AN ABSTRACT OF THE DISSERTATION OF

Maria Francisca Belart Lengerich for the degree of Doctor of Philosophy in Sustainable Forest Management presented on July 6, 2016.

Title: Forest Harvest Residue Moisture Management in the Pacific Northwest, USA

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John Sessions

Moisture content management is a key requirement to improve forest harvest residue economics for bioenergy production. This dissertation aims to contribute towards better management through these three general objectives (1) Determine average moisture content of fresh forest harvest residues and its changes over the different seasons of the year, focusing on the three main commercial forest species growing in the Pacific Northwest, (2) Determine in-forest stored drying rates of this material for two harvest systems and the same species specified in objective (1) and (3) Determine the cost effectiveness of in-forest drying for two harvest systems and the advantages of drier material when its energy content is considered at a cogeneration facility.

A repeated measures experimental design was conducted to determine average branch moisture content in live trees during each season of the year in four different locations in Oregon. At the same time, an innovative sampling protocol was employed to determine moisture content for in-forest stored of piled and scattered harvest residues for one year in four different Oregon sites. These data were used to calibrate finite element analysis (FEA) models to predict residue drying rates based on weather information such as temperature, relative humidity,

precipitation and wind velocity. Finally, one of the FEA models was used to determine drying rates on real Douglas-fir units harvested with different harvest systems (a case study). These harvest units were employed to set a mixed integer linear program to optimally deliver harvest residues to a hypothetical cogeneration plant over 24 periods (months) and determine processing and transport costs.

Major findings indicate that from all sites, the highest moisture recorded was 50% (wet basis) in ponderosa pine during the winter; the lowest was 43% in the summer for both the same ponderosa pine and Willamette Valley Douglas-fir. When compared by season, ponderosa pine had significantly higher moisture content in the winter than in other seasons (1.6 to 9.8% higher). Summer moisture content was also significantly lower than fall moisture content for ponderosa pine (5.4 to 2.5% lower). Willamette Valley Douglas-fir had significantly lower moisture content during summer than during other seasons (0.8 to 3.9% lower).

FEA models were successfully developed to determine drying rates for four different climate regions in Oregon. These models were compared with data obtained in the field and statistical tests show model agreement with correlations between 0.56 and 0.92 (Kendall's tau) on all sites.

The harvest residue generated from the case study was sufficient to optimally deliver the necessary volume to supply 63% of a hypothetical 6 MW-hr cogeneration plant. Approximately 98% of the harvest residue generated with cable logging system was delivered to the plant compared with only 56% of the residue generated with a ground-based system. By considering the energy content of drier residues, the amount of ODMT needed to supply the plant can be reduced by 13.3% without affecting the energy output over a 6-period planning horizon. A lower ODMT demand and shifting to drier material results in 16.5% lower cost, which represents a more accurate estimate of the production cost.

We conclude that forest harvest residues that are mainly composed of branches should not have moisture content levels greater than 50%. Seasonality should not affect the average moisture content of this material unless it is composed of ponderosa pine.

After harvesting, piling residues in a berm (windrow) shape will promote drying in the summer and re-wetting in the winter. It is best to reduce pile size to facilitate drying in summer, and increase pile size if material will be left in the field over the winter. Drying times can be reduced up to 1/3 if the material is cut and left to dry during the dry, warm summer months versus starting in the winter.

I this case study, residues coming from cable harvest units present a cost advantage compared to ground-based harvest units. Collection cost from the drier ground-based units was too large to offset the higher moisture content of piled residue in the cable harvest units. Recognizing the energy value of drier material has potential to improve the supply and cost estimates of the utilization of forest harvest residues for power generation.

Forest Harvest Residue Moisture Management in the Pacific Northwest, USA

by

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

Maria Francisca Belart Lengerich, Author

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CONTRIBUTION OF AUTHORS

Dr. John Sessions contributed to the design and review of all the chapters in this document. Dr. Ben Leshchinsky was a major contributor to the model development, calibration and writing of Chapter 3. Dr. Glen Murphy contributed to the design and review of Chapter 2. Dr. Lisa Madsen contributed to the statistical analysis and review in Chapter 2.

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DEDICATION

This dissertation is dedicated to Brian, Jon, Rex, Kyle and the people who work in the Oregon forests. Thanks for working with me and believing in this project.

1 General Introduction

Bioenergy is energy originated from biologic renewable resources. Its consumption has increased by 60% on average in the last 16 years in the United States (EIA, 2016), driven by environmental consciousness, policymaking, fuel prices and fuel security concerns. The renewable fuel standard (RFS) created by Congress in 2005, includes a specific target of cellulosic-based biofuels to replace or reduce petroleum-based fuels by 61 billion liters per year by 2022. This requirement was included to address concerns about the use of food crops for biofuels. For this reason, researchers have been encouraged to study how to produce cellulosic-based biofuel in an economical and environmentally responsible manner. This material can come from many sources; this study focuses on forest harvest residues (forest harvest residues), how to manage them in the field to reduce its moisture content and make its transportation efficient. In order to understand the focus of this study, forest harvest residues, their availability, production and economics are described in the following section.

1.1 Forest harvest residues in the Pacific Northwest, USA.

Forest harvest residues are mainly tree branches, tops, log chunks, breakage and non-merchantable trees left after a tree harvesting operation, branches being a major component, especially when pulp wood prices are high (Figure 1.1a). The Pacific Northwest produces 14 million m^3 of forest harvest residues annually; Oregon contributes 45 % of them (TPO report, 2016). Part of these residues are currently consumed by the cogeneration industry to produce electric power, and the rest is burned for site preparation before establishing a new plantation or left to decompose if there are sufficient planting spots and there are no concerns about fire hazard. The Oregon Forest Practices Act requires landowners to re-plant within one year after clear-cut harvesting, leaving a maximum amount of time of one year for residue treatment (Oregon Department of Forestry, 2014). Burning this material is not only a source of carbon release to the atmosphere (Figure 1.1b), but also adds costs to the landowner. Collecting, piling, burning the material and paying a smoke generation fee or burning permit in states such as Oregon and Washington (DNR, 1998 and ODF, 2009) are the main associated costs. However, disposal remains a better economic option for most landowners who would otherwise consider selling residues for energy purposes mainly because of the high costs involved in the collection and processing. Collection cost is highly dependent on the residue distribution; the further it is from the landing or roadside the more expensive it is to collect (Zamora-Cristales and Sessions, 2016).

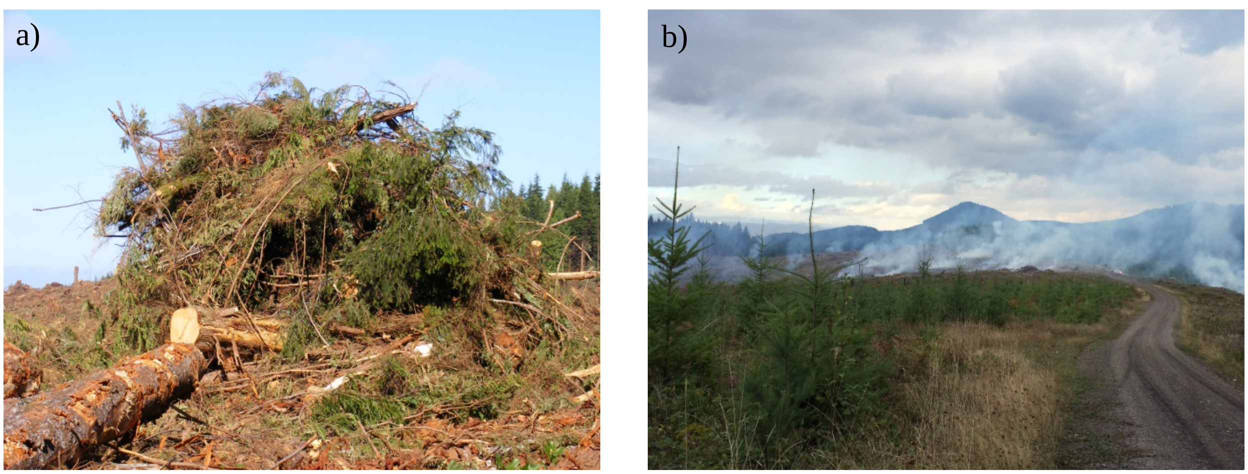

Figure 1.1 a) Piled forest harvest residues in the Oregon Coast; b) Forest harvest residues being burned near Dexter, Oregon

1.2 Forest harvesting systems and residue distribution

Forest harvest residues are distributed in the unit depending on the harvesting system used. In steeper terrain, with a cable logging system, whole trees are yarded to a landing where they are delimbed and bucked into logs depending on a purchase order specifications from the mill buying them. Consequently, harvest residues are usually accumulated in large piles at the landing.

In gentle slope, a common logging method in the Pacific Northwest is shovel logging. When this logging system is used, tree delimbing and bucking occurs at the felling site or is yarded as whole tree. Then, an excavator swings the logs or trees to the roadside. When trees are delimbed and bucked at the felling site, residues are left scattered over the harvest unit and when yarded as whole trees, branches fall as a product of the tree handling. This prompts the need for collection, adding cost to the operation. Collection can be done using an excavator, a forwarder that is loaded by an excavator adapted for handling residue or a self-loading forwarder (Figure 1.2). The excavator is more economical for material closer to roadside and the forwarder for material that is further away (Zamora-Cristales and Sessions, 2016). Independent from the harvesting system, once residues are left at the landing or roadside, the process continues with residue comminution and transport.

Figure 1.2 Self-loading forwarder carrying ponderosa pine harvest residues in Sisters, Oregon

1.3 Forest harvest residue processing and transport

A common forest harvest residue processing operation in the Pacific Northwest for bioenergy production consists of reducing the material size by a grinder fed by a track-based hydraulic loader often referred to as an excavator. The grinder reduces the size of the residues to a range between 0.92 to 7.6 cm grindings (Zamora-Cristales *et al.*, 2014) and loads a chip trailer (van) through a conveyor belt in about 20-30 minutes or more depending on the trailer size (Figure 1.3a). The three machines are interdependent in the process, which makes it logistically challenging and expensive when there are machine breakdowns, interference, or other delays (Zamora-Cristales *et al.*, 2013). Trucks used to transport this material have lightweight chip trailers (Figure 1.3b) that can be 9.8, 11.6, 12.8, 13.7 and up to 15.2 m long (Sessions *et al.*, 2010). Regardless of distance to a consumption center, this material is costly to transport because of its high moisture content (MC) and low bulk density. When moisture content is high, chip vans reach their legal weight limits before reaching their volume capacity due to wood moisture content. Oppositely, when moisture content is low, trailers reach their maximum volume capacity while being below legal weight limits due to the material's low bulk density. Parts of the residues received by cogeneration plants contain high moisture content (Kevin Tuers (Seneca Sustainable Energy), 2016 pers. comm.); this gives an opportunity to reduce costs by managing the material to increase drying rates.

Wood moisture can be reduced in the forest by transpiration and air-drying. It has already been shown that drying rates, and therefore optimal storage time, will depend on climate conditions, species, storage configuration and initial moisture content (Hakkila, 1989). The initial moisture content of this material will depend on the moisture levels of the trees that are being harvested.

Figure 1.3 a) Forest harvest residue comminution on a cable yarding unit near Vida, Oregon; b) Chip trailer (van) transporting comminuted residues near Vida, Oregon

1.4 Standing tree moisture content

Several researchers have studied moisture patterns at tree stem levels. Clark and Gibbs (1957) did a detailed study in Eastern Canada in bole wood of different species of birch (*Betula spp*.). They found that the highest moisture content occurs in mid-spring and the lowest in early-fall. They identified two marked stress periods, the first at the end of winter (right before breaking dormancy) and the second in late summer. Highest MC in mid-spring would be due to the breaking of tree dormancy, and then the lowest MC in early-fall would be due to the gradual loss of water during the growing season. In this study it was also found that species within a same genus closely follow the same MC seasonal pattern. For these species, orientation is also important since during winter and spring the bole is being exposed to direct solar radiation while in summer and fall it is being protected by foliage. These broadleaf tree MC patterns seem to agree with many species studied by Gibbs (1957). However, some families seem to have a MC peak later in the year (by mid-summer) and their transition through winter is less dramatic.

Clark and Gibbs (1957) did some studies in Eastern hemlock (*Tsuga canadensis*), Balsam fir (*Abies balsamea*), Red spruce (*Picea rubens*) and Eastern white cedar (*Thuja occidentalis*). They observed that conifers tend to have a more stable MC though the year compared to broadleaves due to their evergreen habit. As for seasonal MC variation, there is no general pattern for these species. Some of them have minima in late spring (Eastern hemlock, Balsam fir); others in late summer (Red spruce and Eastern white cedar). However, all seem to have lower MC in early to mid-fall. Most of the variation and moisture content is occurring in sapwood, and in all species, tops are wetter than the lower parts of the bole. This is due to a higher proportion of sapwood in the upper part of the tree.

These findings are not fully consistent with Greenidge (1957) who reported that patterns in moisture movement in normal trees differs widely within species, between species and different structural types (i.e. ring porous, diffuse-porous and gymnosperms).

Gingras and Sotomayor (1992) studied MC variation in standing trees, harvested trees and stored logs for over one year. They found that in standing trees MC is higher in soils where water is not secured (trees store more water) and observed that there is an effect on the tree between different geographical areas. Seasonal patterns are similar to what Clark and Gibbs (1957) found (there is not a general pattern; however there is a lower MC in early-fall). They also found that MC falls rapidly within the first five weeks of felling and leaving branches and tops attached to the stem greatly increases overall MC loss.

Beedlow *et al.* (2007) concluded in a study in Douglas-fir that there is little seasonal variation in 100 year-old trees. Different to what Clark and Gibbs (1957) found, they concluded that MC markedly increased during late spring and reached a minimum in fall. They reported these differences from maximum and minimum to be approximately 5% MC.

All of these authors except for Beedlow *et al.* (2007) took sample wood discs and used the oven drying method to determine moisture content. The study performed by Pong *et al.* (1986) described bole wood moisture pattern through tree height. Their study was done in Douglas-fir and Western hemlock. Their tree selection was from a randomly stratified sample based on tree DBH (diameter breast height). This is also supported by Maguire *et al.* (1999) whose study concludes that tree diameter is a good predictor of branch size in second growth Douglas-fir. Pong *et al.* (1986) sampled wood discs and cores in different trees with no temporal consideration. They found that highest moisture content occurred at the base of the tree, decreased to a lowest point in the middle third of the tree, and then increased again in the upper stem. Western hemlock was considerably wetter than Douglas-fir at all heights and in both heartwood and sapwood. Results suggested that the moisture profile in green sapwood remains fairly constant with height, and the impact of moisture in green density profiles was much more evident in heartwood than sapwood. This study indicated that higher MC should be expected higher up in the trees.

Markstrom and Hann (1972) studied three species from the Rocky Mountains, including Douglas-fir. They sampled five trees of each species during each four physiological seasons, and five additional trees per species during each month of the growing season. They also extended their study for an additional year to verify if there was an effect of annual changes. They found that sapwood MC were the highest during winter freeze-up for all species. They also concluded that both the outer and inner heartwood of Douglas-fir showed no real change in MC throughout the year, but season does have an effect in the sapwood MC.

Parker (1954) studied ponderosa pine and Douglas-fir stem moisture content through 10 months. His study revealed that Douglas-fir heartwood remains practically constant through the year (~23% water, wet basis [100*weight of water divided by wet weight]), sapwood is wettest in early winter (~55% water, wet basis) and driest in early summer (~50% water, wet basis). Heartwood in ponderosa pine is much wetter than Douglas-fir and follows the same pattern as sapwood through the year. Heartwood and sapwood are wettest in early spring (~53% and 56% water, wet basis respectively) and driest in mid fall (~47% and 52% water, wet basis respectively). He also concludes that needles greatly impact the amount of water loss in the branches and that stem water content apparently depends on the weather.

1.5 Modeling harvest residue drying rates

Fresh woody material that has been recently cut will approach equilibrium moisture content with its environment. The main factors affecting wood water transport in a controlled environment is ambient temperature and relative humidity, but in the forest, rain and wind are additional factors that can speed or delay the drying process. The relationship between wood drying and environmental factors can be described with laws of physics, and there are tools that can be used to model wood drying rates from their interaction.

Researchers have used a numerical method, Finite Element Analysis (FEA), in order to determine drying rates for wood and other materials (Ferguson and Turner, 1996; Hozjan and Svensson, 2011, Kováks *et al.*, 2010; ElGamal *et al.*, 2013, Marchant, 1976; Irudayaraj *et al.*, 1992). This method was initially created to solve structural mechanics problems and has expanded to many different research fields. The basic idea is to discretize problems into a finite number of elements where solving sets of equations in a continuous tridimensional object would be otherwise nearly impossible, especially when the problem is dynamic and complex differential equations need to be solved. The method gives an approximate solution and there are commercially available solvers that allow designing geometry, discretizing and describing the physic phenomena governing a certain problem.

Since weather drives changes in moisture and can be used to the economic advantage of the feedstock production, it is of interest to find drying rates through in-forest storage and determine how weather relates to its moisture content. FEA can be used to model drying rates of these residues over time using weather data and assumptions about their structure and material properties.

1.6 Harvest residues for energy production

Harvest residues can be used for energy production in form of liquid fuel as isobutanol, NARA (2016a) or by combustion for power generation within others such as briquettes or biochar. Currently, the most common use of this forest harvest by-product in the Pacific Northwest region is for power in co-generation plants.

The first step for power generation is combustion. During combustion, water evaporates first, and then wood volatile components are driven off at high temperatures. At a final stage, the combustible volatiles burn and carbon is oxidized (Bowyer *et al.* 2003). These exothermic reactions are the ones creating heat energy. However, the process has some energy loses; one of them is the energy to vaporize the wood water. After energy loses, the energy that can potentially be used is named *recoverable heat energy*, and it is inversely related to wood moisture content (Ince, 1979). This concept of the available and recoverable heat energy can be represented with a ratio named *combustion efficiency* and it can range from 80 to 60% depending on the wood moisture content (Bowyer *et al.*, 2003).

The energy produced by combustion heats water in a boiler to generate steam. Steam passes through a turbine making turn a rotor connected to a generator. The generator turns the mechanical energy from the rotor into electrical energy. Additionally, steam is recovered, cooled, condensed and stored in a water tank to be recycled back into the system.

1.7 Economic implications of moisture content reduction

Drier material is desirable for many reasons. It increases combustion efficiency for cogeneration resulting in higher price premiums paid by power plants; wet material generates less net energy per unit of input therefore creating a higher operation cost per KW-hr of power generation (Sessions *et al.,* 2013). Operational cost can be reduced by making transportation more efficient. As an example, a 13.7 m chip van transporting chips at 40% moisture content on a 5 hr round trip can save 18% in transportation cost compared to the same chip van with feedstock at 50% moisture content (calculation based on transportation cost of 100$/hr and load weight capacity of 24 green metric tons).

In general, residue collection and comminution are operations that follow timber harvesting. However, from the residue moisture standpoint, theory indicates that it would be the least convenient time to process and transport the material. As indicated in the previous sections, drying in the field can reduce the residue moisture content and with that, improve the economics to use it as a source of bio-fuel instead of burning it. Researchers such Acuna *et al.* (2012) already demonstrated the benefits of drying in the supply chain economics for a biomass operation in Australia.

1.8 Study sites

The Pacific Northwest has different climate regions that range from humid coastal in the states of Washington and Oregon, and alpine to semi-arid climate in rain shadow areas of Oregon, Washington and Idaho. This climate diversity provides growing conditions for different tree species, of which three have a major commercial role and sustain the forest sector economy in the region. The most relevant in Washington and Oregon is Douglas-fir (*Pseudotsuga* *menziesii*) growing along the Coast, central valley and up to 1,520 m elevation (Burns and Honkala, 1990), next in importance is western hemlock (*Tsuga heterophylla*) growing in the humid regions of coastal Oregon and Washington, and finally, ponderosa pine (*Pinus ponderosa*) growing in the arid regions of each state. Only Douglas-fir and hemlock represent more than 74% of timber harvested in Oregon by 2003 (Brandt *et al.*, 2006) and over 69% in Washington in 2014 (DNR, 2014) and is reason why this study focused on these species and the distinctive climate regions they grow in.

