirety of a log, weight to cubic foot scaling conversion relationships prove more accurate than weight to board foot volume conversions (Yerkes 1966). Implementation of cubic foot scaling can lower the number of sample scale loads to produce accurate conversions by half when compared to the Scribner log rule (Markstrom and King 1993). With high initial investment costs weight scaling in combination with sample scaling may not appear worth it. However, the long term benefits of fewer scalers, increased truck turn time, and less landing congestion provide a better alternative to traditional 100 percent scaling practices.

Differences in species physiology, tree taper, and combinations of species in mixed-species loads are important sources of variability in the development of weight to volume conversion equations. Physiological changes in tree structure occur between U.S. regions, among trees of varying ages, and in relation to stand and site characteristics (Meinzer et al. 2011). The ability to accurately predict volume of multiple products by weight has been accomplished by (Guttenberg and Fasick 1973; Amateis et al. 1984). However, the variations within the individual products are still difficult to assess. Weight scaling is most efficient when truckloads consist of single species and uniform logs (Husch et al. 2003). In order to increase the accuracy of weight to volume conversion factors, data are often stratified into separate categories, including species, season, and location. Tables have been constructed to determine these differences in weight relationships based on log diameter and length (Mann and Lysons 1972). However, weight scaling has generally not been deployed for use with certain products, such as hardwoods in the northeastern U. S. and cedar poles in the western U.S., because of the high variability in value associated with these materials (Trimble, 1965; Fonseca, 2005). Additional studies also reported density as a factor of log diameter and species (Schumacher 1946; Taras 1956; Guttenberg et al. 1960). Tree densities are not only affected by diameter and species, but also heartwood to sapwood ratios within a log (Yerkes 1966). The death of cells and transformation into heartwood follows cell wall thickening and results in increased densities of heartwood when compared to softwood (Bowyer et al. 2007). Continual development of sample scaling methods will help improve the accuracy and efficiency of weight scaling, ultimately providing a strong alternative to pure traditional volume scaling and a defensible, objective measurement method that logging contractors, landowners, and mills can agree on.

Conclusions

The process of accurately estimating log volume in specific product quantities such wood chips, and dimensional lumber is a difficult task (Amateis et al. 1984). Not only are there many combinations of log size, heartwood to sapwood ratios, moisture contents, species, and regional and seasonal differences, but tree physiology also changes as trees age (Meinzer et al. 2011). To increase their potential for financial success, foresters, logging contractors, and mills have always looked for methods to improve efficiency of their operations. The growth and evolution of the industry are evident in weight scaling, both from the advancement of new techniques and through simplification of a complex system. While much of western North America continues to report harvest volumes in either board of cubic measurements, the method of obtaining volume harvested is predominantly founded on applications of weight scaling through sample scaling. The use of sample scaling offers accountability for the driving factors affecting weight scaling, adjusting as loads change based on characteristics of each harvested stand. The process of sample scaling can also be improved greatly through stratifying weight to volume relationships. Identifying weight to volume relationships by season, species, and region among other factors can supply small variation when compared to using more general relationships encompassing wider perspectives. While the initial investment in weight scaling far exceeds implementation of updated or new scaling rules such as the cubic foot rule, weight scaling has shown to positive results over time. Weight scaling is only as accurate as the scaling method used in combination; however the increases to log yard efficiency, including truck turn time, decreased congestion, and fewer scalers remain greater than current scaling procedures and mill practices. While the benefits for weight scaling blanket mills, land owners, and logging contractors, each group redeem the benefits differently. Estimation of weight to volume relationships through representative, replicated studies can help mills to improve efficiency in volume estimation. Increasing the understanding of specific regional factors that affect weight relationships such as moisture content and loss over time could encourage broader applications of weight scaling. Current forest practices of harvesting salvaged beetle kill and burned timber makes grasping moisture loss in sawlogs more important. Weight scaling of logs through the establishment of weight to volume conversion factors specific to species, region, diameter, length, and other variables has shown potential to better predict volume output more consistently than traditional volume scaling (Lothner et al. 1974; Donnelly and Barger, 1977).

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Table 1. Equations for predicting sawlog volume and their respective R^2 values.

Study	**Species**	**Scaling Rule**	**Equation**	$\mathbf{R^2}$
Guttenberg, Fassnacht, Siegel (1960)	southern pine	Doyle	$V_T = W_T + W_T^2 + L_T + (W_T L_T) + (W_T^2 L_T) + SG_T + M_T$	.97
Row and Guttenberg (1966)	southern pine	Doyle	$V_T = W_T + (W_T N_T)^{1/2} + (W_T N_T L_T)^{1/2}$	.98
Row and Guttenberg (1966)	southern pine	International ¼	$V_T = W_T + (W_T N_T)^{1/2} + (W_T N_T L_T)^{1/2}$	.99
Yerkes (1966)	ponderosa pine	Cubic Ft.	$V_T = W_T + SED_T + D_T$	.97
Guttenberg and Fasick (1973)	southern pine	Doyle	$V_T = W_T + N_T + (W_T N_T)^{1/2}$	.78
Donnelly and Barger (1977)	ponderosa pine	Scribner	$V = W_T + N_T + (W_T N_T)^{1/2}$	.51-.73
Van Deusen, Watson, and Evans (1981)	southern pine	Doyle	$V_T = MSED_T (W_T) + MLED_T (W_T)$	.92
Van Deusen, Watson, and Evans (1981)	southern pine	International ¼	$V_T = MSED_T (W_T) + MLED_T (W_T)$	.96
Markstrom and King (1993)	ponderosa pine	Cubic Ft.	$V_T = W_T + N_T$	.51-.61
Markstrom and King (1993)	ponderosa pine	Scribner	$V_T = W_T + N_T$	.33-.59

$\mathbf{V_T}$ = Predicted truckload volume (net cubic feet or net mbf)
$\mathbf{W_T}$ = Net Truck Weight (Tons)
$\mathbf{N_T}$ = Number of logs per load
$\mathbf{L_T}$ = Average Length of logs per load
$\mathbf{SED_T}$ = Average Small End Diameter of logs per load
$\mathbf{MSED_T}$ = Maximum Small End Diameter of logs per load
$\mathbf{MLED_T}$ = Maximum Large End Diameter of logs per load
$\mathbf{D_T}$ = Average Percent of Defect of logs per load
$\mathbf{SG_T}$ = Average Specific Density of logs on load
$\mathbf{M_T}$ = Average Moisture Percent of logs per load

Table 2. Prominent weight scaling research denoted by study location, species, and product volume predicted.

Study	Location	Species	Scaling Product
Taras (1956)	Southeastern, USA	southern pine and hardwoods[1,2]	Pulpwood
Guttenberg, Fassnacht, Siegel (1960)	Arkansas, Louisiana	loblolly pine, shortleaf pine	Sawlogs
Page and Bois (1961)	Georgia	shortleaf pine	Sawlogs
Row and Guttenberg (1966)	Georgia, Virginia	southern pine and hardwoods	Sawlogs
Yerkes (1966)	South Dakota	ponderosa pine	Sawlogs
Guttenberg and Fasick (1973)	Southeastern, USA	southern pine	Sawlogs
Tyre, Fasick, Riley Jr., and Lege (1973)	Southeastern, USA	southern pine	Sawlogs, Pulpwood
Lothner, Marden, and Kallio (1974)	Minnesota	aspen and black spruce	Pulpwood
Donnelly and Barger (1977)	Arizona	ponderosa pine	Sawlogs
Van Deusen, Watson, and Evans (1981)	Mississippi	loblolly pine	Sawlogs
Amateis, Burkhart, Greber, and Watson (1984)	South Carolina	southern pine	Sawlogs, Pulpwood
Donnelly and Barger (1977)	Arizona	ponderosa pine	Sawlogs
Markstrom and King (1993)	South Dakota	ponderosa pine	Sawlogs

[1] Common southern pine species associated with weight scaling are slash pine (*Pinus elliottii*), loblolly pine (*Pinus taeda*), shortleaf pine (*Pinus echinatai*), and longleaf pine (*Pinus palustris*)

[2] Common hardwoods sampled in early weight scaling studies included red oak (*Quercus rubra*), white oak (*Quercus alba*), sweetgum (*Liquidamber styraciflua*), and cypress (*Taxodium distichum*)

Chapter 3

Effects of harvesting systems and bole moisture loss on weight scaling of Douglas-fir sawlogs (*Pseudotsuga menziesii*)

Abstract

Characterizing the moisture loss from felled trees is essential for determining weight-to-volume relationships in softwood sawlogs. Several factors affect moisture loss, but research to quantify the effects of bole size and harvest method is limited. This study was designed to test whether bole size, harvest method, and the associated changes in stem moisture content of felled Douglas-fir (*Pseudotsuga menziesii* var. *glauca* Franco) affected the W-V relationship of sawlogs. Thirty trees in three sizes classes (12.7-25.4 cm, 25.4-38.1cm, 38.1-50.8 cm) were felled and treated with one of two harvesting processing methods. Moisture content was sampled every two days for four weeks**.** Results show greater moisture loss in the crowns of stems that retained limbs after felling compared to stems with limbs were removed after harvesting. Additionally, moisture loss rate increased as stem size decreased.

Introduction

Since the 1960s, weight scaling of sawlogs for volume based transactions has developed into a widely applied method used by forest industry across North America [1-2]. Interior British Columbia uses weight scaling to scale 97% of its harvested timber [3]. Developments in timber harvesting techniques and lumber production processes, such as improved supply chain procedures and mechanized machinery, have increased harvest efficiency and retrievable products [4]. In order to meet the growing demand for increased forest products while reducing scaling costs for mills, a systematic random sample of trucks arriving at the mill is often used to determine truck weight-to-volume (W-V) relationships. The process of weight scaling, however, relies heavily upon regional knowledge of wood characteristics and seasonal trends to accurately estimate harvested volumes [5].

Water content is among the many variables associated with W-V relationships affecting sawlog inventory [6]. Stem moisture content in weight scaling systems has been found to be significant in southern hardwoods and not significant in some mid-western softwood sawlogs studies at the alpha = 0.05 level [2, 7**].** Sap flux density and thus log moisture vary spatially within stems, commonly peaking towards the outer edges in the radial direction and declining toward the heartwood, leading to different moisture contents between heartwood and sapwood [8- 9]. For softwoods, the moisture content of heartwood is typically considerably lower than for sapwood [10-11]. Variation in canopy conductance has also been related to stem size and environmental variables including relative humidity, temperature, soil moisture, and soil temperature [12]. Additional studies have identified seasonal patterns associated with stem moisture content of pulpwood [13]. Previous studies have explored similar methodologies for measuring bole moisture loss of softwoods [14-17]. Producing common trends of moisture loss related to season and the presence of tree crowns. Results have shown faster moisture loss immediately following felling, with trees that have intact crowns losing more moisture over the study duration. However, these studies are characterized by small sample sizes and narrow sample diameter ranges. Additionally, no previous work has explored current operational logging practices and its connections between the observed moisture loss and weight scaling practices using mixed-effects models which account for correlations among subsequent moisture measurements on the same subject logs. Although decreasingly common in the northern Rocky Mountain region, operational practices that have been the focus of past research, such as sour-felling and floatation of logs for transportation purposes provide insight into understanding changes in wood moisture content for weight scaling [18]. For example, sour felling works to encourage moisture loss in harvested stems in an effort to increase the amount of volume that can be transported on each truckload [19-20]. Reducing transportations costs to lower biomass moisture content can also provide increased energy yields in forest products burned for energy [20]. This process also increases the buoyancy of logs for transportation through floatation [18]. However, while increased moisture loss benefits harvest operations based on volume based transactions, it negatively impacts profit margins of operations using weight based transactions by removing a source of profit in the bole moisture content and subsequently total stem weight. Additionally, fuel moisture content studies have modeled stem moisture changes and rates based on stem size; limitations of such approaches have included the coarse temporal-resolution of samples (weekly) and that key information such as time since felling (i.e. proportion of dead and green stems) is often not included in the regression models [21-22].

Douglas-fir (*Pseudotsuga menziesii*) is one of the predominant species of the forests in the interior Pacific Northwest [23]. The water stored in standing timber is progressively reduced by as much as 50% in sapwood during the summer season, relative to the reduced winter draw down or reduction of sapwood moisture content [24-25]. The relationship between reduced moisture content in the sapwood of felled timber and the ratio of stem W-V is not well understood [26-28]. Log buyers and land appraisers are challenged with accurately establishing the value of standing timber; but either stumpage or mill-delivered log values must incorporate changes to value that result from felling, processing, and delivery practices. Improved knowledge of the uncertainties in mapping moisture loss within softwood sawlogs with respect to current operational harvesting practices is needed to better understand potential changes to scaled product and ultimately profit margin.

The objective of this study was to determine the effects of harvesting method, bole size, and environmental factors on moisture content of felled Douglas-fir sawlogs. In keeping with the concept of seasonal bole water storage and draw-down [13, 29], we hypothesized that stemwood moisture content would be affected by relative humidity. While we also expected that larger stem size and cut-to-length harvesting would retain more moisture, we also hypothesized that additional environmental factors such as soil moisture and stem ground contact would not significantly affect changes in moisture content. However, we also expected alternative environmental factors such as atmospheric temperature, relative humidity, and vapor pressure deficit (VPD) would be significant in changes to the moisture content. Moisture loss observed with respect to the measured variables will help determine the impact of moisture loss on weight scaling practices.

Methods

2.1 Site description

The research site was selected to represent high potential evapotranspiration using a southern aspect in late summer in order to provide longer radiation exposure to the felled samples. The mature, closed canopy Douglas-fir stand was located in the West Hatter Creek unit (WHC) of the University of Idaho Experimental Forest in north-central Idaho (46° 50’05.15” N / 116° 50’25.19” W). The WHC unit is located 15 km northeast of Moscow, Idaho, on the north slope of the Palouse Range (Figure 1). The Palouse Range is a heterogeneous mosaic of second-growth mixed conifer forest stands distributed across a topographically complex landscape and, consequently, a diverse range of habitat types [30]. The stand was predominantly Douglas-fir, but scattered Grand fir (*Abies grandis*) was also present in the understory at less than 20 trees per hectare. The sampled stems showed no visible signs of defect or loss of structural integrity. The site reflected a shelterwood stand following the study treatments. Within the sample area, stems were randomly spaced and mixed between size classes, with canopy cover conditions similar for all sample stems. The site featured the expected seasonal and environmental conditions, including low precipitation and average daily temperatures associated with the time of year (Table 1).

In addition to gathering gravimetric moisture content, we also collected relative humidity [+/- .5%], soil moisture [+/- 0.03 m^3/m^3], soil temperature [+/- 1 °C], air temperature [+/- 1 °C], and precipitation [+/- .1mm] throughout the study. The environmental measurements were collected using a Decagon EM50 data logger, Decagon 5-TM soil moisture and temperature sensors, Decagon ECRN-100 high resolution rain gauge, and Hygrochron ™ Ibuttons. Ibuttons are small (1 cm diameter) battery-powered temperature sensors that can be deployed with inexpensive radiation shields to record surface air temperature [31]. Data was collected continuously over the duration of the study at 15 minute intervals. The data was then structured to represent daily means. Through combining the factors of atmospheric temperature and relative humidity both vapor pressure deficit and adjusted degree days were calculated. Vapor Pressure Deficit (VPD) was calculated by taking the difference in saturation vapor pressure and actual vapor pressure [Equ.1]. Degree days were determined by assessing the daily high temperature (C°) and calculating the difference from 0° C [Equ. 2]. The inclusion of VPD and degree days offered greater ability to assess variation in daily moisture change during the study. VPD was calculated using the formula expressed in [32].

[Equ. 1] $$\boldsymbol{SVP = 0.611 * \exp\left(\frac{17.3*T}{T+237.3}\right)}$$

$$\boldsymbol{AVP = \frac{RH}{100} * SVP}$$

$$\boldsymbol{VPD = AVP - SVP}$$

SVP = Saturation Vapor Pressure

T = Atmospheric Temperature C°

AVP = Actual Vapor Pressure

RH = Relative Humidity (%)

VPD = Vapor Pressure Deficit

[Equ. 2] $Degree\ Days = T_{max} - 0°\ C$

T_{max} = Daily maximum temperature C°

2.2 Tree measurements

Co-dominant Douglas-fir trees with complete crowns and free of noticeable signs of injury or disease were selected by diameter at breast height (DBH, 1.37 m) to represent the size range of sample selected. A total of 30 trees were chosen and separated by three size classes of 12.7 cm intervals (Table 2). The diameter classes represent commercial sawlog sizes ranging from lower end merchantability standards to the larger limitation of conventional mechanized felling equipment. Samples were felled according to two treatment types representing harvesting systems commonly applied in the northwestern United States. Ground based harvesting systems comprise a large portion of the timber annually harvested in North America. Within the ground based category, independent procedures and operations are adjusted depending on machinery availability and contractor preference. Two of the most prominent methods are cut-to-length harvesting and whole tree harvesting which vary when and where the felled trees are processed for transportation to mills.

Samples identified as treatment 1 were felled and immediately processed into sawlogs, which included removing all limbs manually with a chainsaw. This method represented a cut-to-length harvesting system where trees are processed at the stump. Samples identified as treatment 2 were felled and left intact. The process of felling-only and leaving the bole with limbs intact represented a whole-tree harvesting system. Trees were sampled every other day for a period of 4 weeks. The cores were collected using a 5.15mm diameter increment borer (Haglöf, Sweden). After felling, all stems were measured for height using a steel tape [Feet, 1/10^{th}] and relative proportion in contact with the ground. Ground contact percentage was measured by dividing the length of the stem in contact with the ground by total stem length. Previous studies have assessed field wood moisture content with samples containing some portion of ground contact [33] and alternative research where samples were suspended above the ground [34]. The establishment of ground contact percentage helped to identify the potential effect of soil temperature and moisture on adjusting stem moisture content.

To avoid broken cores or sampling in close proximity to prior cores, grids of each sampling location were identified and each sampling point was separated by 7.62 cm in all directions from other sample points. After the completion of drilling charts on each stem, cores were taken randomly from each sample location throughout the study. In order to better characterize potential vertical variability along the bole, trees were sampled at two locations on each stem. The lower core sample was taken at 1.37 m from the base of the tree established prior to felling, and the upper sample was taken at the mid-point of the crown. The upper stem sample locations averaged diameters of 15.7, 18.5, and 24.1 cm respectively for the 12.7 – 25.4**,** 25.4 – 38.1**,** and 38.1 – 50.8 cm size classes. For each sample removed, heartwood and sapwood were separated using a razor blade. During analysis, total stem moisture content was derived by accounting for the heartwood to sapwood ratio of from each sample location. Samples were immediately placed into air-tight, pre-weighed plastic bags and placed in an environmental container. The heartwood-sapwood barrier was determined visually. In the laboratory, samples were weighed within three hours of collection and an initial weight was recorded with the samples still in bags. The predetermined bag weight was then subtracted and samples were dried according the ASTM International Standards for drying wood to obtain moisture content [35]. After drying, samples were reweighed and percent moisture content of each sample was calculated as the mass of water in the sample divided by the potential maximum value of water in the sample, often considered determining moisture content on a green basis. [Equ. 3] [36]. Similar processes using Equation 3, or variations on it, have been implemented in previous studies exploring mositure content of surface fuels in fire models [33,34].

[Equu. 3] $$\mathbf{MC} = \frac{\mathbf{M_g - M_{od}}}{\mathbf{M_{od}}} \mathbf{x100}$$

MC = Wood moisture content (%)

W_g = Green weight of wood (pounds or kilograms)

W_{od} = Oven-dry weight of wood (pounds or kilograms)

2.3 Statistical Analysis

All statistical analysis was completed using R [37]. A series of one way ANOVA tests were used to evaluate the significance of days since harvest, treatment type, size class, and sample stem location. To further understand the influence of size class, treatment type, and sample stem location, Tukey's HSD test was used to evaluate interactions between these variables ($\alpha = 0.05$). From the ANOVA analysis a series of linear mixed-effects model were developed using the significant variables and also days since harvest, VPD, RH, soil moisture content, soil temperature, atmospheric temperature, and percentage of ground contact for each felled log segment to test the H_o that size class, and environmental factors have no affect on stem moisture content of felled sawlogs. Within the model analysis, sample trees were treated as random variables to reduce the magnitude of temporal effects and limit the influence of standard error across the study days. All models were tested using a similar form to: $Y(mc) = \beta_0 + \beta_1$ Days Since Harvest + β_2 Size Class + β_3 VPD + β_4 (1|tree) + u. Akaike's Information Criterion (AIC) test was run to assess which model performed the best in predicting stem moisture content over the study duration. AIC evaluates the statistical quality of a model in comparison to others by balancing goodness of fit against model complexity [38], were individual AIC values are unit less and non-meaning without other model values to compare against. When comparing between model AICs, lower values indicate better fitting models [39]. In the case of negative reported values it is the highest negative value that identifies the best model. The delta AIC (Δi) statistic is commonly used to assess the statistical difference between competing models and is calculated as [40, 41] [Equ. 4].

[Equ. 4] $$\Delta AIC_i = AIC_i - \min(AIC)$$

Where AIC_i is the value for an individual competing model and min(AIC) is the minimum AIC value among tested models. The AIC and R^2 values from the model were derived from conditional R^2 and AIC procedures established in Nakagawa and Schielzeth, 2013 [42].

Results

Moisture loss was recorded from the point of harvest through the duration of the study, a period of four weeks, with ANOVA showing that only size class by itself showed significant influence on moisture loss. In testing the interactions between the variables, Tukey's HSD identified significant differences in moisture loss when looking at interaction within size class and between size class and treatment type and also sample location and treatment type (Table 4). Within the smallest size class (12.7-25.4 cm) 58% of the stem moisture content was lost during the four weeks compared to 34% in the largest size class (38.1-50.8 cm) (Figure 2). The interaction between whole-tree harvesting with size class accelerated moisture loss over the rates observed in the cut-to-length harvest system (Table 3). The effect of treatment type on stem moisture loss was also significant when looking at sample location within the stem (Figure 3 and Table 3), with upper stem locations treated with cut-to-length harvesting losing moisture significantly slower than stems treated with whole-tree harvesting. This supported our hypothesis that leaving the limbs on felled stems would provide greater surface area and increase evapotranspiration potential from each stem. The change in stem moisture content slowed as average atmospheric relative humidity (RH) and stem moisture content drew closer later in the study (Figure 4). Although stem heartwood moisture content was lower to begin with, mean heartwood moisture content experienced less loss than the mean sapwood moisture content over the study period, losing an average of 42% compared to 62% (Table 4).

Different combination of size class, treatment type, VPD, RH, days since harvest, soil moisture content, soil temperature, atmospheric temperature, and percentage of ground contact for each felled log segment, and the significant interaction terms were used within the linear mixed-effects model analysis. This rigorous analysis approach has not been previously applied to predicting moisture loss of harvested sawlogs, were each sample tree is utilized as a random variable to account for influences in standard error between sample days. The application of a linear mixed-effects model recognized the interaction between sample days through using each sample tree as a random variable. Model evaluation using the AIC test showed the strongest model to be Model 3: $Y(mc) = \beta_0 + \beta_1$ Days Since Harvest + β_2 Size Class + β_3 VPD + β_4 (1|tree) + u (Table 5). The inclusion of treatment type nor RH by themselves did not improve the models fit enough to overcome the added model complexity (Table 5). Model 3 used the covariates days since harvest, harvest treatment, and VPD combined to explain 82% ($R^2 = 0.819$) of the total variability in the bole moisture content of the sampled stems (Table 6). The identification of these variables supported the hypothesis that size class and environmental factors would significantly affect predicting stem moisture content, which declined with increasing time after harvest. In contrast though when including soil temperature, soil moisture, and stem percentage in contact with the ground there was no significant influence on stem moisture content of the harvested sawlogs. However, the model containing the interaction term of size class*treatment type provided the second best AIC result. This result supports the intention of AIC whereby goodness of fit and model complexity are evaluated to identify the model with the best statistical quality.