1.9 Summary

Fresh moisture content for forest harvest residues, specifically branches, is not found in the literature for the tree species in which this study is focused. In addition, the moisture content levels occurring on each season is not clear.

Numerous authors have been focusing on drying rates and moisture content prediction models of forest harvest residues or small logs for bio energy production. However, none of the current methods allows the flexibility to change residue distribution (shape), size, location, aspect, slope and other factors like a FEA model can.

Given the low profit margins of the utilization of forest harvest residues for biofuel production, this study is focused on finding ways to take advantage of climate conditions to reduce costs and increase feedstock value through making better management decisions. In order to achieve this goal, there are three specific objectives covered in this dissertation:

a) Determine initial moisture content of fresh forest harvest residues and its seasonal changes for the main commercial forest species in the Pacific Northwest (western hemlock, Douglas-fir and ponderosa pine)

b) Use FEA to model drying rates for in-forest stored harvest residues driven by weather variables to maximize drying and determine best storage configurations.

c) Determine economic advantages of delayed harvest residue collection and transport for the two main forest harvesting systems used in the Pacific Northwest and refine supply and cost estimates by considering the energy content of harvest residues for energy production.

This dissertation includes three manuscripts; each one is interdependent of the other. The first manuscript (Chapter 2) presents moisture content of fresh tree branches and their changes over the four seasons of the year. How moisture content depends on branch size and height on the tree. This study was performed as a repeated measures statistical design in forest sites representing the four main climate regions and commercial tree species in Oregon. The second manuscript (Chapter 3) presents the development of four FEA models predicting drying rates for similar sites described in Chapter 2. In addition, it shows how does residue drying rate changes given different pile shape, volume, porosity and season in which drying starts. The last manuscript (Chapter 4) focuses on determining the lowest cost of harvest residue delivery depending on the logging method (cable or ground-based), the different drying rates occurring for both types of harvest units and the advantages of considering their energy value for energy production. This problem was developed as a mixed integer linear program for the first objective and as a mixed integer non-linear program for the second using a case study with real Douglas-fir harvest units. Drying rates were determined with one of the Chapter 3 FEA models that had similar climatic and geographic conditions.

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2 Seasonal changes in live branch moisture content of three forest species in the Pacific Northwest, USA

2.1 Abstract

Moisture content management is a key requirement to improve forest harvest residue economics for biofuel production. The best way to approach a moisture management strategy is to understand how much moisture is in fresh forest residues at different seasons of the year. Branches are a large component of these residues, especially when pulp prices are high, diverting residual bole components to pulpwood. Literature is not clear about seasonal moisture patterns for the main commercial Pacific Northwest species and most of it focuses on bole wood. A repeated measurements experiment design was implemented in order to determine seasonal moisture content changes at four sites in Oregon: Willamette Valley Douglas-fir, higher elevation Douglas-fir, ponderosa pine and western hemlock. From all sites, the highest moisture recorded was 50% (wet basis) in ponderosa pine during the winter; the lowest was 43% in the summer for both the same ponderosa pine and Willamette Valley Douglas-fir. When compared by season, ponderosa pine had significantly higher moisture content in the winter than in other seasons (1.6 to 9.8% higher). Summer moisture content was also significantly lower than fall moisture content for ponderosa pine (5.4 to 2.5% lower). Willamette Valley Douglas-fir had significantly lower moisture content during summer than during other seasons (0.8 to 3.9% lower). Water supply seems to be an important factor contributing to branch moisture content changes. Regression equations were developed for the different species to predict branch moisture content from branch height with a coefficient of determination (R^2) ranging from 0.73 to 0.84. Branch heartwood diameter, with a coefficient of 0.90 for all species, was found to be a

more accurate alternative for predicting branch moisture content, but it requires destructive sampling.

Keywords

Moisture content; branch; seasonal; harvest residues; Pacific Northwest

2.2 Introduction

One of the biggest challenges for the use of forest harvest residues as an energy source in the Pacific Northwest is its high transportation cost. The main causes for high transportation costs are long distance to consumption centers, low biomass bulk density and high moisture content. Material with high moisture content decreases truck load capacity by reaching vehicle allowable weight limits before the trailer volume limit is reached. Up to 50% of the mass of the trailer load of harvest residues can be water. Transporting water, rather than wood, increases transportation cost and, in the case of material used for boiler fuel, decreases heating value (Sessions *et al.*, 2013).

It has been demonstrated that wood moisture content can be decreased in-forest by air drying. It has also been reported that drying rates depend on several factors such as season, local weather, initial moisture content and storage configuration (Hakkila, 1989). Having an understanding on how these factors affect moisture content changes presents an opportunity to make changes in management decisions in order to facilitate in-forest drying.

Forest harvest residues are composed of tree tops, chunks, small diameter trees and branches. Branches are an important component, especially when pulp market prices are high. During periods of high pulp prices, log utilization increases as logs of smaller top diameter (pulp logs) are removed during logging, and if the pulp price is high enough, log chunks are recovered during a post-harvest operation, leaving primarily branches. For that reason, this study is focused on branch moisture content.

The starting point in managing branch moisture content is to understand the moisture content of the branch at the time the tree is cut. Current literature presents different conclusions regarding live tree moisture content and seasonal changes. Numerous authors have studied tree moisture content changes at different seasons of the year; some of them have focused on broadleaves and some in conifers (Clark and Gibbs 1957, Gibbs 1957, Greenidge 1957, Gingras and Sotomayor 1992, Beedlow *et al.* 2007, Pong *et al*. 1986, Markstrom and Hann 1972, Parker 1954). Most agree that there is a moisture content minimum in mid to late fall; others state it varies greatly within species and trees and others have concluded that fluctuation is minimal. All their moisture content observations have been based at tree level.

Live branch moisture content (initial moisture content) is currently not available; having this information for the three main commercial species in the Pacific Northwest would be valuable to determine what levels of moisture can be expected when this material is fresh, and whether the felling season makes a difference. For those reasons, the objective of this study is to determine the seasonal average moisture content for tree branches and their seasonal changes, focusing on Douglas-fir (*Pseudotsuga menziesii*) ponderosa pine (*Pinus ponderosa*) and western hemlock (*Tsuga heterophylla*) as the main commercial forest species in the Pacific Northwest. With this study, we intend to be able to answer the following research questions:

- What is the seasonal average moisture content of fresh branches for the three main commercially relevant Pacific Northwest tree species?
- Are these average moisture contents statistically different between seasons?

- Is there an effect of height on branch moisture content?
- Is there an effect of heartwood on branch moisture content?

2.3 Methodology

2.3.1 Site selection

According to the available forest resource that is being currently harvested in the Pacific Northwest and has potential for biomass production, three species and four locations were identified to place research units (Table 2.1).

The main requirement for each forest unit was a forest at harvest age or close to harvest age for typical forest landowners in the region. Location and description for each site are the following:

Table 2.1 Research unit location

Site description	Location	Elevation (m)	Average annual rainfall (mm)	Coordinates
Willamette Valley Douglas-fir	Corvallis, OR	283	1,092	44°39'29.13"N, 123°15'40.30"W
Higher elevation Douglas-fir	Oakridge, OR	871	1,154	43°30'17.80"N, 122°21'04.91"W
Ponderosa pine	Sisters, OR	1,003	330	44°18'37.75"N, 121°36'05.43"W
Western hemlock	Newport, OR	201	1,778	44°47'09.42"N, 124°03'04.67"W

While all research units were close to harvest age, they had differences given the varied management purposes and species. Twelve trees were sampled at each site (Table 2.2).

Table 2.2 Total height and DBH (diameter at breast height) of twelve sampled trees at each site

Site description	Age (years)	Total height (m)		DBH (cm)	
		Average	SD	Average	SD
Valley Douglas-fir	40-100*	34.7	5.2	55.6	10.9
Higher elevation Douglas-fir	51	30.5	4.2	38.9	8.1
Ponderosa pine	50-150**	19.6	3.3	38.6	7.6
Western hemlock	45	19.1	3.6	37.1	8.1

*Uneven aged stand estimate, ** Age estimated from stand structure and a report on a similar study (Youngblood *et al.*, 2004)

2.3.2 Sampling procedure

To obtain branch moisture content, branches in live trees were cut by a tree climber and then immediately sampled in the field. In order to minimize tree-to-tree variation, the same trees were repeatedly sampled through each season. The effect of cutting a few branches would not have a significant effect on the overall tree moisture; trees lose branches naturally through their life cycle (Dr Kate McCulloh, pers. comm. May 2013).

The number of trees to be selected was determined using information from a woody biomass moisture content data base. This data base consisted of moisture content measured in biomass on trucks arriving to a cogeneration plant in Eugene, Oregon. The data was collected from January 2011 to June 2012 corresponding to 3,109 loads and was separated by Eastern and Western Oregon provenance. This data was the best local information at the time that could be used to make an estimate of the seasonal moisture content averages and variability.

In order to eliminate the microsite variability that would exist if different trees were to be sampled each season, the experiment was performed as a repeated measures design. One thousand simulations were performed to find the appropriate sample size to achieve power greater than 0.80. The test result indicated that having 4 trees was enough to achieve power of 0.99; however, knowing the data not only includes branches and was processed (ground) before sampling, a safety factor of 3 was used to determine the number of trees to be sampled, that is a total of 12 trees per site.

After a buffer zone was defined to avoid selecting edge trees, a tree was chosen systematically approximately every 24 m following a bearing along the unit length. This was done so one or two transects were formed depending on the forest unit shape (Figure 2.1).

Figure 2.1 Tree selection in two transects following North bearing

The number of branches to be cut per tree was a decision based on a combination of criteria: literature, field experience and cost. We did not have branch moisture content information specific for these forest types that could give us a better lead to determine branch sample size.   Temesgen *et al.* (2011) worked on a study to estimate crown biomass through branch measurements. They found that the root mean squared error for biomass estimation was reduced by 43% when sample size was increased from 6 to 12 branches, for that reason we decided selecting 9 branches was a good compromise. However, in practice, many trees do not have enough branches to destructively sample four times and cut 9 branches each time without having a significant effect on the tree. For that reason we decided to take three branches each season and reduce that number if a tree still seems to have too few branches to return four times.

Dead branches were initially planned to be sampled since they are likely to have different moisture content than regular live branches. However, we expect that none of them (or very few) will end in a forest harvest residue pile. Most will shatter when they hit the ground.

Temesgen *et al.* (2011) also found random sampling not to be ideal for biomass estimation and stratified sampling works better. In their sampling, they divided the crown in thirds and randomly selected branches within each section.

Drawing from all this information, the best sampling protocol for our purposes and budget was to randomly choose and cut one branch from each third of the crown. Then, since literature suggests that sapwood and heartwood have different moisture contents, a wood disc was cut every 0.6 m on each branch in order to better capture moisture content as heartwood proportion decreases along the branch (Figure 2.2).

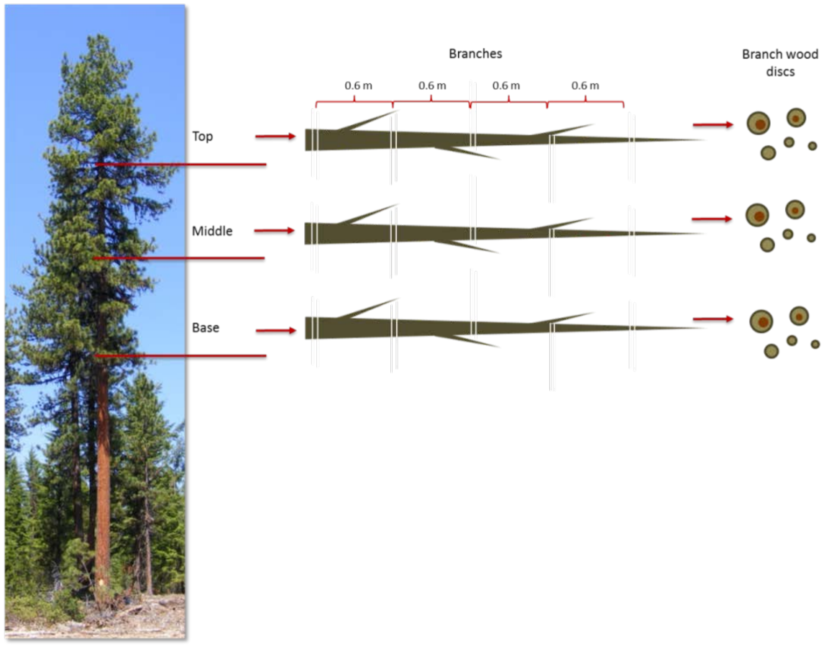

Figure 2.2 Branch sampling protocol

Samples were placed in air tight bags and weighed green right after collection. Later, they were oven dried for 24 hours at 103°C and weighed dry following ASTM standard E871-82 for moisture analysis in particulate wood fuels (ASTM international, 2006).

Branch disc diameter under/over bark and sapwood was recorded. Moisture content was determined and reported in this document on a wet basis (weight of water divided by total weight including bark). In addition to the samples, tree total height, branch height on the tree, tree DBH, and branch length was collected in order to investigate any wood moisture content correlation with other measurable characteristics. The branch sampling protocol was repeated on the same 12 trees once per each four seasons during one year between 2013 and 2014.

2.3.3 Statistical analysis

Different statistical procedures were used to be able to answer the questions needed to address the objectives of this study.

2.3.3.1 Average moisture content by species

In order to determine the differences in average moisture content by species, we needed to define a random effects model. Let y_{ij} be the average branch moisture content of tree j of species i, the model can be described as follows:

$$y_{ij} = \mu + A_i + B_{ij} \quad (i=1,2,3,4\ ;\ j=1,2,\ldots 12) \qquad \text{(Eq. 1)}$$

Where μ is the average branch moisture content for the entire population. A_i is the species-specific random effect and B_{ij} the tree-specific random effect.

After performing one-way ANOVA, Levene's test for homogeneous variances (Kuehl, 2000) indicated departures from the equal-variance assumption. For that reason, Welch's test two-sample t-test was used to determine differences in means, and the Bonferroni correction for six procedures applied in order to make the appropriate inferences.

2.3.3.2 Seasonal moisture variation

Since field measurements were performed on the same individuals on four different times of the year, one-way repeated measures ANOVA was used for this longitudinal study. In order to determine seasonal differences, each species/site analysis was made separately to isolate any effect the species may have. That is, a total of four separate analyses were performed. The model for this analysis is described in Eq.2. Let y_{jk} be the average branch moisture content of tree j in time (season) k,

$$y_{jk} = \mu + C_j + D_k + e_{jk} \quad (j=1,2,\ldots.12\ ;\ k=1,2,3,4) \qquad \text{(Eq. 2)}$$

Where μ is the average branch moisture content for the entire population. C_j is the individual difference component for tree j, D_k is the effect of time (in this case season of the year) and e_{jk} error for tree *j* and season *k*. Since the sphericity assumption was not possible to assess accurately, a Huynh-Feldt correction factor was applied to the probabilities for a conservative estimate.

If there was a significant effect of season for a specific species, the procedure followed with pairwise comparisons (pairwise t-tests) to determine which seasons differed with each other.

2.3.3.3 Branch height effect on moisture content

In order to establish the relationship between branch height and branch moisture content, a one-way ANOVA was performed to determine if there was an effect of height in moisture content. If there was convincing evidence of an effect, several linear regression models were fitted (linear, polynomial, logarithmic, etc.) following the general model described in Eq. 3. Let *y* be the average branch moisture content of a given tree at height *h*, the model can be described as follows:

$$y_h = \beta_0 + \beta_1 x + e \qquad \text{(Eq. 3)}$$

Where x is the branch height within the tree, β_0 and β_1 are model parameters. When the data set was separated by species, the general regression was set as follows:

$$y_{ih} = \beta_0 + \beta_1 x_i + e \quad (i=1,2,\ldots.12) \qquad \text{(Eq. 4)}$$

Where y_{ih} is the average branch moisture content of a tree of species *i* at height *h* and x_i is the branch height of a tree of species *i*.

2.3.3.4 Heartwood effect on branch moisture content

In order to find the relationship between branch heartwood diameter and branch moisture content. First a two-sample t-test was performed to determine if there was an effect of heartwood presence in average moisture content of a branch wood disc. If there was convincing evidence of an effect, several linear regression models were fitted (linear, polynomial, logarithmic, etc) following the general model described below.

$$s = \beta_0 + \beta_1 hd + e \quad \text{(Eq. 5)}$$

Let *s* be the average branch wood disk moisture content of a given branch, and *hd* is the heartwood diameter of that given wood disk, β_0 and β_1 are model parameters.

Once this relationship was demonstrated, an ANOVA was performed to determine if there was an effect of the heartwood diameter at the branch attachment point (named "first sample") and the average branch moisture content. Once the effect was established as significant, a linear regression model was fitted that would allow to predict average branch moisture content from the heartwood diameter of the branch at the point of attachment on the tree. The model is shown in Eq 6.

$$y_d = \beta_0 + \beta_1 hd1 + e \quad \text{(Eq. 6)}$$

Let *y* be the average branch moisture content of a given tree with heartwood diameter *d*. And *hd1* is the branch heartwood diameter at point of attachment; β_0 and β_1 are model parameters. When the data set was separated by species, the general regression was set as follows:

$$y_{id} = \beta_0 + \beta_1 hd1_i + e \qquad (i=1,2,\ldots.12) \qquad \text{(Eq. 7)}$$

Where y_{ih} is the average branch moisture content of a tree of species i with branch heartwood diameter d and $hd1$ is the branch heartwood diameter at point of attachment of a tree of species i.

A randomized subset of 30% of the data was excluded from the regression analyses so it could later be used for validation. All the analyses were performed using R except for the contrasts performed in SPSS.

2.4 Results

2.4.1 Bark proportion

During four seasons and in four sites, 3,245 wood discs were collected from 759 branches. Branch length ranged from 38 cm in ponderosa pine up to 871 cm in Douglas-fir. Diameter over bark ranged from 5.1 to 109 mm. The highest branch was located at 40 m and the lowest at 2.4 m.

Bark proportion in ponderosa pine samples was highest, followed by Willamette Valley Douglas-fir. Western hemlock presented the lowest proportion. As the branch diameter increases, bark proportion decreases for all species (Figure 2.3).

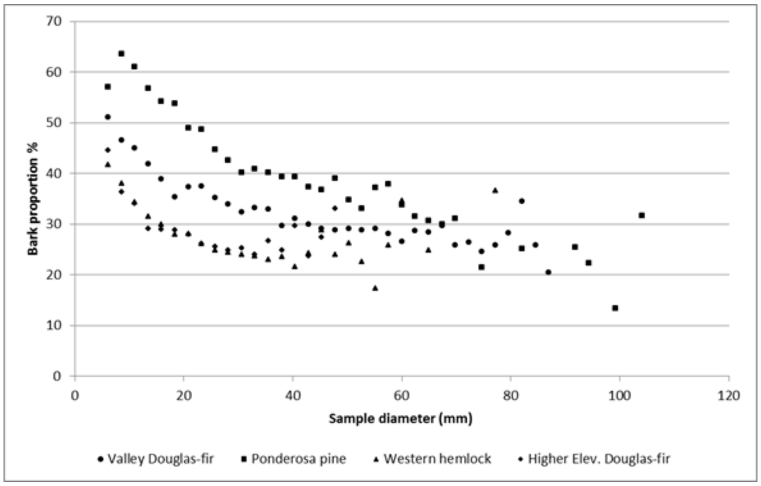

Figure 2.3 Branch bark proportion (100* [(A_{DOB}-A_{DUB})/A_{DOB}]). Where A_{DOB} is the sample cross sectional area over bark and A_{DUB} is the sample cross sectional area under bark

2.4.2 Average branch moisture content

The first observation after calculating a diameter-weighted tree branch moisture content average is the variability within species and sites. After making an assessment for assumptions, data showed departures from equal-variance, for that reason Welch's test was used to test for differences in means. Only Valley Douglas-fir compared with Western hemlock and higher elevation Douglas-fir have significant differences in weighted average moisture content (Welch's two-sample t-test with the Bonferroni correction p-values < 0.001) (Figure 2.4). The test was adjusted with Bonferroni for six procedures (number of comparisons of species pairs).