Past studies using procedures established by Burnham and Anderson, 1998 utilized the ΔAIC to also explore alternative model configurations [39-41, 43]. Calculation of the ΔAIC [Equ. 4] has been shown to interpret the statistical difference between competing models [39-41, 43]. While Model 3 provides the best balance between fit and complexity of the models compared, Model 5 had the second best AIC and arguably the inclusion of size class and treatment type interactions carries greater implications for management prescriptions. The ΔAIC between Model 5 and Model 3 is small enough (<10) to suggest there is moderate difference between the alternative model and Model 3. Utilizing this consideration as well as operational importance with current management shifts towards younger harvesting rotations and increased commercial thinning where stems contain greater crown ratio, further investigation of Model 5 was conducted. Model 5 explained a higher proportion of variation in the response variable based on R^2 (0.849 Model 5 vs 0.819 Model 3).

The individual effects of days since harvest, size class*treatment, and VPD are shown in Table 6 using size class 1, treatment 1, and their interaction as the base treatment in the model. After determining that the interaction of size class and treatment type was significant, Tukey's HSD test was evaluated and showed significant difference between the upper stem portions of treatment 1 and treatment 2 at the alpha = .05 level (Table 7). The effect of treatment type on stem moisture loss was also significant when size class was not included in the analysis (Figure 4). The greatest difference between treatment types occurred in the mid-crown sample location, resulting in stems treated with cut-to-length harvesting losing moisture significantly slower than stems treated with whole-tree harvesting. This supported our hypothesis that leaving the limbs on felled stems would provide greater surface area and increase evapotranspiration potential from each stem. Moisture loss was also different between stem size, while there was no significant difference between stem sample locations at the base and crown of each tree (Table 7). Increases in stem diameter resulted in decreased moisture loss, providing evidence in support of the study hypothesis. The moisture loss of stems in the whole tree harvesting treatment was faster and therefore the stem lost greater moisture amounts throughout the study.

We further predicted that soil temperature, soil moisture, and stem percentage in contact with the ground would not affect stem moisture content of the harvested sawlogs. This proved accurate as the variables soil temperature (p=0.815), soil moisture (p=0.644), and ground contact percentage (p=0.417) were not significant at the alpha = 0.05 level. Predicting sawlog moisture content using a generalized linear mixed effects model provided the best fit. While the moisture content loss was significant when comparing stem size regardless of treatment, the impact of the loss is much greater when viewed within the context of active logging operations. The results showed whole tree harvesting stems averaged lower moisture content over the duration of the study than cut-to-length.

Discussion

In support of our hypothesis that stem size would affect the moisture content in felled Douglas-fir, we saw significant correlation between stem moisture content and stem. The greatest amount of moisture loss was observed in the days immediately following harvesting. In addition, the majority of the moisture lost was contained in the sapwood compared to the heartwood, indicating that the majority of each tree's pre-treatment moisture was located primarily in the sapwood. The best model identified by the AIC test included the variables days since harvest, size class, and VPD. However, in accordance with previously published research, the second best AIC model was also evaluated. This model included an interaction term between size class and treatment type. The AIC model with the smallest number should be considered the best overall, the limited difference between the first two models (<10) supports using the second best model when operationally prudent.

Studies looking at seasonal changes in live tree stem moisture have reported a range of results, including increased sapwood moisture content during the growing season [27, 44]. In contrast, several studies show increased stem moisture content in winter months [7, 13]. While the standing, seasonal moisture content of conifers fluctuate by region and species, the moisture content of felled trees exhibits variability. The large quantity of water lost suggests that even under alternative seasonal conditions, the effect of harvest system and time between harvest and delivery could prove significant when working in a weight scaling system. Tree age and size can affect wood characteristics and in turn water storage capacity [45].

The effect of stem size on moisture content over time from this study is consistent with conventional fuel moisture models used to characterize 1,000 and 10,000 hour fuel moisture content. These rates classify the time needed for moisture to change 1/3 of the way towards equilibrium moisture content. While these rates prove efficient for fire predictions and fuel modeling, they contain general practices that reduce their effectiveness when applied to weight scaling. For example, they do not account for the time a given species has been dead or downed. In addition, the percentage of bark cover is not identified and base moisture contents for 1000-hour fuels are averaged over 7 day periods.

We found that harvesting and processing of sawlogs affects log moisture content, and that the results depend on sawlog diameter. Because moisture content directly affects sawlog weight, the relationship of W-V, and thus log value, would be affected when using weight scaling systems that do not account for these variables. As identified in the results, stems harvested using whole-tree harvesting system with limbs remaining on the stem after harvesting and prior to processing showed greater moisture loss than stems harvested using cut-to-length harvesting, where processing occurs at the stump and logs are limbed and bucked to length immediately. While the harvest method was important in our study, significant moisture loss occurs in each scenario. In practice, operators may modify practices to minimize loss, depending on which system is being deployed and what current environmental conditions are at the time of harvest. For example, in the current study, 38.1-50.8 cm. sawlogs lost an average of 34% moisture content from each log over a one month period after harvest, regardless of harvest system. Assuming a truckload contains 24,500 kilograms, roughly matching state averages and legal highway limits, a 34% moisture content loss would result in 4.16 metric tons of lost water weight or 17% loss in total truckload value if paid using a weight basis system. Current industry weight-to-volume relationships for Intermountain West Douglas-fir during the 3rd seasonal quarter are 5.51 tons/mbf or 2.33 tons/m^3. A 17% loss in weight would shift the ratio to 6.39 tons/mbf or 2.71 tons/m^3. This increase in weight-to-volume ratio could impact the financial productivity of landowners and contractors. Converting between Scribner board foot to cubic volume was derived from [46]. While the very dry, warm conditions during the study may have increased moisture loss, moisture loss was present in all felled trees and should be considered operationally.

Altering harvesting practices to change bole moisture content and improve profit margins greatly depends on the scaling unit employed. Losses in moisture content are viewed negatively when associated with transactions based on weight. However, loss in bole moisture content has long been sought out when product transactions are based on mbf or cubic meter volume. Methods such as ‘sour felling’, which consists of whole tree harvesting followed by transpirational drying to allow moisture loss, have been applied in efforts to increase loaded truck net volume per load [16]. While effective, these practices encourage increased defect in harvested product in the form of checking, insect infestation, and staining [17]. The increase in volume per load profit can be counteracted in the subsequent loss of usable product; retaining the idea that sour felling is best applied when working with pulpwood or woody biomass where profit margins are limited and defect is less important [14, 16, 17, 47]. Sour felling practices are also applicable in harvesting systems where floating logs is used for transportation or storage purposes. Decreases in the bole moisture content result in increased buoyancy for periods of storage or transportation. Log storage in water, when properly executed, reduces checking, insect activity, and staining of logs [48]. Ultimately, the perception of harvesting method and bole size on moisture loss in sawlogs is considered with direct relation to the unit of volume measure. With western United States scaling practices shifting towards increased transactions through weight scaling, long standing notions of moisture loss in felled sawlogs must be adjusted accordingly in order to maximize profit margin.

Beyond environmental factors present during drying, bark cover and thickness is often assumed to influence drying rates [49-50]. When investigating moisture content of branches however, [51] did not find drying to be significantly faster in bark-less branches. In contrast, Nicholls and Brackley, 2008 [52] identify bark as a barrier to moisture loss. This is supported by Defo and Brunette, 2006 [53] who found that the stem drying rate of aspen is proportional to the percentage of bark absent. Bark is reported to make up 10 to 25 percent of the over-bark volume and weight of a tree [54-55]. Therefore, depending on location and season, bark can prove to be beneficial or costly to the forester or contractors [56]. The simulated processing techniques for the current study were completed using chainsaws as opposed to machinery, leaving the majority of the stem bark intact. This alteration from expected seasonal and operational bark loss from machine processing limits the understanding of bark influence on moisture loss in this study.

While the species characteristics are relevant in mapping stem moisture loss rates, local environmental conditions drive changes to solid wood moisture content. The combination of low relative humidity, high mean daily temperatures, and limited precipitation on the southern aspect provided an extreme setting for moisture loss. The long-term effect of seasonal relative humidity in a region will cause non-living wood to fluctuate with a delayed lag time until equilibrium with the environment is reached. The rate of drying increases with the difference between relative humidity and stem moisture content at the time of harvesting. In order for foresters and contractors to understand and adapt to the variability in sawlog moisture content when working with weight scaling systems in mountainous terrain, sawlog size, harvesting method, and atmospheric conditions present must be considered.

Conclusion

The maximum moisture loss occurred in both the smallest size class and stems in the whole-tree harvesting system. The greatest moisture content variation and subsequent moisture loss also took place in the sapwood portion of the stem. With these results, we reject the null hypothesis that harvested stem moisture loss was unrelated to bole size and harvest system of felled Douglas-fir trees. Trees felled and left intact with limbs proceeded to show increased moisture loss versus stems that were felled and immediately processed into sawlogs. Additionally, we predicted that the moisture content during late summer would not be significantly affected by stem ground contact percentage or soil characteristics, and the results supported that prediction. Consistent with the concept of evapotranspiration, stem moisture content is best predicted by a combination of VPD, stem size, and harvest system. The probable reason for changes in the moisture content variation among treatment types is the increased surface area present of trees containing limbs and foliage. The effect of stem size on moisture content was also likely driven by the reduced amount of external energy required to extract moisture from a smaller object. These findings suggest that understanding the implications of seasonal harvests exposing harvested timber to strong climatic and environmental conditions can significantly alter expected results from areas utilizing weight scaling practices.

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Table 1. Site characteristics during study duration.

	University of Idaho Experimental Forest
Longitude/Latitude	46° 50’05.15” N / 116° 50’25.19” W
Elevation (m)	892
Total study precipitation (mm)	3.1
Mean study temperature (°C)	21.3
Temperature range (°C)	8-39
Slope, aspect	17%, Southern
Mean daily vapor pressure deficit (kPa)	2.58
Mean daily relative humidity (%)	47
Relative humidity range (%)	10-84
Mean soil temperature (°C)	16.7
Mean soil moisture content (%)	7.6

Table 2. Characteristics of the Douglas-fir trees sampled for stem moisture content loss rate.

	12.7 – 25.4 cm	25.4 – 38.1 cm	38.1 – 50.8 cm
No. of trees Sampled	10	10	10
Mean Diameter (cm) at 1.37 m	20.0	32.5	44.7
Diameter range (cm)	14.7-25.4	26.4-38.1	41.1-49.2
Mean height (m)	18.4	24.2	28.0

Table 3. Results of Tukey's HSD test to determine ad hoc differences in bole moisture content between size classes, stem sample location, and treatment type.

Significance Test	p-value
Size Class	
size class 1 – size class 2	.0053
size class 1 – size class 3	<.0001
size class 2 – size class 3	<.0001
Stem Sample Location	
upper – lower	.8214
Treatment Type	
treatment 1 upper – treatment 1 lower	.9857
treatment 1 lower – treatment 2 upper	.0166
treatment 1 lower – treatment 2 lower	.0155
treatment 1 upper – treatment 2 upper	.0008
treatment 1 upper – treatment 2 lower	.0422
treatment 2 upper – treatment 2 lower	.9999

Table 4. The beginning and ending stem moisture contents of all sample stems regardless of size separated by heartwood and sapwood.

	Mean Starting (%)	Mean Ending (%)	Mean Loss (%)
Sapwood MC	116	54	62
Heartwood MC	67	25	42

Table 5. The results of AIC testing to determine the significant model variables.

Model	Form	AIC
1	$Y(mc) = \beta_0 + \beta_1$ Days Since Harvest $+ \beta_2$ (1|tree) + u	-620.86
2	$Y(mc) = \beta_0 + \beta_1$ Days Since Harvest $+ \beta_2$ Size Class $+ \beta_3$ (1|tree) + u	-697.40
3	$Y(mc) = \beta_0 + \beta_1$ Days Since Harvest $+ \beta_2$ Size Class $+ \beta_3$ VPD $+ \beta_4$ (1|tree) + u	-710.42
4	$Y(mc) = \beta_0 + \beta_1$ Days Since Harvest $+ \beta_2$ Size Class $+ \beta_3$ VPD $+ \beta_4$ TRT $+ \beta_5$ (1|tree) + u	-688.17
5	$Y(mc) = \beta_0 + \beta_1$ Days Since Harvest $+ \beta_2$ Size Class*TRT $+ \beta_3$ VPD $+ \beta_4$ (1|tree) + u	-702.17

Table 6. The regression values of a generalized linear mixed effects model assessing moisture content of felled stems using Treatment 1 as the base treatment.

Model – Y *log*(mc) = β_1 Days Since Harvest + β_2 Size Class + β_3 VPD + β_4 (1|tree) + *u*			
Fixed Effects			
Co-efficient	Estimate	Std. error	t-value
Intercept	-0.4948	0.0394	-12.55
Days Since Harvest	-0.0219	0.0006	-33.59
Size Class 2	0.1351	0.0117	11.51
Size Class 3	0.2851	0.0117	24.28
VPD	0.0060	0.0003	3.79
Random Effects			
Groups	Name	Variance	Std. Dev.
Tree	Intercept	0.00001	0.00001
Residual		0.00965	0.09825
Marginal R-Squared	Conditional R-Squared		
0.0818	0.819		

Table 7. The regression values of a generalized linear mixed effects model assessing moisture content of felled stems using Size Class 1 as the base treatment.

Model – Y *log*(mc) = β_1 Days Since Harvest + β_2 Size Class*TRT + β_3 VPD + β_4 (1|tree) + *u*			
Fixed Effects			
Co-efficient	Estimate	Std. error	t-value
Intercept	-0.4948	0.0439	-12.25
Days Since Harvest	-0.0216	0.0006	-33.50
Size Class 2	0.1351	0.0117	9.12
Size Class 3	0.2851	0.0166	16.65
TRT 2	-0.0397	0.0168	4.48
Size Class 2:TRT 2	0.0247	0.0233	2.14
Size Class 3:TRT 2	0.0158	0.0235	1.98
VPD	0.0060	0.0003	2.79
Random Effects			
Groups	Name	Variance	Std. Dev.
Tree	Intercept	0.00001	0.00001
Residual		0.00925	0.09805

Marginal R-Squared	Conditional R-Squared
0.843	0.849

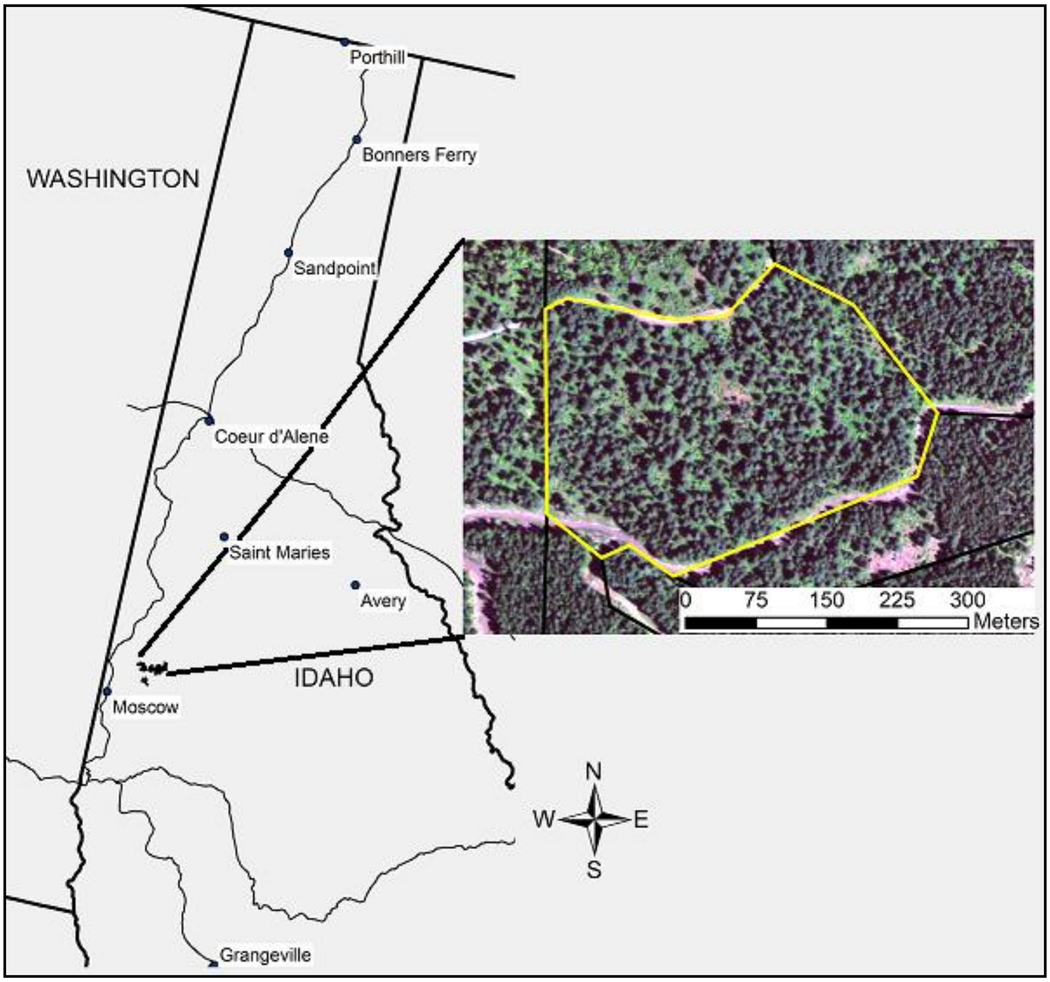

Figure 1. The study unit located Northeast of Moscow, Idaho in the West Hatter Creek Unit of the University of Idaho Experimental Forest (46° 50’05.15” N / 116° 50’25.19” W).

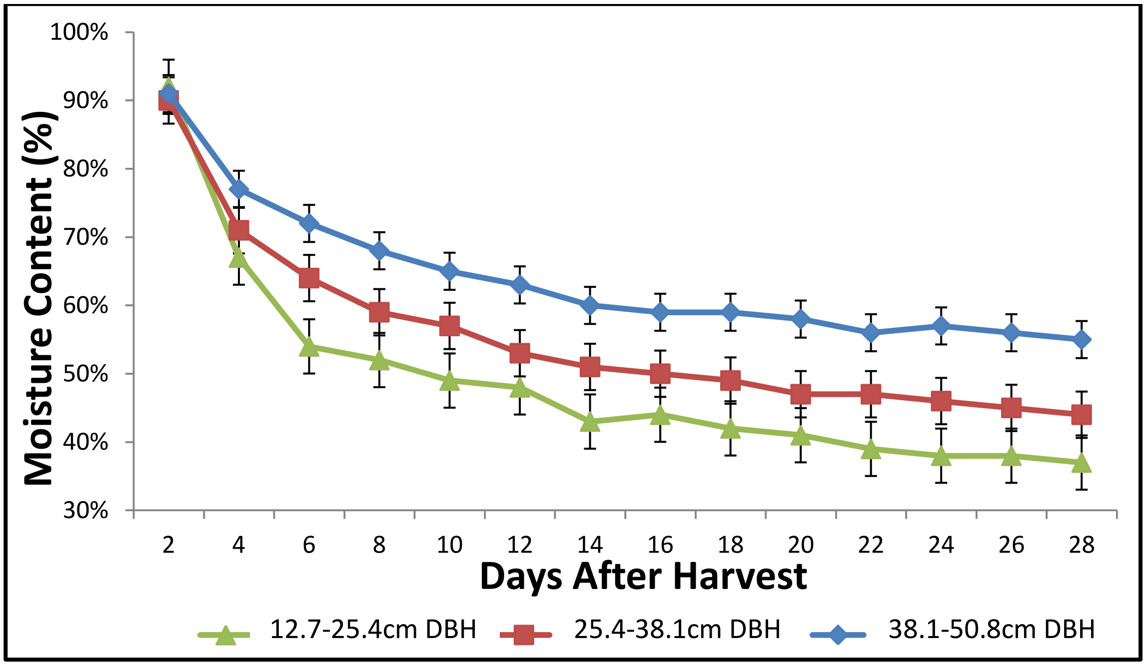

Figure 2. Moisture content (MC) of stem wood, dry weight basis, over 28 days following harvesting. Mean MC values for trees on a given sampling date are shown as solid shapes averaged across both harvest systems, and error bars show one standard error (SE).

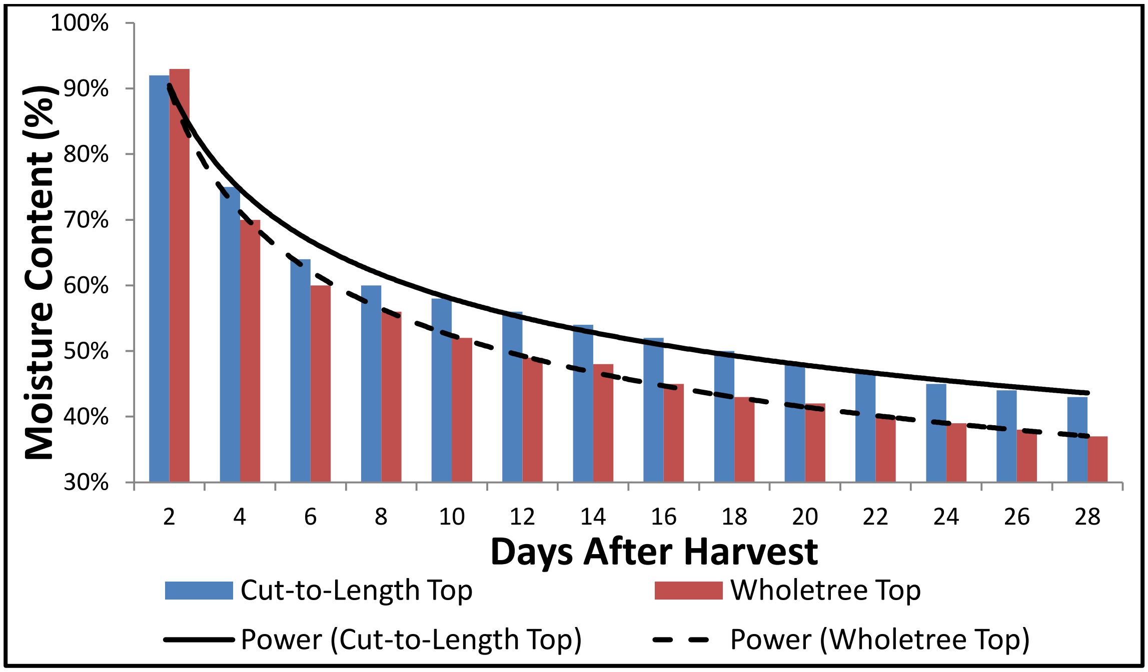

Figure 3. Figure 4 shows the mean moisture content of stem wood separated by treatment type and stem location in the time following harvesting. Treatment 1 represented a cut-to-length harvesting system and treatment 2 a whole-tree system. These results show the MC in the upper portions of the stems.

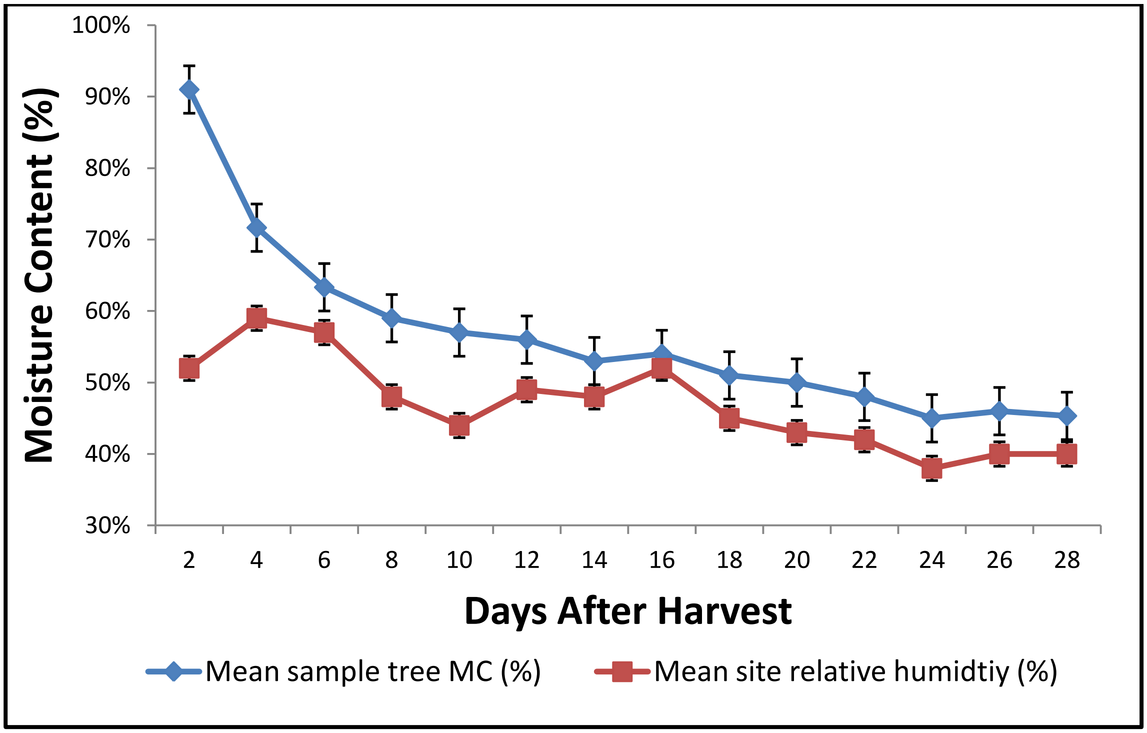

Figure 4. The changes in stem wood moisture content and site relative humidity are shown over the duration of the study. Mean moisture contents and relative humidity are shown in solid shapes with error bars showing one standard error.