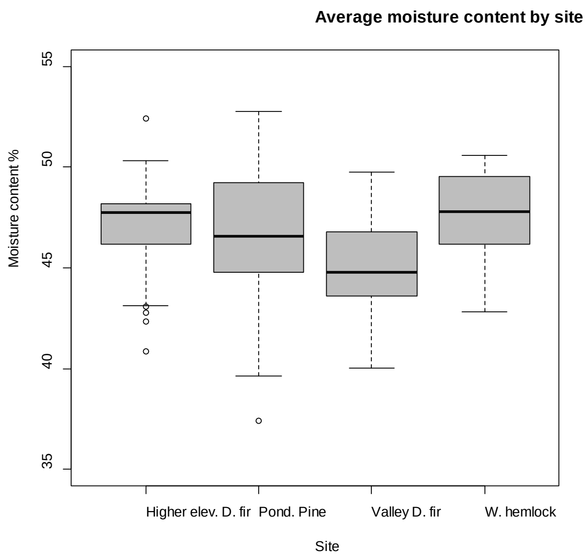

Figure 2.4 Branch moisture content weighted average by site

The boxplots in Figure 2.5 show high moisture content fluctuations within ponderosa pine trees and stability in western hemlock.

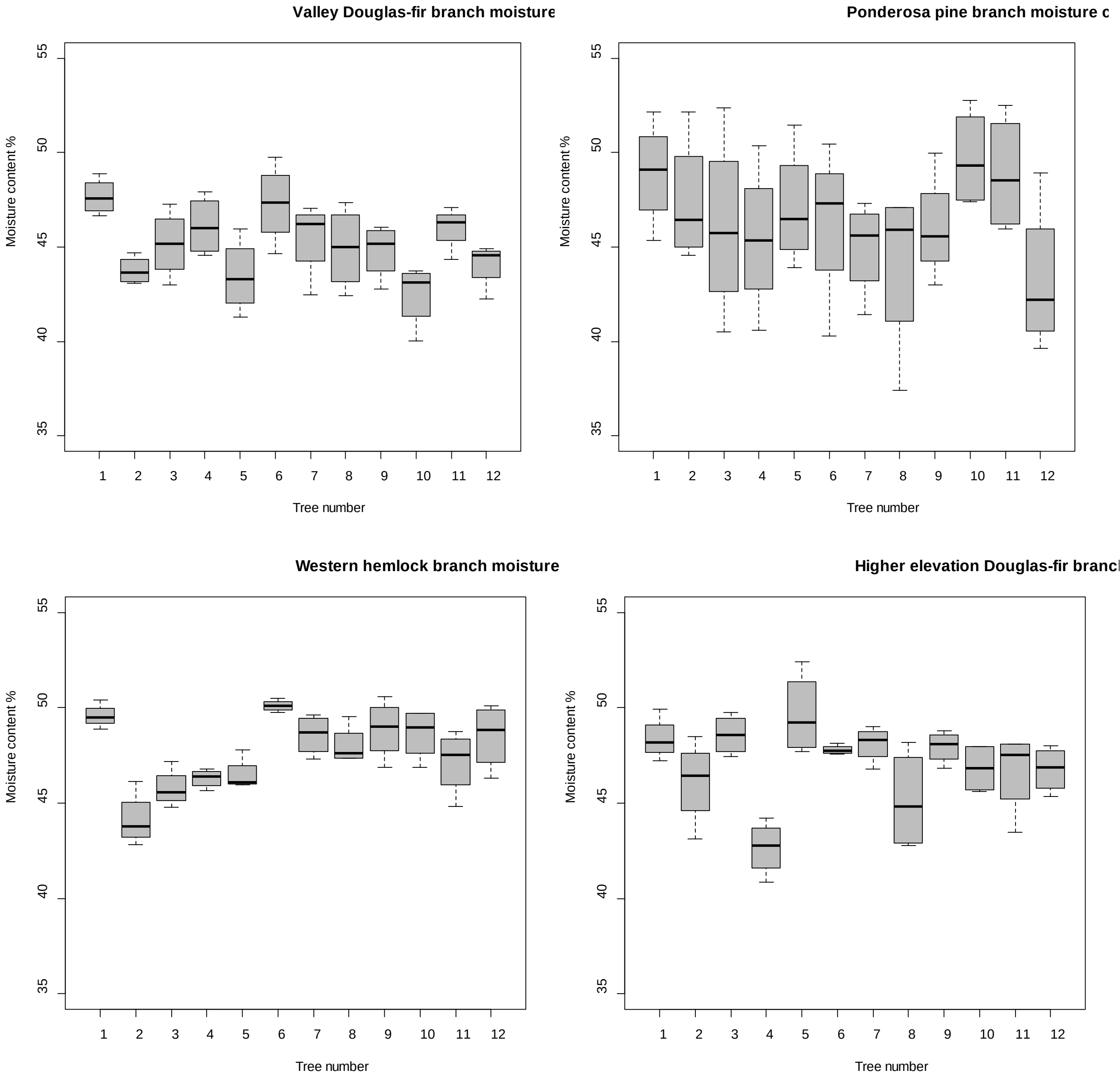

Figure 2.5 Tree average branch moisture content, independent of season

In general, most trees consistently had higher moisture content in the upper third of the crown and lower moisture content in the lower third of the crown, independent from season (Figure 2.6).

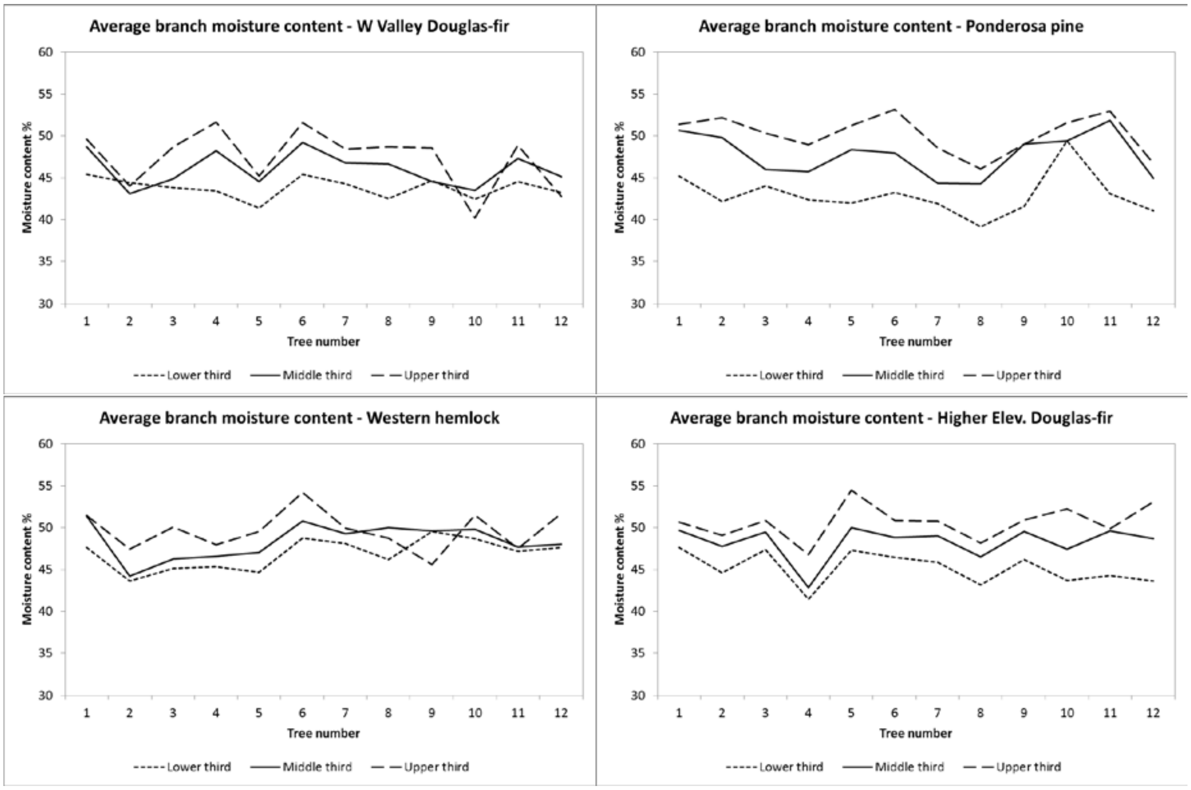

Figure 2.6 Average branch moisture content by crown level, independent of season

When branch average moisture content is examined by season, the lowest moisture contents occur during summer (43 %) and highest during fall or winter (50 %) depending on the species. There is not a clear pattern to identify differences (Table 2.3) without additional statistical analysis.

Table 2.3 95% confidence intervals for weighted average seasonal branch moisture content (%) by site

Site	Fall	Winter	Spring	Summer
Valley Douglas-fir	46 ± 1	45 ± 1	46 ± 1	43 ± 1
Ponderosa pine	47 ± 1	50 ± 1	45 ± 1	43 ± 1
Western hemlock	47 ± 1	48 ± 1	48 ± 1	47 ± 1
Higher elevation Douglas-fir	46 ± 1	48 ± 1	47 ± 1	47 ± 1

2.4.3 Seasonal moisture variation

In order to address the seasonal differences in mean branch moisture content, the best approach was to perform one-way repeated measures ANOVA for each of the species separately. Species were defined a-priori in order to determine whether the seasonal effect is different depending on the regional climate.

Since Mauchly's test is not appropriate to assess the sphericity assumption, all p-values are reported with the Huynh-Feldt correction for conservative probability estimation. At a significance level of $\alpha = 0.05$, results indicate that there is a significant effect of season in ponderosa pine and Valley Douglas-fir branch moisture content (One-way repeated measures ANOVA, H-F $p < 0.0001$). Western hemlock shows a suggestive but inconclusive effect of season (One-way repeated measures ANOVA H-F $p = 0.036$) and higher elevation Douglas-fir indicates no effect of season (One-way repeated measures ANOVA H-F $p = 0.097$).

Valley Douglas-fir and ponderosa pine seem to have the most noticeable moisture content differences between seasons (Figure 2.7), both showing the lowest moisture contents during summer. Most species seem to increase branch moisture content after summer.

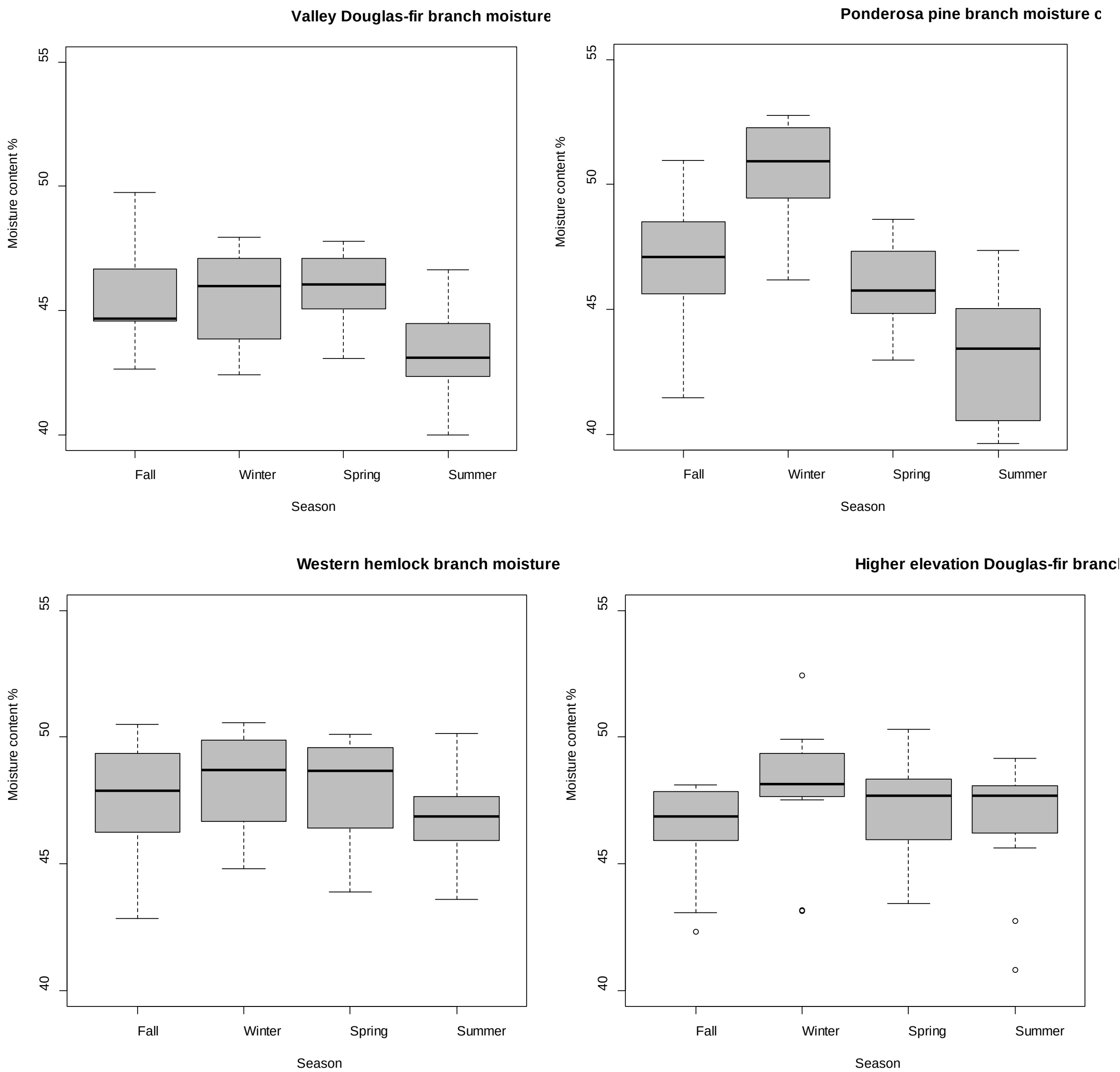

Figure 2.7 Average branch moisture content by season

Since the main effect of season was significant for three species, post hoc pairwise tests were performed. After taking into account the repeated measures, for Valley Douglas-fir, probabilities show that the difference in mean branch moisture content is statistically significant between summer and every other season (pairwise t-test p-values < 0.01), with summer being the season with the lowest mean moisture content. Tests in ponderosa pine indicate significant differences in mean branch moisture content between winter and every other season (pairwise t-test p-value < 0.01), with winter being the season with highest mean branch moisture content. Additionally, for the same species, there was a statistically significant mean branch moisture content difference between fall and summer (pairwise t-test p-value < 0.01) (Table 2.4).

After performing pairwise comparisons in western hemlock, there was no evidence of difference in mean branch moisture content between seasons (pairwise t-test p-values > 0.50).

Table 2.4 Pairwise comparisons for difference in seasonal means

	Valley Douglas-fir			**Ponderosa pine**		
	Confidence Interval			**Confidence Interval**		
Season	**lower**	**upper**	**p-value**	**lower**	**upper**	**p-value**
Spring-Fall	-1.13	1.71	1.00	-4.55	1.22	0.55
Summer-Fall	-3.67	-1.02	0.001*	-5.39	-2.46	< 0.001*
Winter-Fall	-1.98	1.74	1.00	1.55	5.44	0.001*
Summer-Spring	-3.88	-1.38	< 0.00*	-5.66	1.15	0.34
Winter-Spring	-2.15	1.33	1.00	2.70	7.62	< 0.001*
Winter-Summer	0.75	3.69	0.003*	5.00	9.83	< 0.001*

2.4.4 Branch height effect on moisture content

Since branch height is considered a good predictor for moisture content, an analysis was made in order to determine and define this relationship. An analysis of variance test provides convincing evidence (one-way ANOVA p-value <0.0001) of an effect of branch height on mean branch moisture content. Therefore, a regression analysis was made using branch height as an independent variable and mean branch moisture content (weighted average of all samples within the branch) as dependent for all species and seasons. After fitting different types of curves, the best fit was a natural log function ($R^2 = 0.73$), (Figure 2.8a).

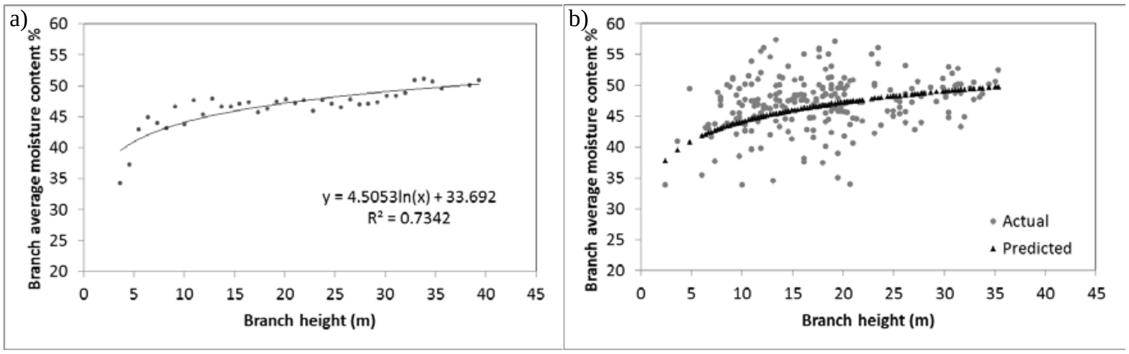

Figure 2.8 a) General equation for average branch moisture content estimation by height, b) Actual versus predicted values for the validation subset

When the data set was analyzed by species, the coefficient of determination increased for all species when compared with the general equation. These specific equations might be a better option if aiming to predict average branch moisture content on these specific sites (Table 2.5).

Table 2.5 Prediction equations for branch moisture content estimation

Site	**Regression equation**	**R^2**
General	mc = 4.50ln(*h*) + 33.694	0.73
Valley Douglas-fir	mc = 9.27ln(*h*) + 15.93	0.82
Ponderosa pine	mc = 7.04ln(*h*) + 28.49	0.74
Western hemlock	mc = 5.19ln(*h*) + 34.337	0.75
Higher elevation Douglas-fir	mc = 7.72ln(*h*) + 23.90	0.84

h = branch height (m)

2.4.5 Heartwood effect on branch moisture content

Another factor considered while gathering data was heartwood diameter. The ponderosa pine data set was excluded from this analysis since it was not possible to distinguish heartwood visually and it could not be measured on the samples.

The graph (Figure 2.9) suggests a difference between moisture content of samples containing heartwood. Apparently, its presence results in a reduction in mean moisture content, ranging between 25 and 50%. The range in moisture for samples without heartwood is wider, given that samples without heartwood are 85% of the total number of samples, with a mean centered at 50%.

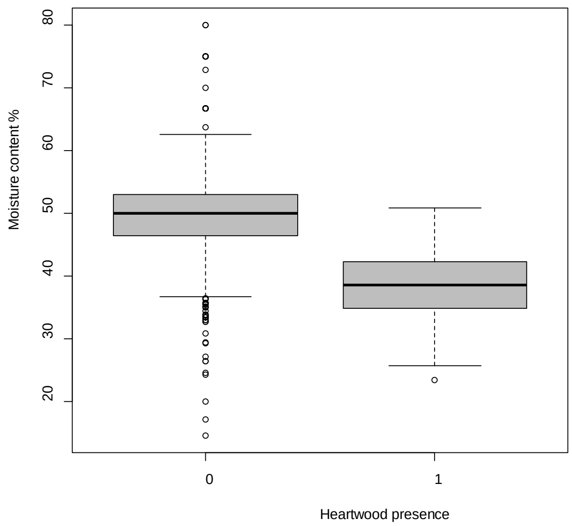

Figure 2.9 Effect of heartwood presence in sample moisture content: 0=not present, 1= present

When performing ANOVA, the test provides strong evidence (two sample t-test p-value <0.0001) of an effect of sample heartwood diameter and sample moisture content. Therefore, a regression model was fitted using branch samples, independent from species and collection season. By fitting a second degree polynomial function to samples with heartwood presence, the coefficient of determination is $R^2 = 0.90$ (see Appendix A) which means that heartwood diameter in the sample, explains over 90% of the sample's moisture content. As the amount of heartwood increases, moisture content decreases (Figure 2.10).