Chapter 4

Environmental and Scaling Factors Affecting Sawlog Weight and Volume Relationships in Idaho

Abstract

As weight-based timber sales become more common in the Intermountain West, characterizing the factors affecting weight-to-volume relationships for softwood sawlogs has become more important. Several factors are thought to affect sawlog weight and volume (W:V) relationships, but the relative importance of weather, topography, species, and region in the western United States has not been quantified. Analysis was conducted to determine the factors affecting W:V relationships across the state of Idaho for commercial softwood sawlogs. Using >7929 sorted and scaled sawlog loads sampled throughout Idaho from 2011-2013, we sampled the relationships between log small-end diameter, region, atmospheric temperature, precipitation, and elevation, to assess changes in W:V. Relationships of W:V were best predicted using mixed-effects models fitted individually by species, with volume modeled as a function of weight, small-end diameter, truckload piece count, percent defect, and seasonal quarter. Y (Bd. Ft. Volume) = β_0 + β_1 Tons + β_2 SED + β_3 Piece Count + β_4 Length + β_5 Defect + β_6 Seasonal Quarter + β_7 (1|Sale Number/Ticket) + *u*.

Introduction

The Intermountain West, USA forest products industry harvests more than 6.9 million m^3 of wood annually (O’Laughlin, 2012). Day-to-day financial transactions of harvested forest logs depend largely upon the accuracy and reliability of log scaling systems. Of the various log scaling methods implemented across North America, most have been derived from diagrammatic or mathematical formulas (Row and Guttenberg, 1966; Freese, 1973). Traditionally, sawmill inventories have been measured in units of board feet, cubic feet, or cubic meter volumes using conventional log scaling procedures such as the Doyle log rule, International ¼” rule, or Scribner log rule. However, with the average sawlog scaling diameter decreasing due to increased industrial harvesting of second growth forest stands and associated increases in scaling costs, the efficiency and affordability of traditional or conventional stick scaling has been questioned (Daniels, 2005). Traditional scaling methods require each sawlog delivered to be measured using a pre-determined set of rules to establish a gross and net volume for financial and inventory purposes. Scribner Decimal C short log scaling rule is the most commonly applied log rule in the Intermountain West, USA. The search for a more efficient and cost effective alternative scaling method has gradually shifted interest towards performing transactions on a weight basis (Patterson and Doruska, 2005).

Weight scaling has been widely adopted within southeastern United States forestry, where sample check scaling has been shown to validate weight scaling conversion factors, providing a reliable and efficient means of scaling (Guttenberg et al., 1960). This is done by stick scaling a known proportion of sawlog loads from each harvest to help improve the accuracy of weight scaling conversion factors (Amateis et al., 1984). The reduction of total conventionally scaled loads and reduced truck turn-times at mill yards has resulted in improvements over conventional scaling practices (Guttenberg et al., 1960; Guttenberg and Fasick, 1973). Research on weight scaling for log inventory and transaction purposes is limited in its application outside of the southeastern United States, where it was originally developed (Daniels, 2005; Fonseca, 2005). Within the southeastern region, several studies have found that various combinations of diameter, length, and specific gravity best improve the prediction of volume from weight in both pulpwood and sawlogs (Taras, 1956; Page and Bois, 1961; Row and Guttenberg, 1966; Van Deusen et al., 1981). The knowledge has led to several states adopting conversion factors that account for local and regional variation in logs (Dicke, 1999). Small-end diameter (SED) and truckload piece count have also improved prediction of scaled volume from weight (Yerkes, 1966; Donnelly and Barger, 1977; and Markstrom and King, 1993). However, these studies are characterized by small sample sizes. Few comprehensive regional assessments that account for the potential influence and relative importance of SED, piece count, species sort, season, and harvest area on weight to volume (W:V) relationships exist.

In the western United States, there is very little published research on W:V relationships (Donnelly and Barger, 1977; Markstrom and King, 1993; Briggs, 1994), with current literature acknowledging but not accounting for the influence of species sort, piece size, season, and local climatic conditions on W:V relationships. Current regional practices use a single W:V conversion multiplier for each supervisory district, which are updated annually based on sample check scaling. The Intermountain West region commonly experiences large disturbances such as catastrophic wildfires and insect infestations, which can dramatically alter forest structure and composition (Brown and Chojnacky, 1996). Large and fine scale climatic and soil variation across the region are known to affect forest composition, growth, and even wood density. For example, wood specific gravity is known to range from 0.30 for western redcedar (*Thuja plicata*) to 0.48 for western larch (*Larix occidentalis*) within the region (Alden, 1997). These climatic factors are also known to influence the moisture content of felled sawlogs at fine temporal scales, carrying significant implications for W:V conversion factors (Saralecos et al., in review).

The objectives of this study were to conduct an in-depth analysis of softwood sawlog W:V relationships across the state of Idaho through the coupling of weather, topography, harvest timing, and log scaling data. The primary goals were: 1) to identify the most important regional factors affecting W:V relationships and 2) to assess the effect of environmental and topographical variables as predictors in weight scaling applications. In keeping with the concepts of Markstrom and King (1993), we hypothesized that including SED and truckload piece count with net load weight would improve the prediction of sawlog volume. We also hypothesized that species, harvest region, and season would improve the regression model used to establish W:V conversions at the alpha = 0.05 level. Finally, we expected that environmental and topographical data would increase the accuracy of model predictions

Methods

1.1 Study Area

The study area encompasses more than 971,000 hectares, largely within the Idaho Panhandle Region (Figure 1), with harvest unit elevations ranging from 400 to 2,100 m. The fine scale variation in physical and environmental characteristics within the Intermountain West region produces one of the most spatially diverse collections of forest habitats types found across North America (Benson et al., 1987). At 42% of its total land area, Idaho has the largest proportion of forested lands of any Intermountain West state (Brown and Chojnacky, 1991). Idaho's forests extend from the Canadian border, south through the rugged central mountains of the Selway-Bitterroots, and Sawtooth Wilderness to the Snake River plain of southern Idaho (Morgan et al., 2001) (Figure 1). State managed forests of the

Idaho Department of Lands are broken into 11 supervisory districts that are overseen by northern and southern management regions (Table 1). Although connected longitudinally, the differences across these areas in species composition and growing season length varies widely from low elevation ponderosa pine (*Pinus ponderosa*) savannah to alpine forests habitat types (O'Hara, 1996). Approximately 65% of the timber volume harvested from state owned land is extracted from the northern management region.

The region has typical interior mountain climate, with distinct seasonal temperature, and precipitation variations (Whitlock and Bartlein, 1993) (Table 2). Annual average monthly temperature ranges from -8.7°C in January to 24.7°C in August. Average monthly precipitation ranges from 0-312 mm, with the 3rd quarter (July – September) being the driest season. Winters are cold, often with heavier snowfall at the higher elevations. The majority of the precipitation occurs during the end of the 4th quarter (October – December) and beginning of the 1st quarter (January – March). Precipitation amounts vary across the supervisory districts, and the rain shadow effect of the Coastal and Cascade Mountains are noticeable as drought conditions are common (Finklin, 1983). The high variability in precipitation and temperature, combined with steep slopes and the moderate storage capacity of the forest soils, result in a hydrologically dynamic area (Goode et al., 2012).

1.2 Scaled Data

Information from scaled sawlog truckloads was collected from across Idaho, USA, representing a range of harvest areas, elevations, species sorts, and climatic conditions from 2011-2013 (Table 2). The truckloads sampled included sorted loads only, consisting of five species sorts common to the Intermountain West: 1) Douglas-fir (*Pseudotsuga menziesii*) and western larch (*Larix occidentallis*); 2) grand fir (*Abies grandis*), western hemlock (*Tsuga heterophylla*), and sub-alpine fir (*Abies grandis*); 3) lodgepole pine (*Pinus contorta*) and ponderosa pine (*Pinus ponderosa*); and 4) western redcedar (*Thuja plicata*). Sample loads of western white pine (*Pinus monticola*) and Engelmann spruce (*Picea engelmannii*) were excluded as there were insufficient representative samples for analysis.

A total of 7,929 pure sorted truckloads of sawlogs covering the entirety of the state of Idaho were sampled (Table 3). Sample loads were proportionally distributed across the state supervisory districts based on each supervisory area's harvest volume in proportion with the total statewide harvest volume (Table 1). For each truckload, gross and net volume (board feet), truck payload (tons), average SED (cm), average log length (m), load piece count (no.), species, and harvest quarter were collected.

Additionally, for each sample load, latitude and longitude corresponding to the centroid of each harvest unit were overlaid on a national 30 meter digital-elevation model to determine elevation and supervisory district. Furthermore, total precipitation (mm) and average temperature (°C) for the thirty days prior to the mill delivery date of each sample load was extracted from the nearest Natural Resource Conservation Service SNOTEL site record (USDA-NRCS, 2013).

1.3 Statistical Analysis

All statistical analysis was completed using R (R Core Team, 2013). Data from the Idaho Department of Lands scaling records collected from 2011-2013 were combined and statistical tests of harvest area, species, and seasonal differences in W:V relationships were conducted. Prior to analysis all variables were evaluated using the Shapiro-Wilk test for normality (Royston, 1982). SED and piece count were *ln* transformed, in order to meet the linear regression assumption of normality. To evaluate any potential interdependence among predictors, a Pearson Chi-Sq test for multicollinearity was conducted. Once all variables had been evaluated for both normality and collinearity, the model improvement ratio (MIR) (Murphy et al., 2009; Tinkham et al., 2013, 2014) commonly implemented in the Random Forest machine learning algorithm (RF; Breiman, 2001) was implemented to evaluate variable importance. Variable importance and MIR have been used to identify important factors correlated with a target parameter (Ahmed et al., *in review*). The RF algorithm was used to produce 10,000 random decision trees for use in determining variable importance. The MIR procedure, which operates by standardizing the decrease in mean squared error achieved by adding a variable across all the trees from zero to one, was used as the primary variable selection criteria for subsequent analysis (Ahmed et al., *in review*).

Based on the outcome of variable importance ranking using MIR from Random Forest, a series of linear mixed-models were fitted to predict net volume using the lme4 package (Bates et al., 2013) in the R statistical programming environment (R Core Team, 2013). The linear mixed-models were separated by species sort. Individual timber sales and scaling ticket numbers were implemented as random effects, and tons, SED, piece count, length, defect, and seasonal quarter as fixed covariates. The variables identified using the MIR and implemented in the mixed-models were further evaluated with Akaike's Information Criterion (AIC; Akaike, 1974), for which R^2 values were derived from the conditional R^2, using procedures established in Nakagawa and Schielzeth (2013). AIC evaluates the statistical quality of a model in comparison to others but balancing goodness of fit against model complexity (Akaike, 1974). Single AIC values contain no meaning. Although when compared between models, lower values indicate better fitting models (Breck et al., 2003). In the case of negative reported values it is the highest negative value that identifies the best model. The AIC and R^2 values from the models were later used with a Tukey's HSD test to evaluate differences between the independent variables. The difference testing was applied with Tukey's DTK package (Lau, 2013) due to unequal sample sizes of species and harvest area. All significance tests were evaluated at the alpha = 0.05 level.