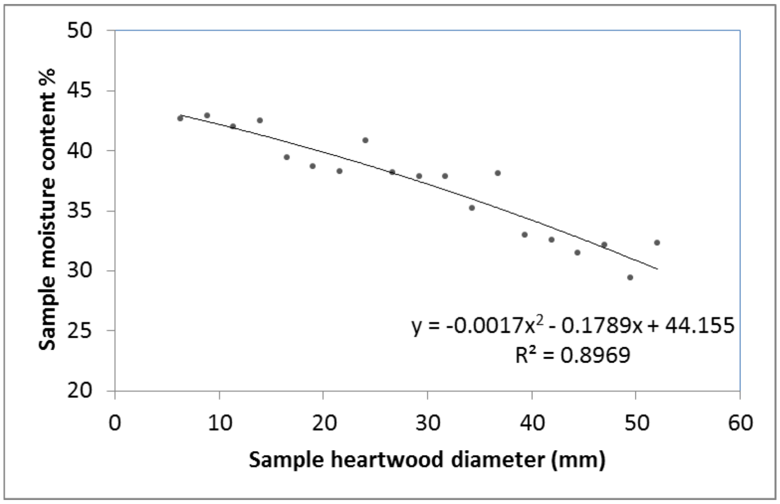

Figure 2.10 Sample moisture content by heartwood diameter

Since having to take samples over the entire extent of the branch in order to predict its moisture content might be time consuming, the possibility of finding a relationship between the branch moisture content and heartwood diameter of the sample taken closest to its attachment point was explored. This would allow making an estimation of the overall branch moisture content by measuring the heartwood diameter at the base of the branch.

This analysis was made ignoring the season and species in order to obtain a general equation for the three species group. Analysis of variance provides convincing evidence (one-way ANOVA p-value <0.001) of an effect of first sample heartwood diameter and branch mean moisture content (see Appendix B). When a regression analysis was performed, the best fit was obtained with a linear function (R^2 = 0.74) (Figure 2.11). The sample closest to its attachment point is identified as “first sample”. Branch average moisture content decreases as the amount of heartwood in the first sample increases (Figure 2.11a). Model validation is shown in Figure 2.11 b); the graph was constructed by using the validation data set.

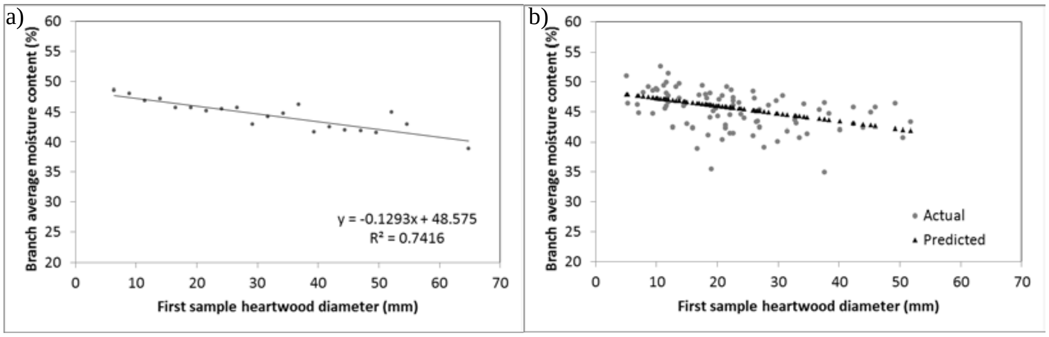

Figure 2.11 a) General equation for average branch moisture content estimation by first sample heartwood diameter, b) Actual versus predicted values for the validation subset. First sample is sample closest to the branch attachment point

When the data set is analyzed by species, the regression models have lower coefficients of determination. However, they all are greater than 50% significance (Table 2.7).

Table 2.7 Prediction equations for branch moisture content estimation

Site	**Regression equation**	R^2
General – 3 species	mc = -0.129*hd* + 48.57	0.74
Valley Douglas-fir	mc = -0.112*hd* + 47.93	0.67
Western hemlock	mc = -0.4061*hd* + 53.41	0.74
Dry Douglas-fir	mc = -0.2831*hd* + 51.31	0.66

hd = first sample heartwood diameter (mm)

2.5 Discussion

Higher bark proportion in ponderosa pine and Willamette Valley Douglas-fir was to be expected, Miles and Smith (2009) reported that ponderosa pine has a higher bark proportion in the bole compared with the other two species in this study, and is a species known to have thick bark due to fire adaptation. Willamette Valley Douglas-fir could have a thicker bark because of its larger tree size. Kohnle *et al.* (2012) showed that double bark thickness is correlated with tree size for various Douglas-fir provenances. Even though bark moisture content was not determined in this study, Hakkila (1989) indicates that bark has a higher branch moisture content compared with wood in the summer; consequently, higher branch moisture content in these species in the summer season could be related to higher bark moisture content.

General branch average moisture content for each species and geographic location was calculated. After testing for differences in mean moisture content between species, only Douglas-fir growing in the Willamette Valley shows significant differences when compared with higher elevation Douglas-fir and western hemlock. This suggests that differences are related to site conditions rather than species. This is consistent with what was found by Gingras and Sotomayor (1992). Furthermore, at the tree level, the higher variability in average moisture content found in ponderosa pine in contrast with more stable western hemlock could explain the same phenomenon. The same authors concluded that MC is higher in trees where water supply is not secured; this is most likely the case of ponderosa pine in the high desert during winter (Figure 2.7).

Data shows that higher moisture contents are found in higher branches in the tree and lower moisture contents in the branches of the lower portions of the tree, this trend was found in 96% of the trees sampled and it is consistent with what was found for bole wood by Clark and Gibbs (1957) and Pong (1986). The average moisture content variability within different seasons is not large, corroborating findings of Clark and Gibbs (1957), Beedlow *et al.* (2007) and Gingras and Sotomayor (1992). However, two species were found to have statistically significant differences in average moisture contents between seasons. Douglas-fir growing in the Willamette Valley contains significantly lower moisture content in summer compared with all other seasons; this difference ranges from -3.9% to -0.8% (95% CI for difference). This result agrees with what was found by Beedlow *et al.* (2007) for Douglas-fir bole wood, where differences in moisture content were less than 5% MC.

In ponderosa pine, significant differences in mean MC were found between winter and every other season, with winter being the season with highest moisture content. Differences range from 1.6% to 9.8% (95% CI for difference), summer being the season with the largest difference. Additionally, there were significant differences between summer and fall ranging from -5.4% to -2.5% (95% CI for difference). These differences could indicate rapid water replenishment with the first fall rain events.

In general, these results do not agree with lowest moisture contents reached by bole wood in the fall as found by Clark and Gibbs (1957) and Beedlow *et al.* (2007). It has been reported by several authors (Dobbs and Scott (1971), Waring and Running (1978), Loustau *et al.* (1996), Phillips *et al.* (2003), Cermák *et al.* (2007)) that bole sapwood serves as a water reservoir. In trees that are subject to drought it could be that they adapt to keep amounts of water storage during most of the growing season until summer drought when they can no longer replenish it until first fall rains. Waring and Running (1978) observed that bole sapwood MC decreases in old growth Douglas-fir during the growing season reaching a minimum of 50% in mid-August. Additionally, Cermák and Nadezhdina (1998) found that for adult Norway spruce, bole sapwood was maximally hydrated in early spring and dehydrated substantially as summer drought approached.

Tree height and heartwood effects in moisture content are well described in the literature. After testing for main effects, both variables have a significant effect on MC and can be effectively used to predict branch moisture content independently. This is, because they are related to each other. Branches located closer to the tree top have a smaller proportion of heartwood than branches located at lower crown levels. Therefore, they have higher moisture contents. Species-specific regression equations have a correlation up to 0.84 using only the branch height to predict its average moisture content. Using the heartwood diameter at the branch attachment point does not increase the coefficient of determination compared with branch height (R^2 =0.74, for general species equation).

2.6 Conclusions

Seasonal branch moisture content was determined for four major commercial forests areas in the Pacific Northwest. This information is valuable to determine the starting moisture content of a significant portion of forest harvest residues prior to their in-forest storage depending on the harvesting season, forest species and location. Literature reports Douglas-fir bole sapwood moisture content at 53%, heartwood at 27%, ponderosa pine at 60% and 29% respectively (Bowyer *et al.* 2003). Becerra (2012) reports Douglas-fir small log moisture contents of 33% and 55% in summer and winter respectively; 51% and 66% moisture contents for western hemlock and ponderosa pine in the winter. Hakkila (1989) reports 54% for pine and 44% for spruce branches. In our study, only ponderosa pine averaged 50 ± 1% during the winter, all other site averages are below this MC although a few individual branches exceeded 55%. Residues with MC higher than 50% (wet basis) reported at cogeneration plants is probably due to re-wetting of the material, the inclusion of needles/leaves in the moisture content calculation and different species mix. White fir is a common species in the Pacific Northwest that can contain up to 62% MC in the sapwood (Glass and Zelinka 2010).

Higher initial moisture content can be expected in ponderosa pine residues during the winter. MC can be from 1.6% to 9.8% higher compared with other seasons. For Douglas-fir, initial moisture content can be expected to be lowest when water supply is limited during summer drought. MC can be from 0.8% to 3.9% lower when compared with other seasons. Western hemlock and Douglas-fir growing with a secured water supply do not present significant differences in MC.

Branch height and heartwood content have a strong correlation with branch average MC. Branch height explains up to 74% of branch moisture content by a simple regression. These equations can be used as a non-destructive method to estimate live branch moisture content. Using a sampling destructive method to measure heartwood diameter does not improve the coefficient of determination, making the branch height the simplest and most accurate predictor to estimate average branch moisture content in this study.

The scope of inference for this study is limited to the species and region where samples were taken. It cannot be generalized for other species. Further research could be performed by additionally measuring soil water supply and its effect on branch moisture content.

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3 Finite element analysis to predict in-forest stored harvest residue moisture content

3.1 Abstract

Numerous researchers have focused on ways of measuring and predicting wood moisture content in order to find the best field management practices that increase the economic value of small logs or forest harvest residues for bio-energy production. Most have focused on small logs and predicting models include methods such as heuristic fitting and multiple regression. Finite element analysis (FEA) is a method that provides the possibility of determining drying rates while offering the flexibility of changing the way in which these residues are stored, their shape and location, material properties and drying seasons within others. FEA was used to develop drying rates for four different climate regions in Oregon including, Willamette Valley (Douglas-fir), Higher elevation Douglas-fir, Coast (Western hemlock) and Eastern Oregon (Ponderosa pine). These models were compared with data obtained in the field in the same regions using an innovative sampling protocol. Statistical tests show model agreement with correlations between 0.56 and 0.92 (Kendall's tau) in all sites. After performing a sensitivity analysis, we can conclude that selection of pile shape or size can be beneficial or detrimental towards the rate of drying depending on ambient conditions. A berm (windrow) is the shape that promotes drying in the summer and re-wetting in the winter the most. It is best to reduce pile size to facilitate drying in summer, and increase pile size if material will be left in the field over the winter. Drying times can be reduced up to 1/3 if the material is cut and left to dry during the dry, warm summer months versus starting in the winter.

Keywords

Moisture content; drying rates; finite element analysis; harvest residues; Pacific Northwest

3.2 Introduction

Starting in 2005, the Renewable Fuel Standard program requires increasing amounts of renewable fuel blended into transportation fuel sold or introduced into commerce in the United States. By 2022, 80 billion liter of advanced biofuel will be required. Out of this amount, 61 billion liters should be cellulosic biofuel (Energy Independence and Security Act of 2007), which may be derived from various sources, including woody biomass.

Forest harvest residues are widely available in the US with estimates of over 127 million cubic meters produced yearly (Smith *et al.*, 2009). Despite a small demand from cogeneration plants; most of this material is burned in-situ for site preparation and fire hazard reduction, mainly because of high production costs and a developing market (U.S. Department of Energy, 2011).

High moisture contents of woody biomass are prohibitive factor in its application for bioenergy. Transportation costs can comprise up to 40% of the production cost (Zamora-Cristales *et al.*, 2015), hence, it is important to improve efficiency in context of moisture levels of transported materials. One notable inefficiency is that material with high moisture potentially limits transportation capacity based on weight constraints, but not by volume. That is, a significant proportion of the payload is free and bound water. For example, reducing moisture content from 50% to 40% reduces transportation costs up to 18% due to the increased bulk volume (calculation based on transportation cost of 100$/hr and load weight capacity of 24 green metric tonnes). This inherent moisture is also a primary cause for losses in recoverable heat energy when used for power generation. When a cogeneration plant pays for delivered biomass depending on its moisture content, potential price premiums can be as high as 14% per dry ton for moisture content reduction from 50% to 30% wet basis (Sessions *et al.*, 2013).

Moisture content of forest harvest residue has potential for in-situ drying with knowledge of ambient conditions. It responds to exposure to different environmental factors such as temperature, relative humidity, precipitation and air flow (Hakkila, 1989). Although ambient conditions cannot be controlled, other management factors can be altered in context of environmental conditions to expedite the drying process. Wood is usually stacked to increase air flow and facilitate drying (Simpson and Wang, 2003). In agriculture, hay is left to dry in windrows and several studies have been performed to determine the effects of ambient conditions and conditioning in their drying (Thompson 1981, Smith *et al.* 1988, Savoie and Beauregard 1990). However, there is limited literature that describes evaluation of the drying process for forest harvest residue, either experimentally or numerically.

Some studies have addressed the effect of storage time in forest harvest residue moisture content. Gautam *et al.* (2012) determined moisture content and fuel quality in the summer for piled residue of different ages (1, 2, 3 years old). Baxter (2009) determined changes in moisture for piled residue over ten months using digital meters. Routa *et al.* (2015) determined residue moisture content changes over 35-85 weeks using constant weight monitoring. Afzal *et al*. (2010) determined piled residue internal moisture content with destructive methods in three-month intervals over one year.

Gjerdrum and Salin (2009) built a drying model for poles using weather data and pole dimensions. Sikanen *et al.* (2012) developed biomass drying models for whole trees based on heuristics fitting and local weather in Finland. Kim (2012) developed drying models in Oregon for Douglas-fir and hybrid poplar small logs based on precipitation, evapotranspiration and piece size using linear mixed effects multiple regression models. These authors confirm the relationship between weather and drying rates in wood. However, none of them has focused on the use of physics to make moisture predictions or has focused in forest residues.

Since real-time monitoring and instrumentation of residue piles is not practical at a large scale, modeling physical changes driving residue drying serves as a better means of evaluating drying of residue under field conditions. One potential approach towards evaluating coupled physical processes under transient conditions is through application of Finite Element Analysis (FEA), which is used to solve sets of differential equations for a given continuum, boundary conditions and constitutive properties, discretized through a finite mesh of interconnected elements and nodes. The FEA framework is frequently used to evaluate a variety of physical behaviors exposed to change, including structural analysis, thermodynamics, diffusion, electrical conduction, and drying behavior of wood under controlled conditions (Ferguson and Turner, 1996; Hozjan and Svensson, 2011, Kováks *et al.*, 2010; ElGamal *et al.*, 2013, Marchant, 1976; Irudayaraj *et al.*, 1992). The equations governing each element are solved through a system of equations that can give an approximation of the body behavior as a whole (Fagan, 1992).

Ambient drying is a complex problem that involves various interdependent physics relationships, primarily including heat transfer, diffusion and laminar flow (movement of air and moisture surrounding a continuum), but can also include solar radiation and in some cases, turbulent flow (Curcio *et al.*, 2008). Heat transfer occurs by three different mechanisms: radiation, convection and conduction (Monteith and Unsworth, 2008). In the model presented, convection and conduction are considered to describe heat transfer between surrounding air and the residue pile. Both depend on the temperature gradient between the pile and air, and area normal to the direction of heat flow. Convection will also depend on the convective heat transfer coefficient of the surrounding fluid (air/water) and conduction, in both, air and pile thermal conductivity (Welty *et al.*, 2008). Diffusion describes the movement of species between media dependent on concentrations; in this case, the diffusion of moisture between the surrounding air and residue pile, which is most often described by Fick's law, demonstrating the relationship between the flux of diffusing species and the concentration gradient (Welty *et al.*, 2008). Therefore, diffusion will depend on concentration gradient and diffusivity coefficients. For wood, diffusivity will depend on its moisture content since the water contained in cell lumens can escape at a different rate compared to water bound to the cell walls (Baronas *et al.*, 2001). This water is chemically bonded, and it occurs when moisture content is below the fiber saturation point (Bowyer *et al.*, 2003). Diffusion and heat transfer are also driven by fluid momentum transfer, which manifests in this case by the movement of moist air at the surface of the pile (boundary layer). The behavior of this layer depends on fluid properties (in this case air) such as viscosity, density, pressure and velocity and the momentum transfer associated with shear stresses (Monteith and Unsworth, 2008). Often, the presented material properties are related and transient, typically varying with temperature and moisture content, necessitating a numerical analysis that can account for not only changing ambient conditions, but also changing material properties with time, requirements satisfied with FEA.

FEA provides the flexibility of changing drying season and duration, shape, size, location, porosity, moisture distribution within forest harvest residue piles, etc. These advantages cannot be achieved with the current methods and is the rationale for researching this methodology.

This project focuses on implementation of a FEA model that can aid in predicting moisture changes in piled forest harvest residues for given weather variables, informing opportunities to optimize drying of in-forest stored harvest residue. Data collected from a series of field experiments informed a series of baseline FEA models, enabling evaluation of drying sensitivity to various parameters. The results of these models provide further insight into pile drying behavior for given construction and ambient conditions, which can directly utilize data from a given weather station.

3.3 Methodology

3.3.1 Field Tests

In order to capture the primary regional climates and productive forest types of the Pacific Northwest, four monitoring units were set throughout the state of Oregon, located near Depoe Bay, Corvallis, Dexter, and La Grande, representing Coastal Western Hemlock forest, low-elevation Douglas-fir forest, high-elevation Douglas-fir forest and arid Ponderosa Pine forest, respectively (Table 3.1). Each of these units contained three residue piles built specifically to monitor environmental variables and internal drying behavior of the residue. Residue piles were constructed within one month of tree harvest in order to maintain green moisture content as an initial condition, with the exception of the low elevation Valley Douglas fir unit (VDL), which was constructed two months after harvest due to operation constraints. At pile construction, thirty wood samples were randomly cut (of all different diameters) from material that was going to be used to build each pile in order to determine initial moisture content. For clarification purposes, these samples are named “S” samples though the document.

Table 3.1 Site description for each unit

Index	Site	Main species	Location	Elevation (m)	Average precipitation (mm)
CWH	Coast	Western hemlock	Depoe bay, OR	122	1,779
VDL	Valley	Douglas fir	Corvallis, OR	235	1,029
VDH	Valley-East	Douglas fir	Dexter, OR	984	1,384
EPP	East	Ponderosa pine	La Grande, OR	1,158	457

Pile construction followed a consistent instrumentation framework. Construction of each pile occurred in three stages. First, a 12 x 12 m base pad of approximately 0.9 m in height was constructed with three evenly spaced (3 m) conduit of different lengths (9, 6 and 3 m) placed at the top of the constructed layer (Figure 3.1) and equipped with 0.30 m long mesh protectors at their ends (Figure 3.2). After the conduit placement, another layer of harvest residue with a rectangular base of 9 x 9 m and 0.9 m in height was carefully placed on top, subsequently placing two more pieces of conduit of different lengths (6 and 3 m) on top. Finally, the pile of harvest residue was capped with a final residue layer, reaching a final height of 3.5 m. Once the conduit was located in the pile, a Polyvinyl Chloride (PVC) pipe (7.6 cm in diameter) of the same conduit lengths was used to introduce samples coupled with a temperature and relative humidity sensor in the pile (Figure 3.2). These are referred to as "P" samples though the document. Each P sample was approximately 30 cm long and 3.8-4.3 cm in diameter, consisting of a branch or tree top taken from the same pile material. For protection, sensor cables ran through the PVC pipe, providing real-time data to HOBO® Micro Station data loggers. Sensors were programmed to collect temperature and relative humidity readings every 3 minutes and report an hourly average. The mesh at the end of the pipe served as a protective measure while still enabling exposure to internal ambient conditions of the pile.