The best model was fitted using a liner mixed-model design using the lme4 package and lmer regression function. The purpose of including load ticket and timber sale number as nested random effects was to account for lack of independence between sample loads from the same timber sale location (Bates et al., 2013). While sale numbers are unique to each harvest, ticket numbers are repeated, therefore to meet the linear regression assumption of independent errors and constant variance, a mixed effects model was used. The interaction of sale number*ticket assured that each sample load would be unaffected by loads of similar structure by accounting for correlated error.

Fixed effects variables were used to predict net volume (Scribner board foot) separately for each species sort (Table 3). The fitted model had the following form: $Y = \beta_0 + \beta_1$ tons + β_2 SED + β_3 piece count + β_4 length + β_5 defect + β_6 Quarter + β_7 (1|Sale Number/Ticket) + u, where Y is net volume (Scribner bd. ft), SED is small end diameter (cm, Diameter Inside Bark.), piece count is the number of logs in the load, defect is the difference between gross and net volume (%), and seasonal quarter (Quarter) was grouped as follows: Q1, January – March; Q2, April – June; Q3, July – September; Q4, October – December. Seasonal fluctuations in W:V relationships were assumed to be represented through the variables *seasonal quarter*, precipitation (*ppt*), temperature (*temp*), and *elevation*. Mixed-effects models are used widely in natural resources analysis, but have not been previously applied to W:V analysis.

Results

2.1 Weight:Volume

When assessing overall trends using exploratory data analysis, seasonal patterns in the W:V relationship were evident across all supervisory districts and species sorts, with decreases in the second and third quarters (April-September) observed for all supervisory districts and species combinations, followed by increases during the fourth quarter (October-December). Specifically, W:V decreased by 12% for western redcedar between the first and third quarters, while Douglas-fir/larch and grand fir/hemlock each showed a 9% reduction. This seasonal dependence of the W:V relationships, compared with a yearly mean, is shown in Table 4. The trends identified in W:V during the year are tied closely to seasonal changes in mean temperature.

The species with the greatest yearly range in W:V was Douglas-fir/larch (4.00-9.52). The smallest change occurred for redcedar (2.56-6.94). Yearly averages show that Douglas-fir/larch, grand fir/hemlock, and lodgepole/ponderosa pine sorts were not significantly different at the alpha = .05 level. However, redcedar was significantly different with a yearly average W:V conversion 21% less than the other sorts. When separated into quarters, each sort differed between the second and third quarters of the year. Whereas season and species had different conversion factors, the effect of harvest region was much less.

W:V relationships were generally not significantly different amongst supervisory districts. While several districts proved different from each other, the difference was attributed to distinct variations between habitat types and species harvest volumes and not further investigated. Conversion factors consisting of all sorted species also did not produce different results. However, when tabulated by species and region, harvest area differences were observed between only a few areas. The combinations of area and species that experienced the greatest differences were found within the species sorts containing the largest seasonal fluctuation. Subsequently, these differences were highly correlated with local weather observed in each location as well as defect quantities.

Mean defect for different supervisory districts, species, and seasonal quarters was similar. Cedar sawlogs had the highest mean defect percentage over the entire year, as well as in each seasonal quarter. While cedar showed the greatest mean defect overall, the mean defect volume per load of each species increased during the second and third quarters, however no statistical difference in defect was observed. This increase occurred during the seasonal period with the most delivered loads. Finally, the predictability of defect was greater than most other variables evaluated (Figure 2). This ability to accurately predict variation due to season, supervisory district, species, and defect creates a strong base from which to develop W:V relationships for commercial weight scaling.

2.2 Climate variables

Impacts of climatic and topographic variables, including precipitation, atmospheric temperature, latitude, longitude, and elevation, were assessed as potential predictors of W:V relationships. Initial results from a model improvement ratio using RF indicated that all factors were significant predictors of W:V. In comparison, the effects of temperature, latitude, and elevation were identified as stronger predictors of W:V relationships than precipitation and longitude.

2.3 Predicting Volume using Mixed-effects models

The variables *precipitation* and *temperature* had collinearity with *seasonal quarter*, as did the topographic variables *elevation* and *harvest area*. The ANOVA analysis indicated significant collinearity between seasonal quarter and temperature (0.52), and between seasonal quarter and precipitation (.62). Therefore, the climatic and topographic variables were withheld from further analysis. Finally, the MIR was run again, including the reduced variable list. Final variables in the model were species, SED, piece count, length, defect, quarter, and harvest area (Figure 3).

Results from the MIR indicated strong model improvement due to inclusion of *species*. The subsequent AIC testing then separated the analysis into four models representing one for each species sort. Using species sort as a random variable in place of using separate models did not improve the AIC results. Individual species sorts were closely tied to levels of defect. The combined testing of independent variables through the RF model improvement ratio and AIC tests showed the strongest model as [Equ.1]. This model independently predicted net volume (bd. ft.) for each species sort (Table 5). The addition of harvest area, while improving the model, did not significantly improve the model at the alpha = .05 level.

[Equ.1]

$$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ SED} + \beta_3 \text{ PC} + \beta_4 \text{ Length} + \beta_5 \text{ Defect} + \beta_6 \text{ Quarter} + \beta_7 \text{ (1|Sale Number/Ticket)} + u.$$

Seasonal variation of predictions from the linear mixed effects model Equation 1 is shown in Figure 4. This model explained > 74% of the total variability in the net truckload board foot volume of the sampled loads in all models with a conditional R^2 ranging from .74-.90 ($p=<.05$) (.74 WRC, .90 DFL, .85 LPPP, .89 GFHAF) (Table 6). The selection of these variables supported the hypotheses that net weight, SED, piece count, and seasonal quarter affect net volume (bd. ft.). Variability in temperature (°C), precipitation (mm), elevation (m), latitude, and longitude were explained by quarter and harvest area, so these terms were removed from the model, supporting our initial hypothesis. We failed to reject the null hypothesis that species does not affect W:V. While not all harvest areas were significant, differences among individual supervisory areas were evident, based on ANOVA tests.

After fitting each individual species-level model, individual weight to volume conversion relationships were established for each harvest area by species and quarter (Table 4). These multipliers were estimated by developing the ratio of the predicted net volume of sample loads to actual net weights. W:V relationships in Table 4 show changes across seasonal quarter. The conversions of western redcedar contained the greatest variation among W:V relationships and the lodgepole/ponderosa pine sort had the smallest variation. Comparisons of predicted W:V conversions and the observed results showed positive correlation for each species sort (Figure 5).

2.3 Validation

The W:V relationships were further investigated by comparing them with current state conversion multipliers. The current predictors used are annual supervisory district averages of all species. A comparison of predicted values using the current multipliers and predictions from the new model is shown in Table 7. Differences between predictions from the two models were evaluated by calculating absolute and percent differences in prediction error (Figure 6). The greatest differences were observed for western redcedar, which differed between supervisory areas.

The conversion multipliers show minimal differences among other species sorts when compared to harvest region. Much of the variation in current conversion multipliers used is proportional to the percent volume harvested the prior year for a given species. For example, several of the Southern and drier harvest regions have higher ratios when compared to the Northern regions, which harvested a higher percentage of volume of western redcedar on a yearly basis.

Discussion

3.1 Evaluation of hypotheses

SED and piece count improved prediction of net truckload volume, based on the relative magnitude of Random Forests MIR values. In support of our initial hypotheses, species, and seasonal quarter improved the prediction of W:V relationships. However, supervisory district did not reduce regression model prediction error. Net weight, SED, and species explained most of the variability in net truck volume. Seasonal quarter also proved to be highly correlated with temperature, precipitation, latitude and longitude. Therefore, while climate and topography affect W:V, quarter is a suitable surrogate. This empirical model provides a foundation to build future weight scaling practices upon. Although accounted through seasonal quarter, previous research has not investigated the impact of short or long-term weather effects on W:V relationships.

3.2 Additional Factors

3.2.1 Bark

Beyond environmental and scaling factors measured in each harvest load, several notable variables including bark and stem density were not accounted for in this study. Conventional scaling procedures require inside bark diameter for determining the scaling diameter. However, delivered sawlogs may contain bark in varying surface percentage, adding to the net weight of each load, while being unaccounted in the scaling process. Therefore, potential error in the model may arise from variability in bark coverage percentage. Accurate determination of the percentage of bark in each load is difficult to assess. Bark reportedly to makes up 10 to 25 percent of the over-bark volume and weight of a tree in prior studies (Meyer, 1946; Philip, 1994). Depending on harvest location, season, and processing method, operational bark loss can vary (Murphy and Pilkerton, 2011).

3.2.2 Moisture

Bark cover percentage on stems is fixed after mechanical processing, while stem moisture loss continues through the time of log delivery, varying with the season. Long term studies on seasonal effects of moisture changes within standing timber have found seasonal changes associated with extended lag periods (Marden et al., 1975). Additional studies have explored both the rates and quantities of stem moisture loss after harvest (Yerkes, 1967). Sawlogs lose moisture after felling in summertime (Yerkes, 1967; Saralecos et al., *in review*). Wood contains hygroscopic tendencies, with internal moisture content tending to equilibrate with surrounding atmospheric conditions (Siau, 1984). Relative humidity, temperature, and precipitation can all affect moisture loss rates (Siau, 1984). Studies have identified seasonal patterns of bole moisture reduction during summer months (Beedlow et al., 2007). These long-term seasonal changes correspond with relative humidity. However, there are delayed lag times associated with wood and the surrounding environmental conditions (Marden et al., 1975). The rate of equilibration increases with the difference between relative humidity and stem moisture content at the time of harvesting.

Variability in the heartwood to sapwood ratio can cause different densities at points along the stem profile (Patterson and Wiant, 1993). These ratios are characteristic of stem taper, which varies regionally by species (Garber and Maguire, 2003). The potential for regional changes in stem form are accounted for in the previous model using scaled log length. Scaled log volume corresponds highly with log length through the taper rules built into the Scribner Short Log scaling rule. Additionally, changes in specific density also occur regionally (Schumacher, 1946; Bowyer et al., 2007). Regional variability of factors like specific gravity of wood affects log weight. For example, specific gravity of coastal Douglas-fir varies from .36 to .54 and western hemlock vary from .34 to .50 (Hoadley, 1990; Bowyer et al. 2007).

3.2.2 Economic Impact of Conversions

Current organization and infrastructure of weight scaling in the western United States is firmly established. Weigh stations and conversion relationships are present at most sawmills in the western United States. Sample weight scaling is used to continuously update conversion relationships used to predict volume. Research on weight scaling accuracy has shown efficiency and economical benefits (Donnelly and Barger, 1977; Amateis et al., 1984). However, many landowners, sawmills, and contractors use proprietary relationships, rarely sharing production and efficiency numbers (Via and Shupe, 2005). Improvements in understanding of W:V relationships in the Intermountain West associated with this study will benefit landowners and mills in log inventory and sale, but help expand regional knowledge among foresters and contractors.

Although past studies have examined weight scaling for multiple products (Guttenberg and Fasick, 1973; Amateis et al., 1984), accuracy (Yerkes, 1966), effects of moisture (Yerkes, 1967; Lothner et al., 1974), and been completed in varying forest regions across the U.S., little work has evaluated influences of bark and species-specific gravity (Sollins et al., 1987; Harmon and Sexton, 1995). Regional weight scaling could improve vastly through an increased understanding of bark characteristics and specific gravity for weight scaled species.

Large differences between cubic foot scaling and Scribner log rule volume estimates suggest shifting towards cubic scaling practices would significantly improve W:V conversion relationships. Cubic scaling accounts for the entirety of the log volume, opposed to diagram-based methods such as Scribner, which only measure the scaling cylinder board feet within each log segment. Through accounting for more volume within each log, Cubic scaling volumes are more closely correlated with weight (Markstrom and King, 1993). While Cubic volume methods are rarely applied today, the error associated with weight to cubic volume relationships is greatly reduced.

Conclusion

Consistent with the shifting trend towards sample weight scaling in the Intermountain West, we showed that regression modeling can accurately predict sawlog volume. Additionally, we failed to reject our H_o that Tons, SED, Piece Count, Seasonal Quarter, and Defect are significant predictors of net sawlog truckload volume. Furthermore, this study showed that seasonal quarter was autocorrelated and can be used as a surrogate for precipitation and temperature. We then constructed and evaluated four linear mixed-effects models predicting net sawlog volume that can be applied across the region. The models developed for the Douglas-fir/larch, lodgepole/ponderosa pine, and grand fir/hemlock regional sorts proved highly efficient at explaining the error within each model, whereas the western redcedar model accounts for much less model error.

Surprisingly, we rejected our H_o that harvest area would significantly improve the regression models. For the remaining uncertainty of influences affecting weight and volume relationships, several factors such as wood moisture content and sawlog bark coverage percentage were discussed. It is apparent that while coefficients improve the short term model accuracy, increases in data through sample weight scaling procedures provide the best long term improvement to W:V relationships and subsequent scaling conversions factors.

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Table 1. Average supervisory area harvest volumes from 2011-2013 in relation IDL statewide annual harvest volume and sample allocation across each supervisory area.

Supervisory Area	Mean Harvest Volume 2011-2013 (mmbf)	Percentage of State Harvest	Percentage of Sample Loads
Cataldo (N)	7.3	3.1%	1.9%
Clearwater (S)	40.3	17.0%	18.6%
Craig Mountain (S)	9.3	3.0%	8.0%
Maggie Creek (S)	21.0	9.0%	14.9%
Mica (N)	7.7	3.0%	2.2%
Payette Lakes (S)	16.3	6.0%	5.6%
Ponderosa (N)	36.7	17.0%	17.5%
Priest Lake (N)	16.3	7.0%	3.0%
Southwest (S)	8.3	3.5%	2.0%
St. Joe (N)	48.3	20.3%	23.0%
Pend Oreille Lake/ Kootenai Valley (N)	22.4	9.4%	3.3%

Note: N/S denotes whether the supervisory area is located in the Northern or Southern management region of the state.

Table 2. Characteristics collected for each scaled sample load and the coincident IDL harvest locations.

Scaling	**Range**	**Mean**	**St. Dev.**
Net Scribner Volume (bd.ft.)	3.0-7.9	5.0	0.8
Net Weight (tons)	11.5-35.0	27.3	2.2
Small-end Diameter (in)	6.0-27.2	10.5	3.0
Length (ft)	14.1-50.0	29.2	4.5
Piece Count	10.0-359.0	49.7	31.0
Defect (%)	0.0-22.0	7.7	0.03
Climate and Topographic Factors			
Elevation (m)	562.2-2003.0	1073.0	241.3
Precipitation (mm)	0.0-312.0	96.3	68.4
Temperature (°C)	-7.7-23.7	7.6	8.1

Table 3. Distribution of sample loads by supervisory area, species, and quarter.

Supervisory Area	Sample Loads
Cataldo	61
Clearwater	1472
Craig Mountain	665
Maggie Creek	1309
Mica	93
Payette Lakes	420
Ponderosa	1464
Priest Lake	233
Southwest	94
St. Joe	1812
Pend Oreille/ Kootenai Valley	257
Species	**Sample Loads**
WRC	1390
DFL	2260
GFHAF	3536
LPPP	694
Quarter	**Sample Loads**
1	1768
2	1571
3	2634
4	1907

Table 4. Seasonal variation in weight-volume relationship of softwood sawlogs relative to various species sorts common to the Intermountain West region.

Species/Quarter	Defect (%)	Weight:Volume
WRC- 1	8.7	4.85
WRC- 2	8.9	4.64
WRC- 3	11.0	4.25
WRC- 4	9.5	4.70
WRC	9.7	4.61
DFL- 1	8.6	6.03
DFL- 2	8.7	5.70
DFL- 3	9.0	5.51
DFL- 4	8.8	5.90
DFL	8.8	5.74
GFHAF- 1	6.9	6.01
GFHAF- 2	8.0	5.59
GFHAF- 3	6.7	5.49
GFHAF- 4	6.6	6.00
GFHAF	6.6	5.72
LPPP- 1	5.9	6.01
LPPP- 2	5.7	5.81
LPPP- 3	6.1	5.62
LPPP- 4	6.4	5.83
LPPP	6.0	5.80

Table 5. The results of AIC testing to determine the best fit model applying the factors derived from the *Random Forest* model improvement ratio.

AIC Model	**AIC**			
	LPPP	**DFL**	**GFHAF**	**WRC**
$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ } (1 \mid \text{Sale Number/Ticket}) + u$	1661	4311	6941	3423
$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ SED} + \beta_3 \text{ } (1 \mid \text{Sale Number/Ticket}) + u$	1012	2742	5012	2687
$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ SED} + \beta_3 \text{ PC} + \beta_4 \text{ } (1 \mid \text{Sale Number/Ticket}) + u$	871	2678	5001	2667
$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ SED} + \beta_3 \text{ PC} + \beta_4 \text{ Length} + \beta_5 \text{ } (1 \mid \text{Sale Number/Ticket}) + u$	863	2669	4997	2631
$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ SED} + \beta_3 \text{ PC} + \beta_4 \text{ Length} + \beta_5 \text{ Defect} + \beta_6 \text{ } (1 \mid \text{Sale Number/Ticket}) + u$	807	2267	4399	2569
$Y = \beta_0 + \beta_1 \text{ Tons} + \beta_2 \text{ SED} + \beta_3 \text{ PC} + \beta_4 \text{ Length} + \beta_5 \text{ Defect} + \beta_6 \text{ Quarter} + \beta_7 \text{ } (1 \mid \text{Sale Number/Ticket}) + u$	803	1893	3951	2347

Table 6. Mixed-model analysis of covariance for Scribner Net Board Foot Volume using weight, small-end diameter (SED), length, piece count, defect, and quarter as covariates and sale number and load ticket as fixed effects.

	Species Model			
Coefficient	LPPP	DFL	GFHAF	WRC
Weight	0.185±0.011 (17.30)	0.157±0.004 (33.21)	0.167±0.288 (32.32)	0.151±0.007 (20.62)
SED	1.035±0.103 (9.99)	1.783±0.062 (28.50)	1.962±0.005 (33.98)	2.511±0.128 (19.53)
Defect	-5.729±0.652 (-8.78)	-5.582±0.246 (-22.66)	-7.113±0.057 (-27.14)	1.166±0.495 (2.35)
Quarter 2	0.016±0.052 (1.31)	0.349±0.029 (12.04)	0.358±0.262 (14.28)	0.476±0.059 (8.02)
Quarter 3	0.142±0.052 (2.75)	0.493±0.026 (18.80)	0.493±0.025 (21.37)	0.908±0.057 (15.82)
Quarter 4	-0.055±0.055 (-1.99)	0.162±0.028 (5.73)	0.224±0.025 (8.97)	0.383±0.058 (6.57)
Piece Count	-0.556±0.063 (-8.84)	-0.266±0.032 (-8.13)	-0.007±0.031 (-1.21)	-0.117±0.073 (-2.59)
Length	0.006±0.005 (1.47)	-0.014±0.002 (-5.16)	-0.002±0.002 (-1.96)	0.024±0.005 (4.31)
	r^2(RMSE %)			
	.90(±5.8)	.93(±3.7)	.92(±4.2)	.74(±9.0)

Note: The response of net board foot volume to weight was best fit to a linear model, where each model used quarter 1 as the base treatment. Values are means ± SEs (t-value).

Table 7. Comparisons of W:V relationships showing variation between currently employed weight to volume conversions and updated model predictions.

		Model Conversion (% change from current)			
		LPPP	**DFL**	**GFHAF**	**CED**
Supervisory Area	**Current Conversion**	**5.80**	**5.74**	**5.71**	**4.55**
Cataldo	5.57	4.1	3.0	2.5	-18.3
Clearwater	5.07	14.4	13.2	12.6	-10.3
Craig Mountain	5.38	7.8	6.7	6.1	-15.4
Maggie Creek	5.51	5.2	4.2	3.6	-17.4
Mica	5.80	-0.1	-1.1	-1.6	-21.6
Payette Lake	5.65	2.7	1.7	1.1	-19.4
Ponderosa	5.17	12.1	10.9	10.4	-12.1
Priest Lake	5.82	-0.3	-1.3	-1.8	-21.8
Southwest	5.75	0.8	-0.2	-0.7	-20.9
St. Joe	5.54	4.6	3.5	3.0	-17.9
Pend Oreille Lake/ Kootenai Valley	5.78	-0.7	-1.7	-2.2	-22.1

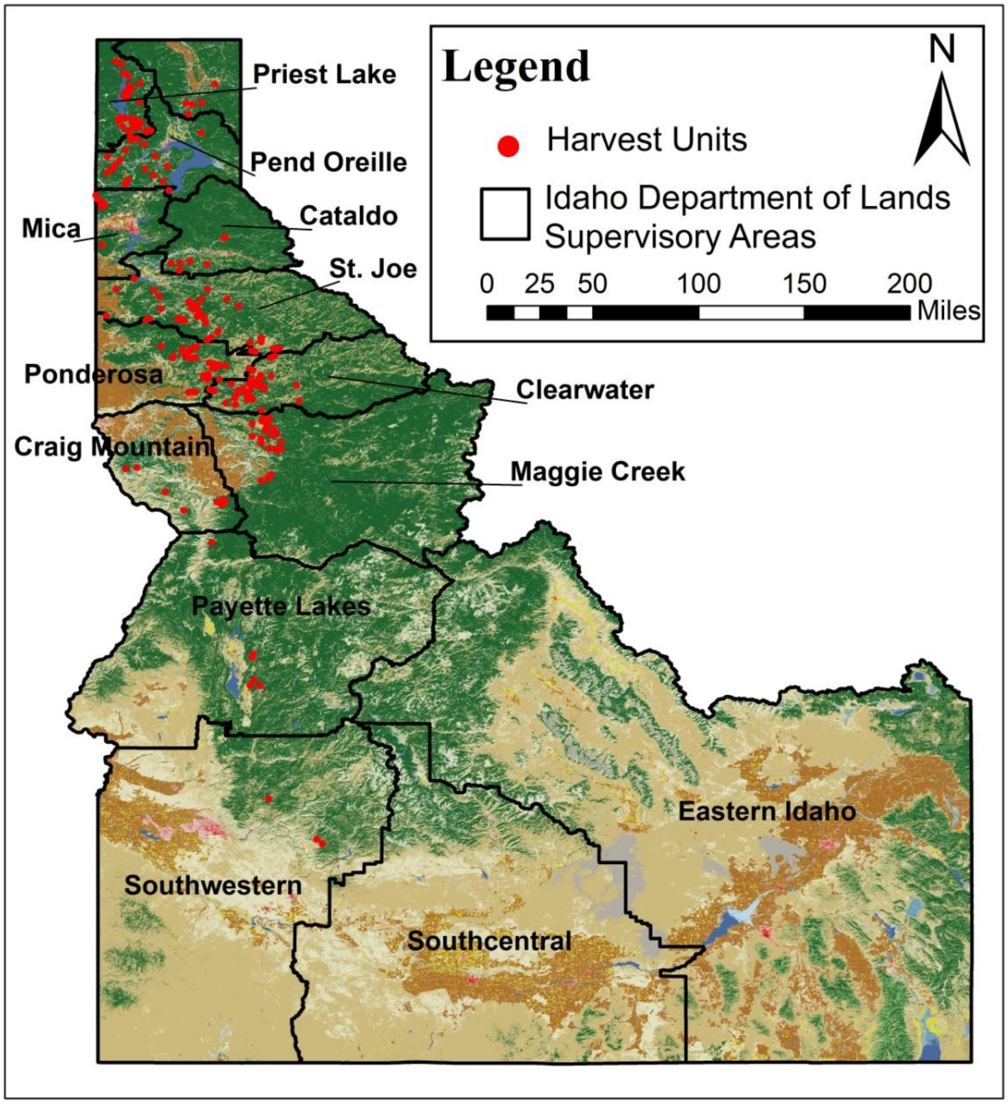

Figure 1. Regional map showing the location and distribution of harvesting units containing sample loads across the state of Idaho.