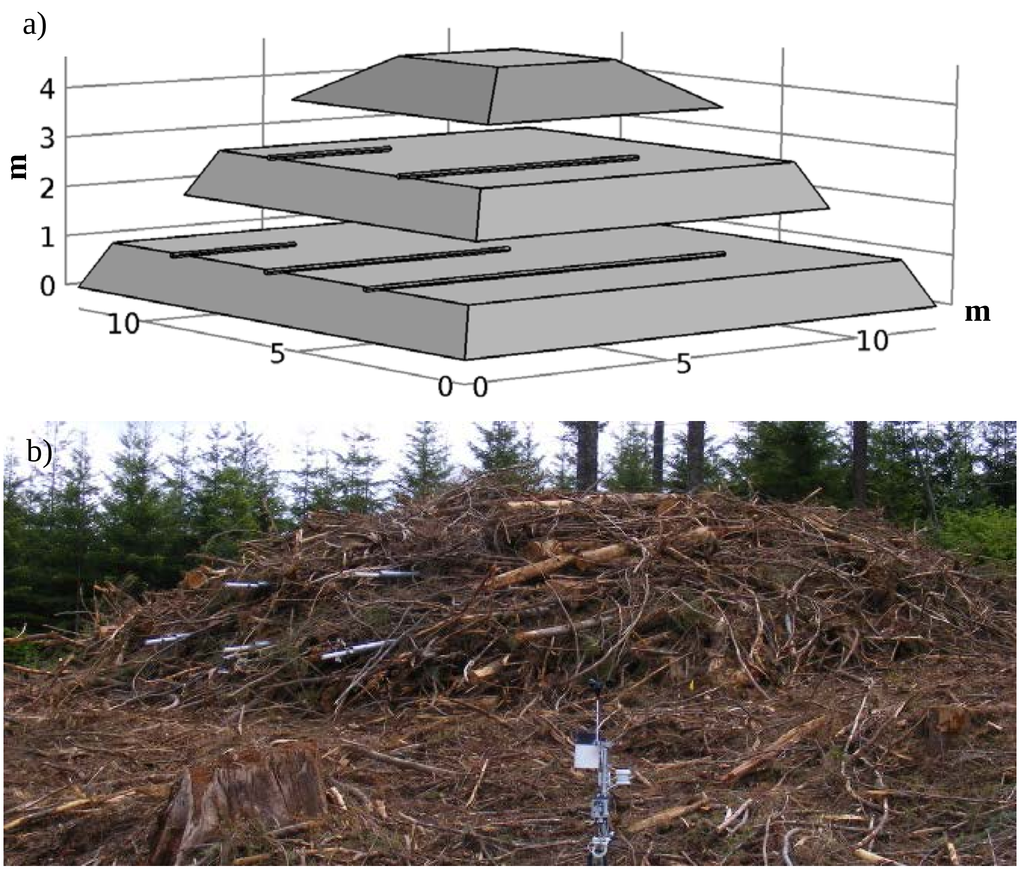

Figure 3.1 a) Schematic of conduit placement in each pile; b) Conduit placement on a pile in the field

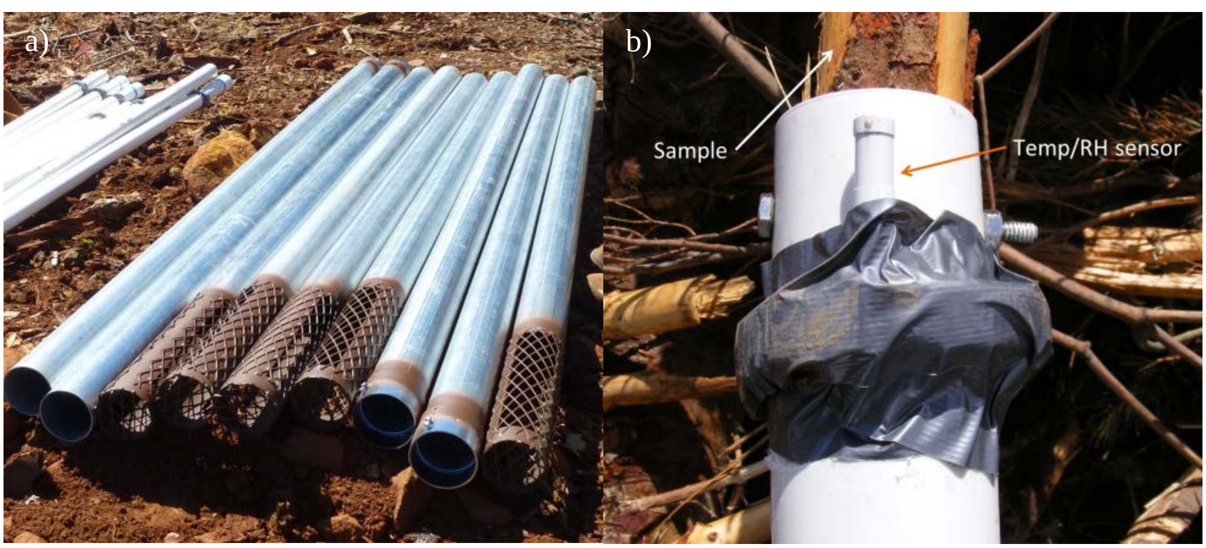

Figure 3.2 a) Left, electrical conduit with screen; b) Right, sample and temp/RH sensor attached to PVC

To comply with rules in Oregon, site preparation for reforestation needs to begin one year after harvest operations on a clear cut (Oregon Department of Forestry, 2014), meaning that forest harvest residue would not remain in the field for longer than twelve months unless it does not constitute fire hazard and does not interfere with the reforestation operation. For that reason, field data collection was limited to one year. Weather stations and pile sensors recorded data hourly for the twelve month monitoring period while P samples were retrieved from the pile and weighed monthly with a scientific scale (0.5 g accuracy) in order to determine their green weight during storage (the monitoring schedule is shown on Table 3.2). After data collection was finished, these P samples were oven-dried to determine their dry weight and calculate the moisture content changes through the year. Weather stations installed next to each pile, were monitoring precipitation, wind, temperature and relative humidity. Finally, when piles were deconstructed, ten more S samples of different diameters were randomly cut at four height levels of the piles (40 per pile) in order to determine final moisture content throughout the pile.

Table 3.2 Schedule of testing sites and sampling*

	2014								2015											
Site	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
VDH	S,P	P	P	P	P	P	P	P	P	P	P	P	P,S							
VDL				S,P	P	P	P	P	P	P	P	P	P	P	P	P,S				
CWH						S,P	P	P	P	P	P	P	P	P	P	P	P	P,S		
EPP								S,P	P	P	P	P	P	P	P	P	P	P	P	P,S

* P wood samples are permanently weighed with constant dimensions, and S samples cut at the beginning and end of each trial covering all ranges of diameters.

3.3.2 Finite Element Models

Finite element analysis (FEA) was applied in order to evaluate the physical process of the instrumented, drying residue piles. Discrete evaluation of individual pieces of harvest residue, although a better representation of actual pile conditions, is difficult to model due to the uncertainty regarding the pile's porous matrix, distribution of material conditions, boundary conditions and associated computational expense, therefore continuum modeling of porous media was employed as a viable approach towards estimating pile behavior. Accounting for porosity within the continuum within FEA enables reasonable evaluation of transient physical behavior for a pile matrix without computational expense of modeling discrete branches or residue. The domain representing a given pile from field monitoring was designed as a half-ellipsoid with approximate 12 m in width and 3 m in height, surrounded by a box that was 10 m, 10 m, and 30 m in height, width and depth, respectively (Figure 3.3). The box dimensions were selected from a sensitivity analysis that demonstrated boundary effects for negligible on the given pile while maintaining computational efficiency. Assigned to the given pile domain was an isotropic, homogenous material representative of the porous matrix (properties are shown in Table 3.3), which applied properties presented in prior literature (e.g. Bowyer *et al.*, 2003; Hardy, 1996; Simpson and TenWolde, 1999; Monteith and Unsworth, 2008; TenWolde *et al.*, 1988; Nield and Bejan, 1998; Welty *et al.*, 2008). Wood and air material properties were weighted proportional to porosity according to Nield and Bejan (1998) in order to obtain a better representation of the residue pile. The fluid properties of air were assigned to the surrounding box to represent ambient conditions.

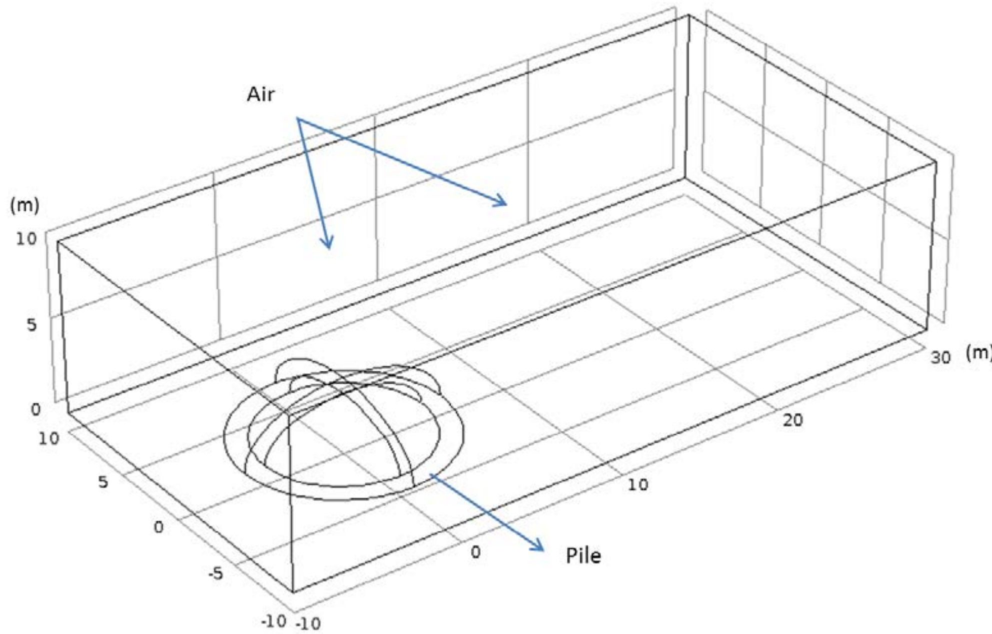

Figure 3.3 Diagram of pile and air domains in Comsol

In order to evaluate transient conditions within a given domain and material properties, meshing, initial conditions and boundary conditions were assigned. A finer mesh was applied to the pile since a higher level of precision is needed in that domain and a coarser mesh applied to the air, both domains were meshed using tetrahedral elements (0.46 m average element size). Since air is not a domain of interest, computational time can be saved by using a coarser mesh, especially around the edges. This analysis accuracy can be refined in areas of interest by increasing element density (reducing element size) where more precision is needed (Cook *et al.*, 2001). Each physics module (heat transfer, laminar flow, convection and diffusion) represents a set of governing differential equations that are coupled through various analytical approaches (Figure 3.4); notably, the Arrhenius equation which determines diffusion through activation energy, the universal gas constant and temperature (Welty *et al.*, 2008).

Water is present in wood in two forms, free water and bound water. For this reason, the diffusion process occurs in two ways: free water may leave the cell lumens as water vapor and bound water is transferred cell by cell through their walls (Baronas *et al.*, 2001). This water is chemically bonded to the cells, a process that requires more energy for the water to be released. According to Baronas *et al.* (2001), the diffusion coefficient depends on wood porosity, the bound water diffusion coefficient D_b and the water vapor diffusion coefficient D_v:

The authors define the vapor diffusion as follows,

$$D_v = \frac{1.29x10^{-13}(1+1.54u)p_S T_K^{1.5}}{(T_k+254.18)} . \frac{d\varphi}{du} \quad \text{(Eq. 1)}$$

Where u is moisture content, T_k is temperature in K (°), φ is relative humidity (%) and p_s is the saturated vapor pressure (Pa), defined as:

$$p_s = 3{,}390e^{\left(-1.74+0.0759T_c-0.000424T_c^2+2.44x10^{-6}T_c^3\right)} \quad \text{(Eq. 2)}$$

Where T_c is the temperature in degrees Celsius. The derivative of air relative humidity with respect to wood moisture content was calculated from sorption isotherms adapted by Simpson (1973) for wood after curve fitting and testing the Hailwood and Horrobin theory for hygroscopic materials. According to Baronas *et al.* (2001) the diffusion coefficient for bound water (D_b) can be defined with the Arrhenius equation to determine the diffusion rate based on a material activation energy, air temperature in and gas constant (8,314.3 kmol K). However, little information exists about relative diffusion rates for piles, which are a porous medium containing porous wood (small voids) and air (large voids), therefore, an effective diffusion rate was determined iteratively based on weighted, relative diffusion rates of wood and air based on wood diffusivity values reported by Nadler *et al.* (1985). In the specific case of the ponderosa pine site

(EPP), diffusion rate was set to zero during the winter freeze; it is assumed that there is no water movement during that period. That assumption was corroborated by constant moisture content of the P samples located inside the pile during that time.

Table 3.3 Material properties for the four sites. Material properties for the Western Oregon sites were assumed to be identical due to species composition

		Site			
		VDL, VDH, CWH		**EPP**	
	Air	**Wood (solid)**	**Pile (porous matrix)**	**Wood (solid)**	**Pile (porous matrix)**
Porosity	1	0.67[1]	0.70[2]	0.72	0.70[2]
Bulk density (kg/m^3)	1	500[3]	150	420[3]	127
Thermal conductivity (W/m K)	0.025[4]	0.11[5]	0.05[6]	0.07[5]	0.04[6]
Heat capacity (J/kg K)	1,000[7]	1,250[3]	1,075[6]	1,250[3]	1,075[6]

[1]Based on 1,520 (kg/m^3) cell wall density (Bowyer *et al.*, 2003), [2]Hardy (1996), [3]Simpson and TenWolde (1999), [4]Monteith and Unsworth (2008), [5]TenWolde *et al.* (1988) Wilkes equation, [6]Nield and Bejan (1998), [7]Welty *et al.* (2008)

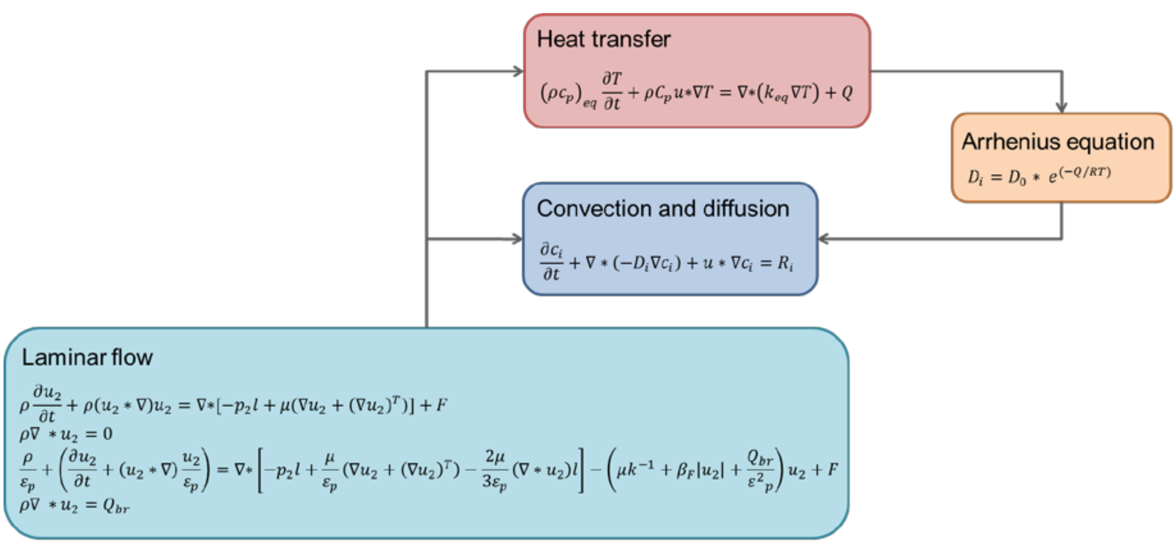

Figure 3.4 Diagram of physics modules and their association

3.3.3 Input of environmental conditions

Weather stations measured environmental variables through a period of one year. To model these environmental factors, mathematical functions were created to approximate weather conditions, including wind, temperature, precipitation and relative humidity for direct entry as boundary conditions for the FEA model. The time-dependent relationships for each site are presented in Figure 3.5.

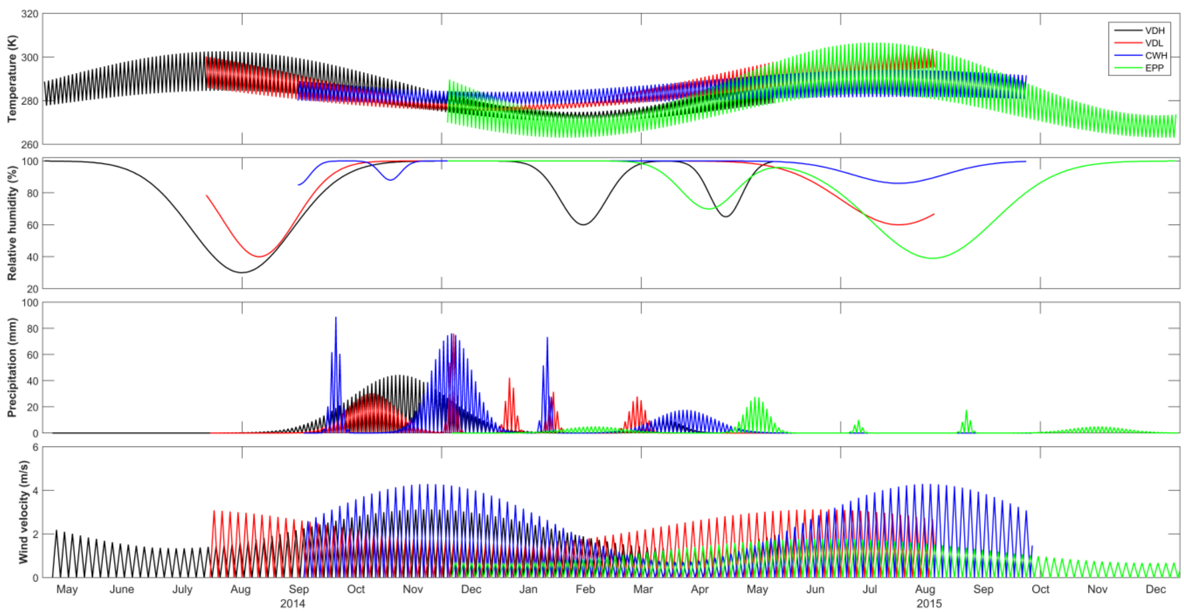

Figure 3.5 Functions for environmental variables on each site over their period of measurement

These functions present an approximation of the data collected in the field starting in the month of May 2014 and ending in December 2015. Solar radiation was not considered in this model as boundary heating could occur, realizing a rise in external pile temperatures and marginal rise in internal pile temperatures. It was, however, omitted from this analysis for computational efficiency and a focus on the diffusion of moisture through diffusive processes greatly influenced by movement of air.

3.3.4 Boundary Conditions and Initial Conditions

Finite element models require initial conditions to define a representation of conditions before changes occur, specified as values on each domain. Boundary conditions are defined on boundaries of domains, representative of known values that govern the calculated differential equations within the bounded domains. Initial conditions are based off of experimental data and similar modelling techniques presented in literature (Sandoval *et al.* 2011, Curcio *et al.* 2008, ElGamal R, F Ronsse, JG Pieters 2013). Initial conditions for each test pile are presented in Table 3.4.