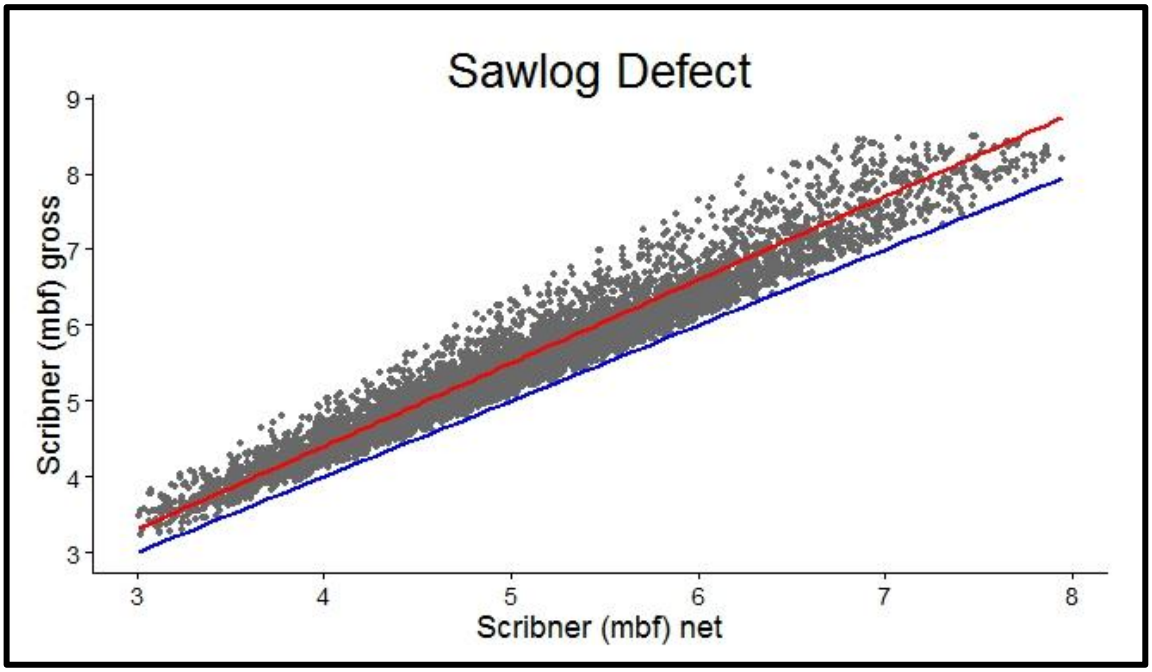

Figure 2. The changes in truckload defect are shown as a comparison of gross and net scaled board foot volumes.

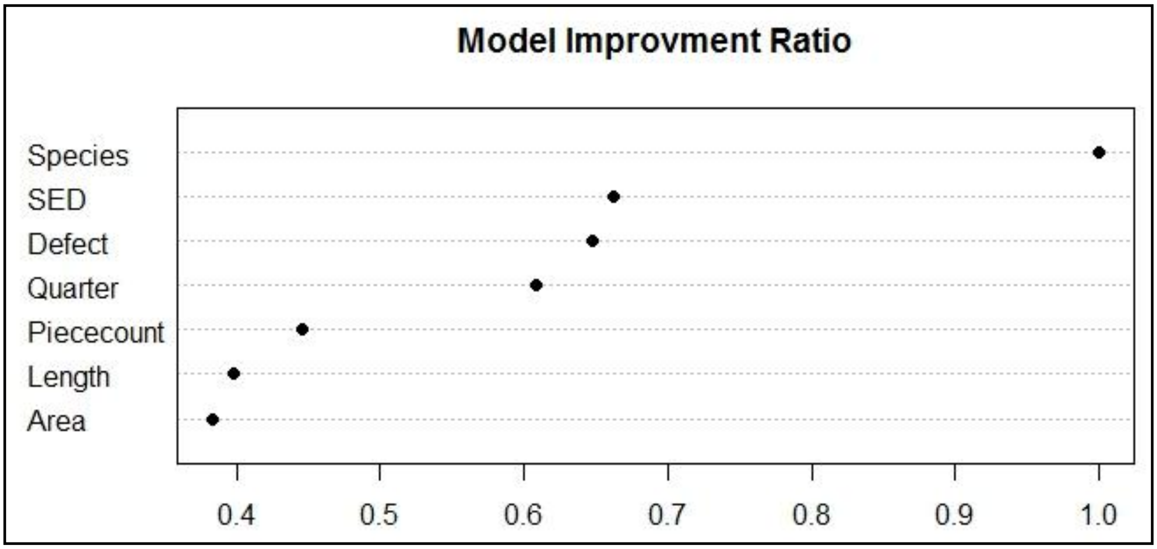

Figure 3. Results of the model improvement ratio derived from *Random Forest* explaining the proportion of the time that each variable best explained sawlog W:V ratio.

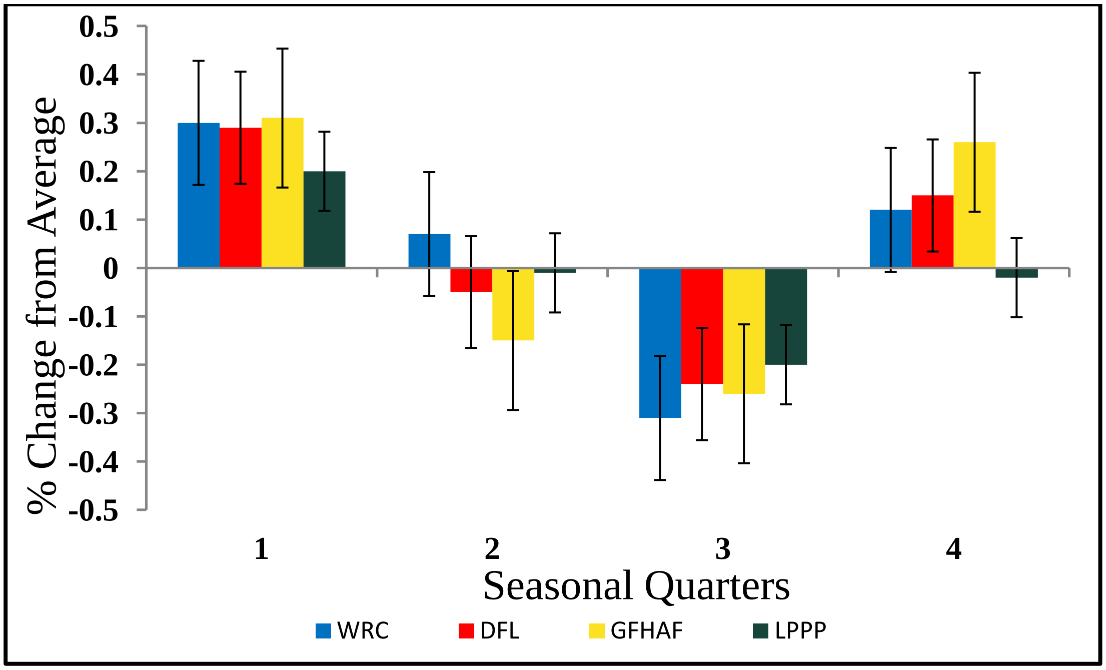

Figure 4. Seasonal percent change from individual species yearly average W:V relationship for each species sort.

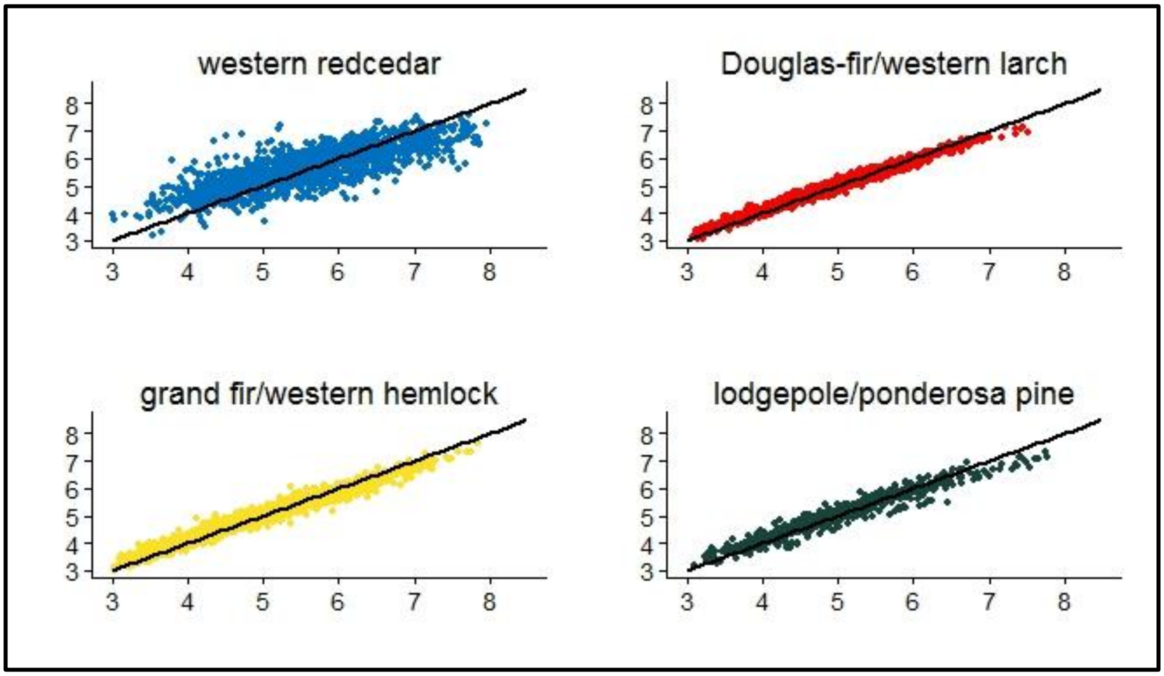

Figure 5. The model predicted truckload volume of delivered sawlogs compared to observed truckload volumes during the study duration, over the net weight of each load separated by species sort.

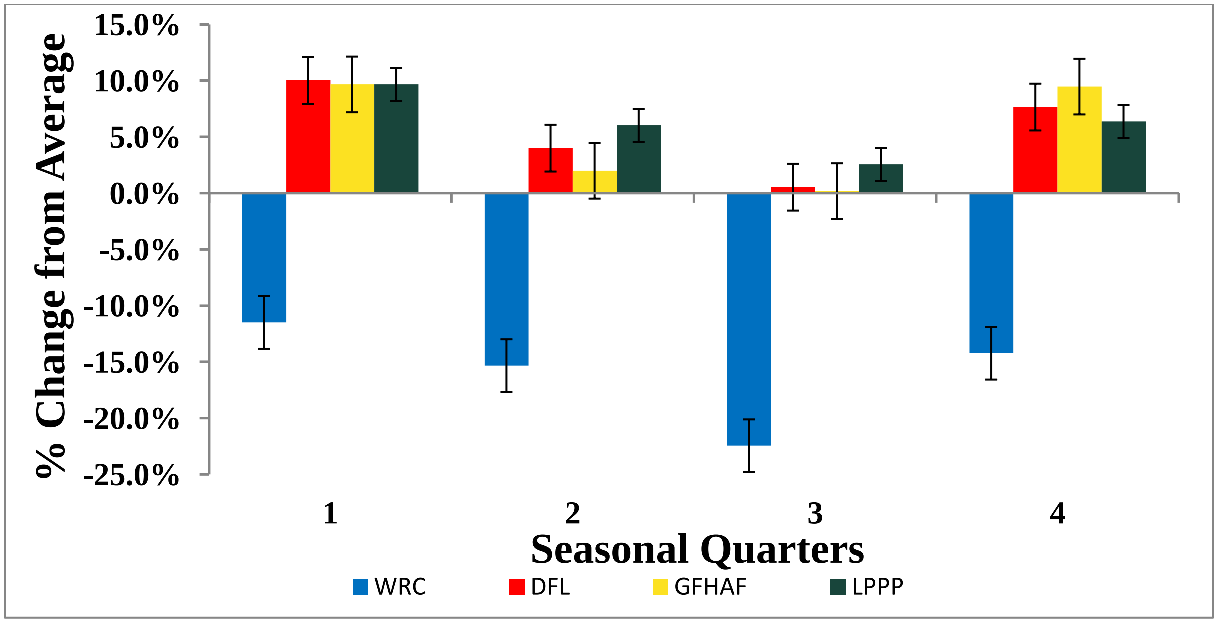

Figure 6. Seasonal variation amongst species sorts showing percent change from the current Idaho Department of Lands quarterly W:V conversion factors (baseline) and the updated species dependent conversion factors.