Table 3.4 Initial conditions for each site

Site	MC_{wb}* (%)	Pile and air temperature (K)	Wind velocity (m/s)
VDH	40	277.6	0
VDL	21	293.7	0
CWH	39	288.15	0
EPP	57	274.3	0

* wb = wet basis

Specific boundary conditions are shown in Figure 3.6. Wind velocity was zero at ground level due to drag, at the inlet was a wind function (m/s) describing the wind fluctuations over time (shown in Figure 3.5) and in the outlet, the reference atmospheric pressure (1atm) to solve for wind velocity. Temperature was set as boundary condition in most walls to represent changes in temperature through the year. There was no heat transfer on the ground since soil temperature was not measured. Equilibrium moisture content was set as a boundary condition in inlet, top and side walls so the wood in the pile would reach equilibrium depending on changing temperature and relative humidity.

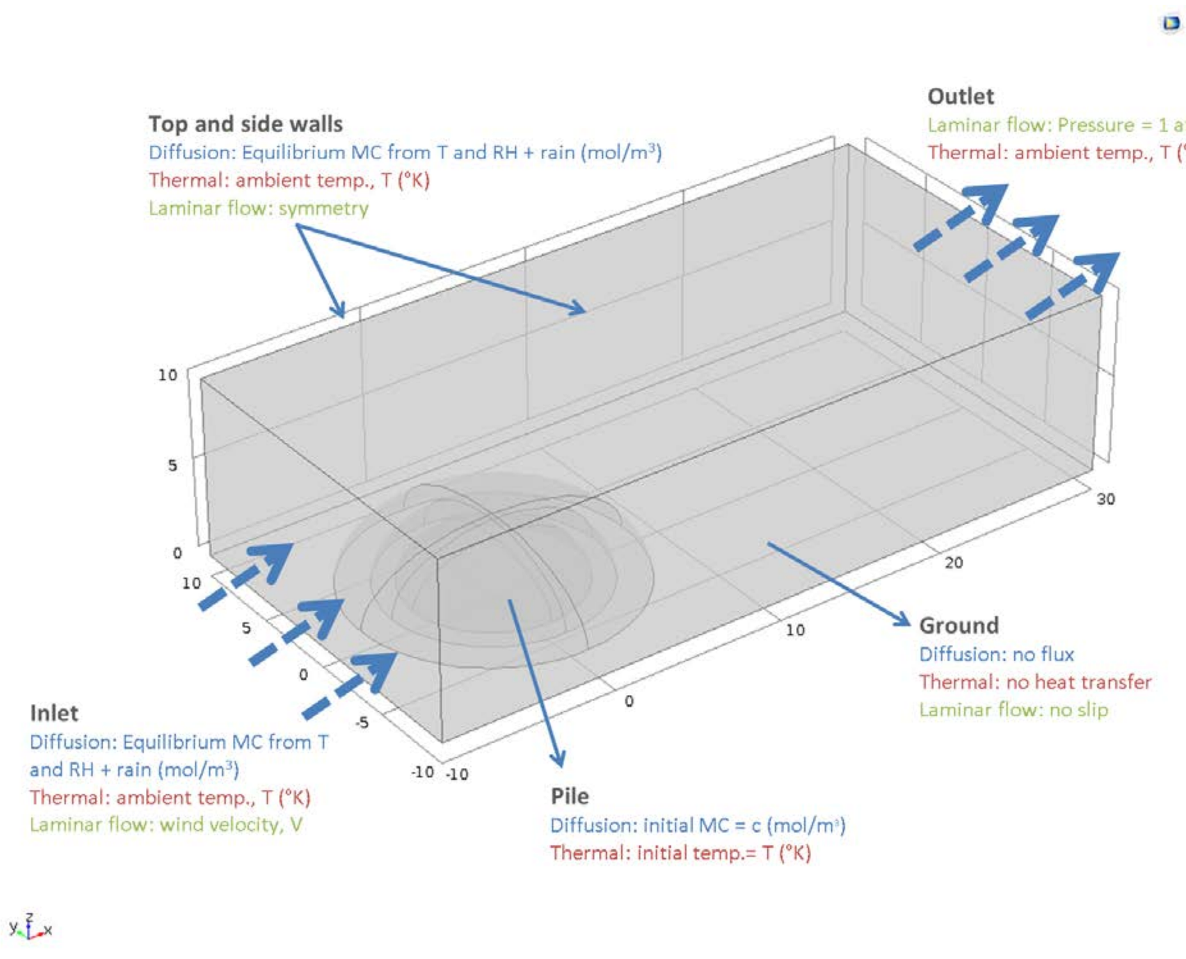

Figure 3.6 Boundary conditions for pile, ground and surrounding air

3.3.5 Solver

For this study, a commercially available Finite Element Analysis solver (Comsol Multiphysics® v5.1 with the Heat Transfer, Laminar Flow and Chemical Reaction engineering modules) was used. After the input of appropriate properties and physics, a transient analysis was performed for given time increments, the maximum of which was 43,200 seconds (12 hours to capture both day and night conditions), subsequently analyzed in a post-processing regime. In order to simulate the pile drying for one year (31,536,000 s), approximately one and a half to 20 hours of computing time was necessary on an Intel Core 2 PC (Windows 7 Enterprise, 3 GHz, 8 GB RAM).

3.3.6 Sensitivity Analysis

Many pile parameters can affect drying rates – in this study, pile shape, porosity, volume and starting drying season were observed. The first study presents the effects of shape, using a semi-ellipsoid as a baseline geometry representative of field conditions and both a cone and continuous berm shape of equivalent volumes for comparison (238 m^3). Besides changing the shape, the element size changed with the different geometries after the meshing process. Ranging from a minimum of 0.06 to 0.52 m maximum for the half ellipsoid, 0.10 to 0.91 m for the cone and 0.11 to 1.06 m for the berm.

Porosity (the volume of voids compared to the total volume of a porous matrix) was observed as a parameter that could affect drying rate. Porosity can vary for a given pile, therefore three reasonable values within a 10% range were chosen for the second study: 70, 80 and 90%. Additionally, half-ellipsoid piles of half (119 m^3) or double (476 m^3) the baseline volume (238 m^3) were evaluated for drying rates was defined as a third study. And finally, the effect of delaying the drying start time was evaluated. The baseline model starting time was delayed 3 and 6 months from the original starting date to assess its effect on drying. Starting month for VDH was May 2014, for VDL August 2014, for CWH October 2014 and for EPP December 2014. The different studies that were implemented are summarized in Table 3.5.

Table 3.5 Model summary for sensitivity analysis

Model	Site	Shape	Volume	Porosity	Start time (mo)
1	VDH	Half ellipsoid	Field (control)	0.7	0
2	VDH	Cone	Field (control)	0.7	0

3	VDH	Berm	Field (control)	0.7	0
4	VDH	Half ellipsoid	Half of field	0.7	0
5	VDH	Half ellipsoid	Double of field	0.7	0
6	VDH	Half ellipsoid	Field (control)	0.8	0
7	VDH	Half ellipsoid	Field (control)	0.9	0
8	VDH	Half ellipsoid	Field (control)	0.7	+3
9	VDH	Half ellipsoid	Field (control)	0.7	+6
10	VDL	Half ellipsoid	Field (control)	0.7	0
11	VDL	Cone	Field (control)	0.7	0
12	VDL	Berm	Field (control)	0.7	0
13	VDL	Half ellipsoid	Half of field	0.7	0
14	VDL	Half ellipsoid	Double of field	0.7	0
15	VDL	Half ellipsoid	Field (control)	0.8	0
16	VDL	Half ellipsoid	Field (control)	0.9	0
17	VDL	Half ellipsoid	Field (control)	0.7	+3
18	VDL	Half ellipsoid	Field (control)	0.7	+6
19	CWH	Half ellipsoid	Field (control)	0.7	0
20	CWH	Cone	Field (control)	0.7	0
21	CWH	Berm	Field (control)	0.7	0
22	CWH	Half ellipsoid	Half of field	0.7	0
23	CWH	Half ellipsoid	Double of field	0.7	0
24	CWH	Half ellipsoid	Field (control)	0.8	0
25	CWH	Half ellipsoid	Field (control)	0.9	0
26	CWH	Half ellipsoid	Field (control)	0.7	+3
27	CWH	Half ellipsoid	Field (control)	0.7	+6
28	EPP	Half ellipsoid	Field (control)	0.7	0
29	EPP	Cone	Field (control)	0.7	0
30	EPP	Berm	Field (control)	0.7	0
31	EPP	Half ellipsoid	Half of field	0.7	0
32	EPP	Half ellipsoid	Double of field	0.7	0
33	EPP	Half ellipsoid	Field (control)	0.8	0
34	EPP	Half ellipsoid	Field (control)	0.9	0
35	EPP	Half ellipsoid	Field (control)	0.7	+3
36	EPP	Half ellipsoid	Field (control)	0.7	+6

3.3.7 Model scaling

Because the residue pile consists of material of different sizes, species, and because the soil activity and water accumulation affecting the lowest portion of the pile is not modeled, the S samples taken at the beginning and end of the trial were used to scale the models at those two points in time. The scaling was achieved by reducing the diffusion rate by 10 or 20 depending on the site, by having pieces with larger diameter, diffusion rates are lower. The shape and the rest of the model parameters remained constant. The rationale for these scaling factors is the fact that larger pieces of wood will dry at a slower rate compared to smaller pieces. Properties that were changed to scale the models are presented in Table 3.6. In order to distinguish these models from the originals, they will be referred as "pile model".

Table 3.6 Model scaling parameters

Site	**VDH**	**VDL**	**CWH**	**EPP**
Initial moisture content$_{wb}$ (%)	34	21	39	54
Final moisture content	27	19	36	39
Diffusion rate m^2/s	2e-8	2e-8	1e-10	4e-8

3.4 Results

3.4.1 Model Comparisons

The monthly average moisture content obtained with the models was compared with the actual average moisture contents acquired in the field on each corresponding month (P samples). Both averages follow a similar trend through the year (Figure 3.7). The greatest disparity can be seen at the EPP site.

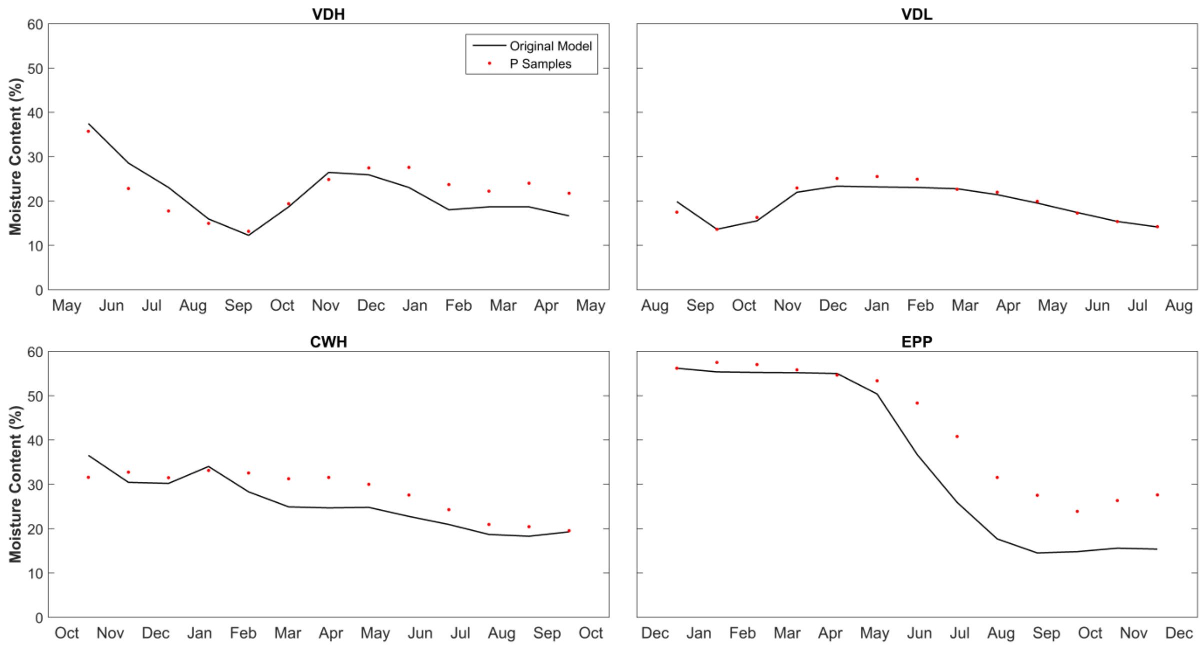

Figure 3.7 Modeled average moisture content (wet basis) versus field P samples

Three statistical tests were performed to verify the agreement between the modeled moisture contents and data obtained in the field, a Wilcoxon signed rank test, a Kendall tau and Spearman's rho correlation tests. At a 0.05 significance level, the modeled and field P sample average moisture content for the two Douglas-fir sites have an identical distribution (VDL and VDH Wilcoxon SR, p-value >0.10). The other two site models (EPP and CWH) have a non-identical distribution when compared with field data. When correlation was tested, all sites present a statistically significant association between the model moisture content averages and field averages. The p-values shown in Table 3.7 for Spearman's rho and Kendall's tau indicate that we can reject the null hypothesis that variables are uncorrelated at a 0.05 level. Spearman's rho indicates correlations over 0.70 for all sites (Table 3.7). This parameter is more sensitive to differences compared with Kendall's tau since it compares the squared differences between pairs of data. A detail of the test outputs can be found on the Appendix C.

Table 3.7 Model correlation and significance tests

Site	Wilcoxon SR test	Spearman's rho		Kendall's tau	
	p-value	Correlation	p-value	Correlation	p-value
VDH	0.4143	0.73	<2.2e-16	0.56	1.8e-6
VDL	0.1272	0.98	<2.2e-16	0.92	1.4e-7
CWH	0.0215	0.90	<2.2e-16	0.77	7.0e-5
EPP	0.0007	0.96	6.3e-3	0.87	6.7e-3

After the model was scaled in order to represent the overall pile moisture content, drying rates over time follow the same pattern as the base models. However, drying and re-wetting occurs at a slower rate. For that reason, the pile dries to a lesser extent over time and moisture content is more stable throughout the year. The two points of comparison with S samples (pile initial-final moisture content) are represented in Figure 3.8.

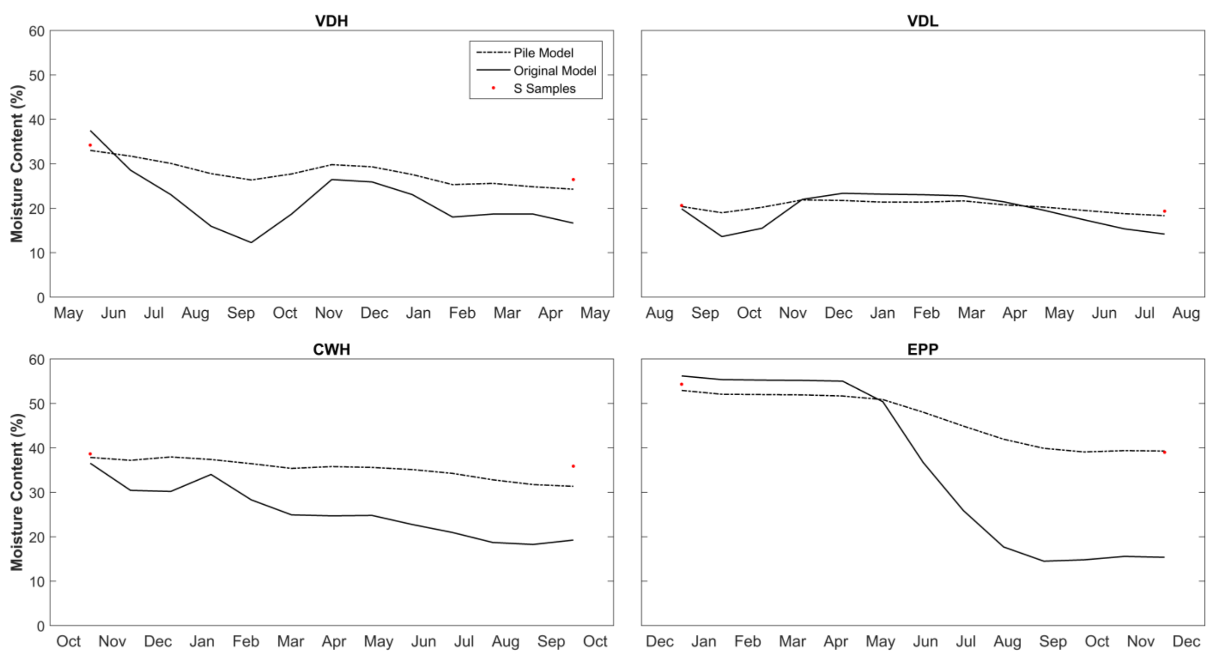

Figure 3.8 Modeled average moisture content (wet based) versus field S samples

3.4.2 Sensitivity Analysis

3.4.2.1 Shape

For the original model, upon comparison of the 10-day moisture content averages of the control pile (half ellipsoid, 0.7 porosity and volume 238 m^3) with the cone pile, differences in MC over time are very subtle with the exception of the EPP site, likely due to similar shape and length (6 m radius). However, the berm pile shows a marked difference (20 m length), especially in the drier and rainy months at the Douglas-fir sites. In the VDL site, the difference can be up to 12% higher MC in the winter and 7% lower in the summer (Figure 3.9).

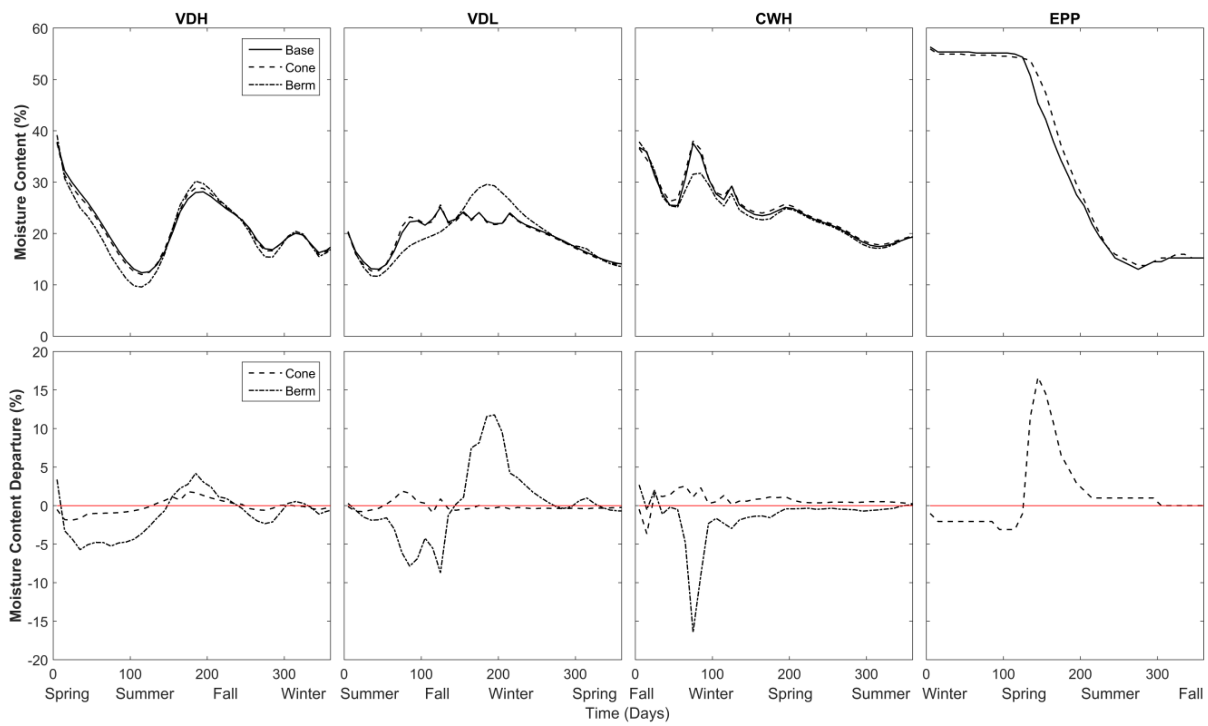

Figure 3.9 Shape effect in moisture content (wet basis) for each site

When the model is scaled to pile averages (S samples), the effect of shape has the same trend as the original model (Figure 3.10), which is implicit due to simple changing of the diffusion rate. For example, when compared to the baseline shape, moisture content can be reduced by 3% during the dry season and re-wet up to 5% moisture content during the rainy months in the Valley Douglas-fir site.

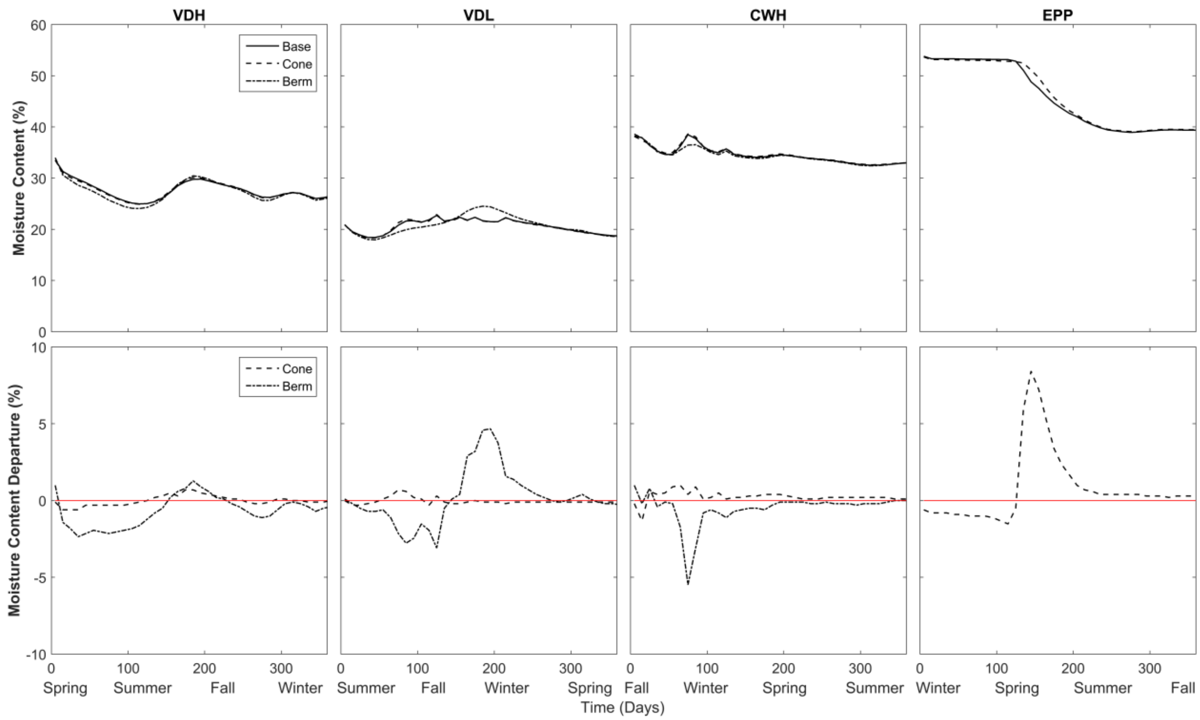

Figure 3.10 Shape effect in moisture content (wet basis) for each site, pile model

3.4.2.2 Volume

Volume is the parameter that affects drying rate of the piles the most. Material on a pile of the same shape and half the volume would have an average moisture content that was approximately 4 to 12% lower during the dry season and almost 9% higher during the wet months depending on the site location and species (Figure 3.11). When the pile volume doubled, average moisture content can remain as high as 26% higher (EPP site) during dry months and oppositely, decrease during the rainy season when compared with the baseline volume. The effect of pile volume is still the greatest within the sensitivity analysis when the models is scaled, but also realize diminished changes in moisture content (Figure 3.12).

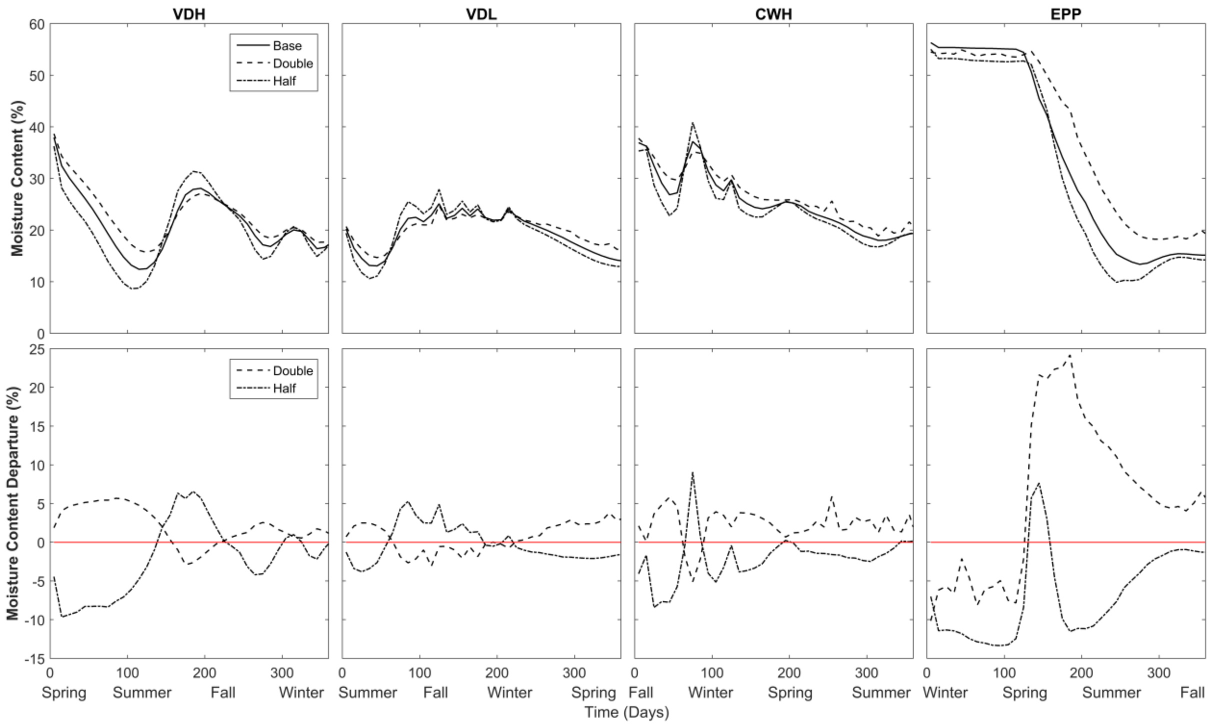

Figure 3.11 Effect of pile volume in moisture content for each site

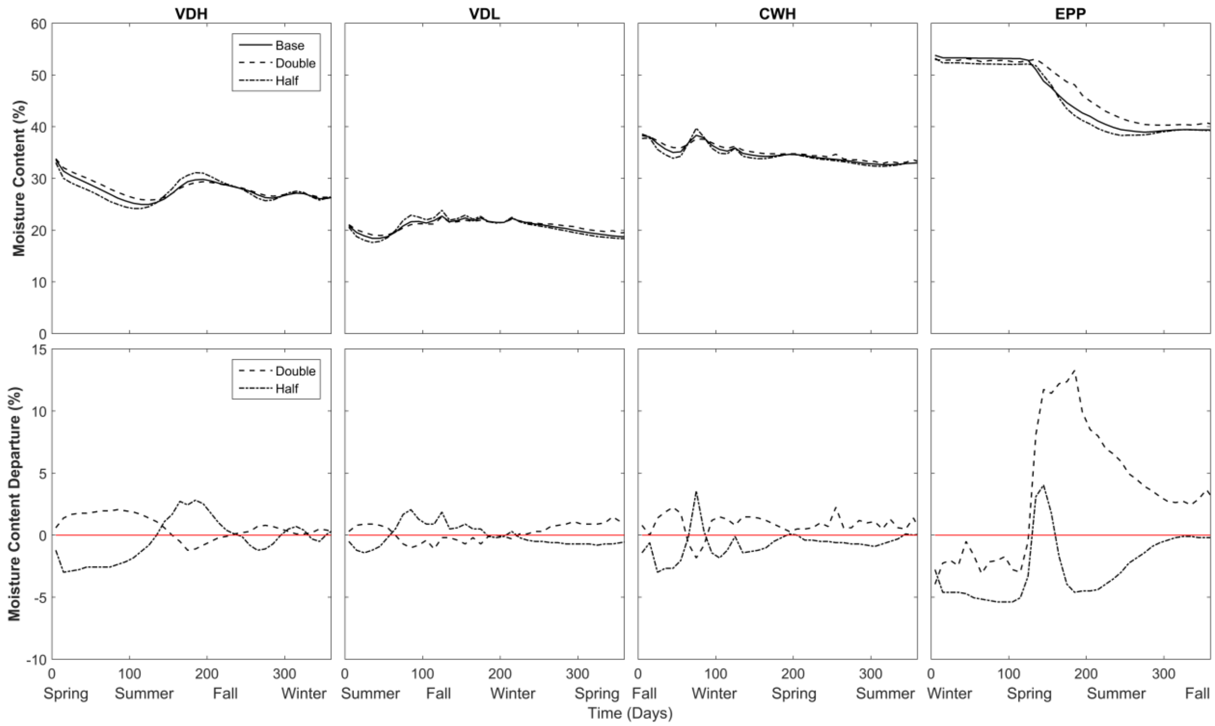

Figure 3.12 Effect of pile volume in moisture content for each site, pile model

3.4.2.3 Porosity

Porosity accentuates the effects of ambient conditions on pile behavior. With increasing porosity, the effects of drying and wetting become exaggerated within the residue pile (Figure 3.13). Average moisture content can be reduced by almost by 5% at any given time for the EPP site when porosity is increased by 0.2 (from 0.7 to 0.9) and increased by 19% during the rainy season when porosity is increased by 0.1 (from 0.7 to 0.8).

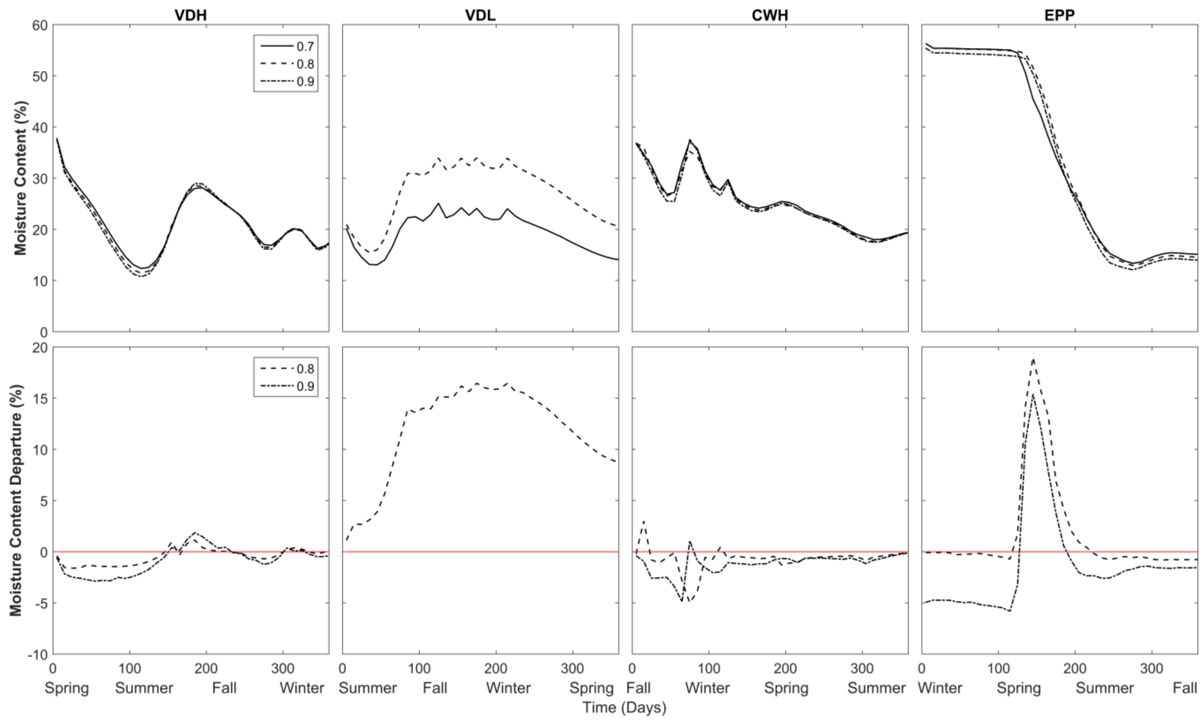

Figure 3.13 Effect of pile porosity in moisture content for each site

In the scaled model, the effect of porosity is marginal in the VDH and CWH sites and significantly smaller in the other two sites when compared with the original model. The greatest effects occur at the ponderosa pine site, were the pile re-wets up to 9% more in a pile with a porosity of 0.8 compared with the baseline (porosity of 0.7) during the spring rains (Figure 3.14).

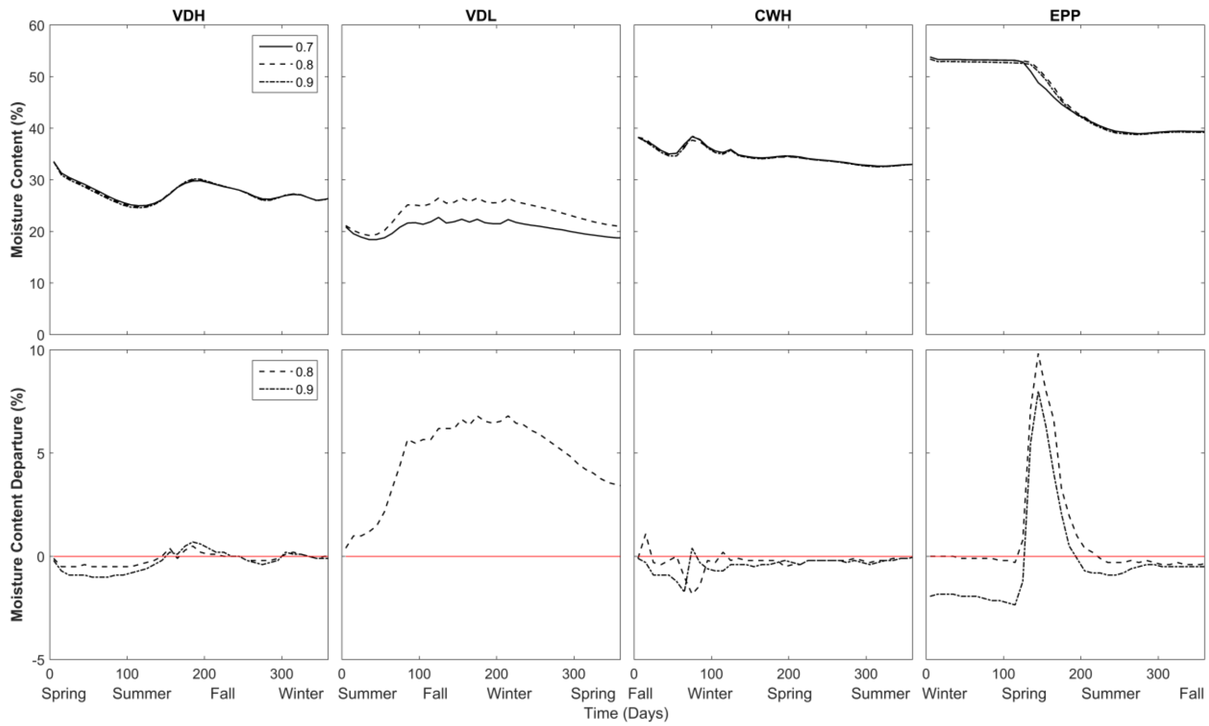

Figure 3.14 Effect of pile porosity in moisture content for each site, pile model

3.4.2.4 Time

Even when the starting moisture content of the residue material that comprises a given pile remains constant, the drying rate changes depending on the starting point in which the material is stored in the forest. For example, in the Valley-East Douglas-fir site, it takes 52 days for the material to reach average moisture content below 20% (wet basis) when drying starts in spring. If the same material is harvested and stored three months later, it would take only 8 days to reach that moisture content. Finally, if it delayed another three months (6 months total), the residues would reach the same moisture content in 73 days. As expected, when drying starts during the dry and warm months, the residue will approach lower moisture contents faster, reaching equilibrium with environmental conditions more expediently (Figure 3.15).

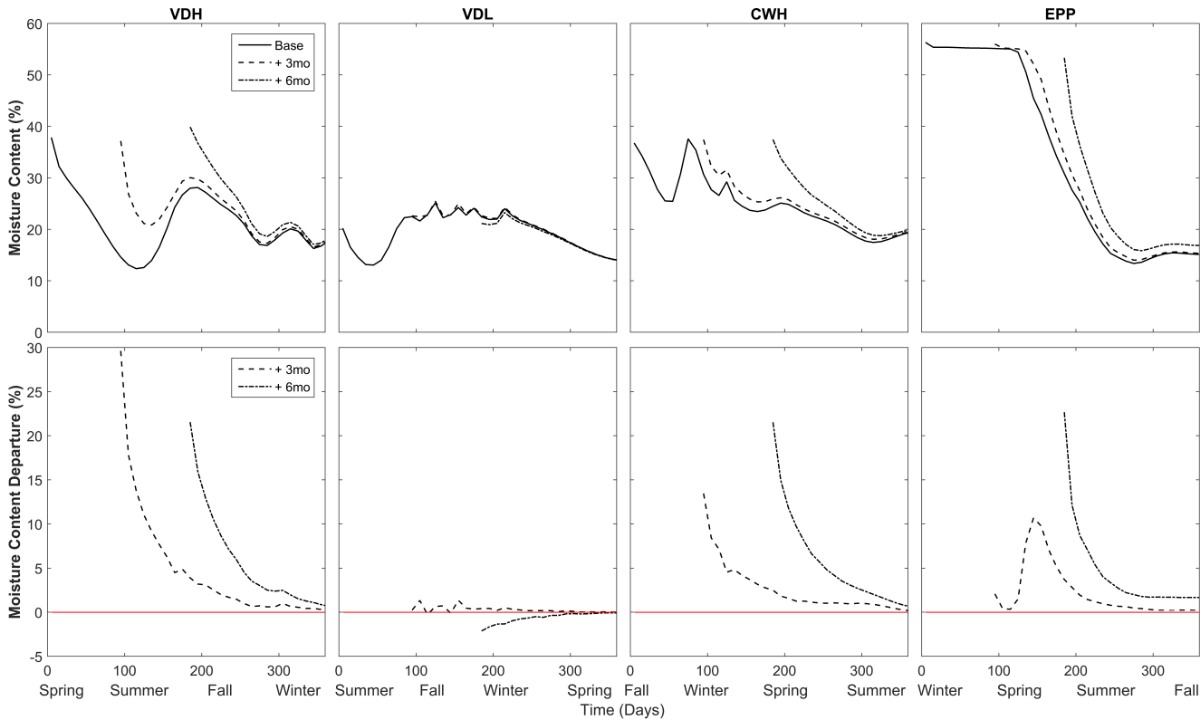

Figure 3.15 Effect of drying time in moisture content for each site

Similar to other parameters, the scaled model has a smaller impact with time changes. For the Valley Douglas-fir site, the effect is marginal. However, for the EPP site, it takes 196 days for the average moisture content to reach levels below 43% (wet basis) if drying starts in winter, 115 days in spring and only 33 days in summer (Figure 3.16).

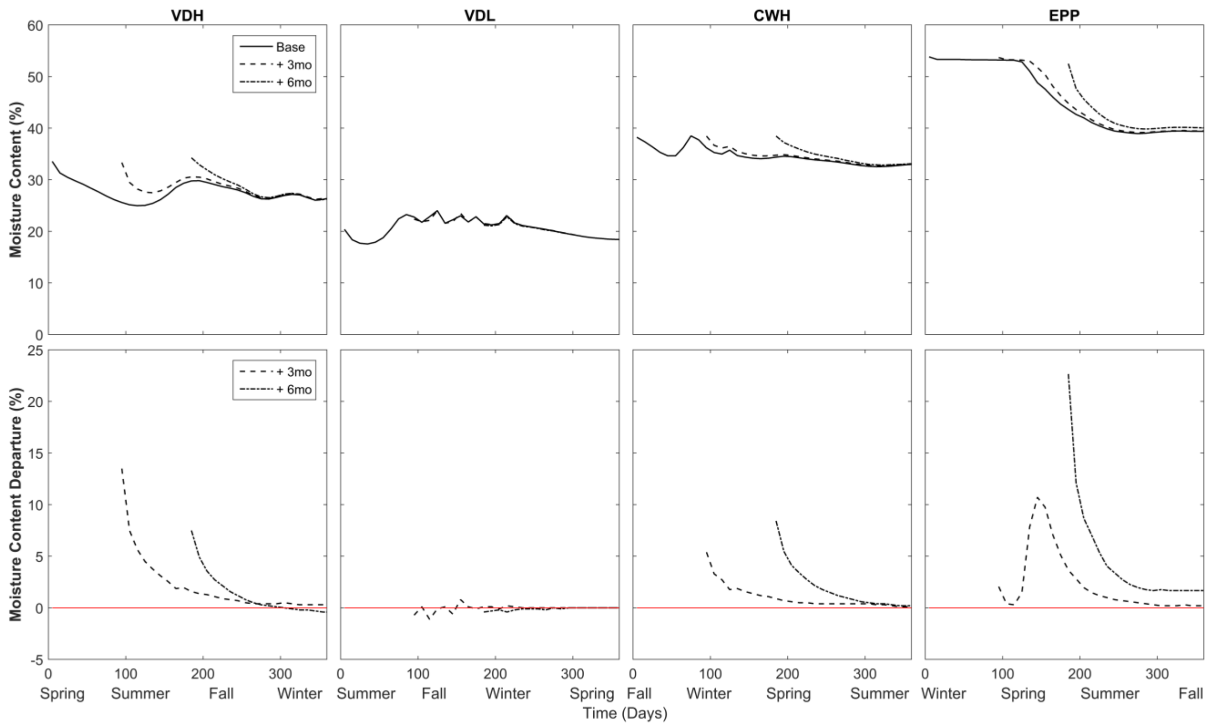

Figure 3.16 Effect of drying time in moisture content for each site for scaled models

3.5 Discussion

The presented series of models offered reasonable agreement with field drying rates, confirmed by statistical tests compared with field data (Table 3.6). This sets a framework to define and compare different means of in-situ residue drying for specific ambient conditions. Although it is difficult to represent all potential conditions, the impact of parameters critical to drying may be evaluated. For all sites, residue piles dry fast during the first months, finding particular dependence on the time of harvest, often reaching a minimum in September-October. The ponderosa pine site (EPP) has almost no drying during the first months, since there is no diffusion during the winter deep freeze. Rain, along with lower temperatures and higher relative humidity allow the material to re-moisten during the wet rainy season.

After the model was scaled with S samples, results showed the same trends compared to the base original models, with lower drying rates. Material of larger sizes dries at a slower rate. For these models, there is little drying in both Valley Douglas-Fir and Coast western hemlock after one year of field storage. Some possible reasons are that the Douglas-Fir began with dry material, likely muting the observed drying effects. The CWH unit was continuously under the effect marine moist air and could be the explanation for stability of the material's moisture content. The greatest drop in moisture content is observed in the EPP unit; this could be caused because of the material being very wet at the start of the trial and the likely lag of freezing preventing diffusion of moisture, particularly underneath a layer of snow.

As expected, berm or windrow geometry works best to expedite the drying process due to large relative surface area and exposure to ambient conditions and convection. This shape has 60% larger surface area directly exposed to wind, which is probably the main cause for the differences. Residue moisture content is reduced between 2 and 5% compared with a half ellipsoid of the same volume during the dry season. However, the same advantageous conditions for drying may also expedite rewetting in the winter. Probably, because more surface area is directly exposed to rain. The cone shape behaves similarly to the half-ellipsoid for all sites likely due to a generally similar shape in relative surface area.

Volume is the parameter that most affects drying. When the pile volume is halved, moisture content can be reduced by 2 to 5% during the dry months, and increased by 3-4% during the wet season in comparison to baseline volume. When the volume is doubled, moisture content can increase from 1 to 13% depending on the site. These changes are probably driven by the same principles that affect the different pile shapes. A pile with smaller volume allows more air flow through the interior of the pile permitting more efficient drying. At the same time, there is less coverage from the rain allowing more moisture to reach the material inside the pile. A larger pile, has the opposite effect, more material is protected from wind and rain.

Porosity is a pile property that is difficult to change in a practical sense, but may have impacts on the rates of drying or wetting for given ambient conditions. Increasing the porosity has a greater effect on sites such as the Valley Douglas-fir site (VDL) and east ponderosa pine (EPP), where more voids may increase sensitivity to weather conditions for the presented baseline model (porosity of 0.7).

The time of harvest has notable effects on residue drying times as the gradient in moisture or temperature for a given time of year may expedite or slow drying. For example, in the case of the ponderosa pine site (EPP), it can take one sixth of the time it takes for the residue to reach 43% moisture content when drying starts in summer versus winter. During summer, higher temperature and lower relative humidity reduce the wood equilibrium moisture content and there is little or no re-wetting of the material.

3.6 Conclusions

Finite element models were developed for four sites representing the main climatic regions in Oregon and their respective commercialized forest species. These models are able to sufficiently predict piled forest residue drying rates with weather data input such as precipitation, wind, ambient temperature and relative humidity. Conclusions include:

- Piled residue moisture content responds to the environmental conditions greatly. The selection of pile shape or size can be beneficial or detrimental towards the rate of drying depending on ambient conditions, namely precipitation.
- A berm (windrow) presents the best option for expedient drying due to its large surface area. Drying is the fastest in this shape during dry summer months; however, the pile also re-wets the fastest during wet, winter months.
- It is best to reduce pile volume if storage will occur through summer and increase size if it will occur through winter. The reason behind this is the same as for the shape, a smaller pile will have more airflow but it will also become wetter in the rainy season when compared to a larger pile.
- Significant reduction in drying times can be achieved if the material is cut and left to dry during the dry, warm summer months. This reduction can be up to 1/3 of the time versus starting the process in the winter.
- This methodology is a tool that has the flexibility to be able to change parameters and conditions in which the harvest residues are stored. For that reason, it opens several possibilities for future research.

The presented models were made with local data and inferences are generally specific to these locations. However, the main concepts and sensitivity of pile drying parameters still present a general understanding for drying conditions in many different climates. As part of future work, the effect of aspect and slope on drying rates will be assessed. Additionally, changing pile porosity with depth will be implemented to produce a refined model. It is anticipated that this change could result on a better model fit with the field sample averages.

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4 Economic implications of moisture content and logging system in forest harvest residue delivery for energy production: a case study

4.1 Abstract

The need for improving the cost effectiveness of forest harvest residue utilization for bioenergy production has been widely recognized. There have been a number of studies showing that reducing residue moisture content presents advantages for transportation and energy content. However, previous studies have not focused on the relative advantages of in-forest drying depending on different logging systems or, in the case of cogeneration, energy-based demand. Drying curves have been developed for harvest residue generated from two main Pacific Northwest logging systems for a case study in Oregon using mixed integer programming to optimize the volume delivery to a hypothetical cogeneration plant with a generating capacity of 6 MW-hr. Approximately 98% of the harvest residue generated with cable logging system was delivered to the plant compared with only 56% of the residue generated with a ground-based system. The advantage of shorter distance and drier material coming from a ground-based unit was not enough to offset the collection cost relative to the availability of wetter residue already at roadside from the cable harvest system, assuming large trailers can access cable landings. By considering the energy content of drier residues, the amount of ODMT needed to supply the plant can be reduced by 13.3% without affecting the energy output on a 6-period planning horizon. The economic effect of the lower ODMT demand and shifting to drier material is a production cost reduction of 16.5%. This approach presents refined supply and production cost estimates of harvest residues for power generation.

Keywords

Moisture content; cost reduction; logging systems; harvest residues; energy content

4.2 Introduction

After passage of the Energy Independence and Security Act of 2007, several initiatives to improve the efficiency and economics of forest harvest residues to produce renewable energy in the Pacific Northwest have been developed. That includes the Northwest Advanced Renewables Alliance (NARA) focused on production of liquid biofuels for aviation from forest harvest residues (NARA, 2016b), Waste to Wisdom focused on developing methods and tools to improve feedstock for biomass conversion technologies such as biochar, torrefaction and briquetting (Waste to Wisdom, 2016) and AHB (Advanced Hardwoods Biofuels Northwest) focused on growing hybrid poplar and developing technologies for conversion into liquid biofuels and bio-based chemicals (AHB, 2016).

In the Pacific Northwest, there is an estimated 14.4 million m^3 (TPO report, 2016) of forest harvest residues produced annually. Of this amount, most of it is piled and burned for site preparation because of the high production costs for biofuel recovery or biofuel markets that are not yet developed.

Forest harvest residues consist of all the tree parts that are left in the forest harvest unit after trees are processed for solid wood products and paper. This includes long butts, tops, limbs, broken pieces and non-commercial species. What is left in the unit varies depending on the pulp markets. When pulp prices are high, fewer small trees and tops are left as residue, and when pulp markets are low, more small trees and pulp logs are left as part of the residue.

In the Pacific Northwest there are two primary logging systems for clear cut harvesting. One is cable logging on steep terrain (slope greater than 40%) and the second is ground-based logging in flat terrain. Cable logging generally consists of manual felling and whole tree yarding along a suspended cableway. When trees arrive at the landing they are bucked into logs, and the harvest residues are left in large piles at the landing. Ground-based logging consists of either manual or mechanized felling, bucking into logs at the felling site or whole tree skidding. In the case of processing at the stump, branches are left near the stump or corridor. If whole tree yarding by shovel, many of the branches break as the logs are rehandled on the way to the landing; leaving harvest residues scattered over the forest unit.

A harvest residue operation generally involves a grinder positioned at a landing or at roadside. The grinder is loaded by an excavator and as it grinds the material, a trailer is loaded through a conveyor belt. Trucks used to transport this material have lightweight chip trailers that can be 9.8, 11.6, 12.8, 13.7 and up to 15.2 m long. For that reason this operation can be challenging as these trucks need roads with larger curve radius, large turn-arounds, and have much lower gradeability than log trucks when empty (Zamora-Cristales *et al.*, 2013). The use of all wheel drive (6 x 6) truck tractors are used by some contractors to improve gradeability and remotely steered trailer wheels are used to improve trailer tracking and reduce turn-around area.

In order to have residues ready for comminution, the residues need to be either at roadside or at the landing. For a cable unit the trees are usually yarded tree length, so the limbs and branches are already at the landing in piles. With the ground system, limbs and tops are either left in the field as part of the harvesting operation or during shovel logging, the limbs and tops often break off after repeated handling. In either case the residues need to be collected and transported at an additional cost. The residues may or may not be in piles in the field.

The effect of forest harvest residue moisture content in the economics of pricing, collection and transport has been frequently recognized by researchers (Sessions *et al.*, 2013; Acuna *et al*., 2012; Ghaffariyan, Acuna and Brown, 2013). High moisture content impacts the volume of residues that can be transported due to the weight restriction on roads and highways (Zamora-Cristales and Sessions, 2015). This causes the truck to reach its weight capacity before reaching its volume capacity due to the extra weight of water, thus making transportation inefficient. On the other hand, when residues are very dry the truck becomes volume limited, caused by lower bulk density (Sessions *et al.*, 2013) and cannot be loaded to its maximum highway weight capacity.

Forest harvest residues start at high moisture content when fresh. Then, they rapidly lose moisture until wood reaches equilibrium with the environment (Simpson and TenWolde, 1999). Storing the material in the forest unit can be beneficial for drying, depending on the season in which they are collected and whether they are stored piled or scattered over the forest unit (Chapter 3).

Finite element analysis (FEA), is a numerical technique to solve complex problems with differential equations (Fagan, 1992). A finite element can be constructed to predict forest residue drying rates over time using the ambient conditions such as temperature, relative humidity, wind velocity and rain in which the residues are being stored (Chapter 2). FEA works by integrating the physics processes such as heat transfer, laminar flow, diffusion and several assumptions such as material, fluid and thermal properties of the components (wood, water and air). This tool allows the prediction of harvest residue moisture changes over time.

Routa *et al.* (2015) determined residue moisture content changes over 35-85 weeks using constant weight monitoring in stacked wood. Sikanen *et al.* (2012) developed biomass drying models for whole trees based on heuristics fitting and local weather in Finland. Kim (2012) developed drying models in Oregon for Douglas-fir and hybrid poplar small logs based on precipitation, evapotranspiration and piece size using linear mixed effects multiple regression models. Both authors confirm the relationship between weather and drying rates in wood. However, none has focused on the use of physics to make moisture predictions or has specifically focused on forest residues and the different drying rates depending on logging systems.

Acuna *et al.* (2012) developed a tool to optimize biomass logistics and determine optimal storage for three different supply chains, including forest residues. They highlight the importance of managing moisture as a way to improve the economics of the biomass supply chain. This study only includes ground-based logging where forest harvest residues are forwarded to roadside.

Lower moisture content also has an advantage from the energy content point of view. Power generating plants need less residues in order to generate the same amount of power if it is dry. We are not aware of this advantage being directly addressed by other authors on a harvest residue processing and transport scheduling problem, possibly due to the non-linearity it introduces into the problem. Ghaffariyan *et al. (*2013) provide bounds on the amount of water that can be delivered to the plant for a set volume delivery and consider that effects of residues of different moisture contents can be linearly added

Because drying rates and costs differ between the two main logging systems it is important to understand the difference in economic value of harvest residue from those two different sources; one piled green at the landing, generally in large piles, which dry more slowly and the other unpiled, or in smaller piles in the field, which dry more quickly. A data set of clear-cut harvest units over Linn and Marion Counties (Oregon) was used to set an optimization problem to minimize cost of harvest residue delivered to a hypothetical co-generation plant. The problem was set from the perspective of an integrated operation were plant and land owner are the same. In order to address our questions the specific objectives of this study are the following:

- Determine the optimal harvest residue delivery to a hypothetical co-generation plant located in Lyons, Oregon.
- Determine production costs of residue generated from cable and ground logging systems.
- Determine the cost effectiveness of expressing the plant demand as a function of energy content of delivered residues in two scenarios (1) assuming the dry tons per MW-hr are constant, and (2) by varying dry tons per MW-hr according to the moisture content We refer to (1) as the baseline scenario and (2) and the energy based residue demand scenario.

4.3 Methodology

4.3.1 Data set

Data was provided by the Oregon Department of Forestry (Justin Butteris, pers. comm) and consisted of approximately 944 Ha of regeneration harvests (clear-cuts) within Marion and Linn counties in Oregon. These 138 units totaled 81,500 MBF, were 87% of the total gross BF was Douglas-fir. The average yield for the harvest units was 86 MBF/Ha and 35% of the forest units were yarded with a cable system.

The date of each truck load delivery was provided and used as a start date in which the harvest residues become available for processing and transport or in-forest storage. Additionally, spatial data was provided, including road networks that allowed distance calculation to a hypothetical co-generation plant located in Lyons, OR.

Harvest volume was provided in MBF and to calculate the amount of generated harvest residue, a factor of 0.82 ODMT/MBF was used (Lord, 2009). Boston (2015) observed different residue recovery rates from cable and ground-based units, but a constant rate was used in this case study. All the material was treated as if it was Douglas-fir and all units with a residue volume below 68 ODMT (approximately three truckloads) were considered uneconomic and excluded from the analysis.

4.3.2 Mathematical formulation

The model was formulated as a mixed integer programming problem with the objective of minimizing the sum of fixed and variable cost of delivered forest harvest residue to a co-generation plant over a 24 month period. The fixed cost is charged once when machinery is mobilized to the harvest unit to grind residues and back, as a result of residue volume flow to the plant. Variable cost is the sum of collection (if unit is logged with a ground-based system), comminution and transportation costs per ODMT of harvest residue produced. The objective function minimized total cost (Eq. 1).

$$Min \sum_{ij} VCost_{ij} * Volume_{ij} + \sum_{ij} FCost_i * MOB_{ij} \ , \forall\, i,j \in \mathbb{N} \qquad \text{(Eq. 1)}$$

Where, i = unit (1,2, 3,….117) j = period (1, 2, 3, …. 24)

Since the volume of residue in each harvest unit is limited and the plant needs to have a continuous supply of forest residues to operate, two constraints need to be in place to ensure these requirements have been met.

The hypothetical co-generation facility is located in Lyons, Oregon with a generating capacity of 6 MW per hour. The consumption of the plant was estimated in 43,105 ODMT/yr. based on 330 days of operation, 24 hours per day during the year, at a conversion of 0.91 ODMT per MW-hr. This plant would be supplied on a 63% by forest harvest residues and the remaining 37% from bark and other residues.

$$\sum_i Volume_{ij} = Demand_j \ , \forall\, i, j \in \mathbb{N} \qquad \text{(Eq. 2)}$$

$$\sum_j Volume_{ij} \leq Capacity_i \ , \forall\, i, j \in \mathbb{N} \qquad \text{(Eq. 3)}$$

Eq 2 specifies the demand of the co-generation plant and Eq 3. limits the harvest residue capacity from each harvest unit.

Additionally, another constraint (Eq. 4) needs to be implemented to ensure that the mobilization cost will be included in the objective function; in the period the unit is accessed to retrieve harvest residues.

$$M * MOB_{ij} - Volume_{ij} \geq 0, \forall\, i, j \in \mathbb{N}\, , MOB_{ij} \in \mathbb{Z}_2 \qquad \text{(Eq. 4)}$$

Since none of the units have enough volume to keep the equipment for longer than a month, a constraint (Eq. 5) is needed to make sure the residue is processed and delivered in only one period.

$\sum_j MOB_{ij} \leq 1\ , \forall\ i, j \in\ \mathbb{N}$ (Eq. 5)

Finally, a minimum volume flow of 200 ODMT in the harvest unit is required to move in the equipment and operate. This constraint was set to avoid having equipment stay in a unit for a very small volume to avoid another move-in cost that would be charged if there is residue delivery in the same unit in inconsecutive months.

$Volume_{ij} - M * W_{ij}\ \leq 0, \forall\ i, j \in\ \mathbb{N}\ , W_{ij} \in\ \mathbb{Z}_2$ (Eq. 6)

$Volume_{ij} - 200 * W_{ij} \geq 0, \forall\ i, j \in\ \mathbb{N}\ , W_{ij} \in\ \mathbb{Z}_2$ (Eq. 7)

The constants are described in Table 4.1. The decision variables of this problem are:

$Volume_{ij}$ a continuous variable representing volume of forest residue processed and transported to plant from unit *i* in period *j* (ODMT)

MOB_{ij} Binary variable [0,1] triggering mobilization cost when material is processed and transported to plant from unit *i* in period *j*.

W_{ij} Binary variable [0,1] to ensure there is a minimum volume flow on unit *i* in period *j*.

Table 4.1 Constants of the mathematical formulation

$VCost_{ij}$	$TCost_{ij} +\ GCost_{ij} + CCost_{ij}$
$TCost_{ij}$	Transportation cost from unit *i* to plant in period *j* ($/ODMT)
$GCost_{ij}$	Grinding cost unit *i* in period *j* ($/ODMT)
$CCost_{ij}$	Collection cost unit *i* in period *j* ($/ODMT)
$FCost_i$	Fixed cost (mobilization cost) of equipment to unit *i* ($)
$Capacity_i$	Available forest harvest residue volume in unit *i* (ODMT)
$Demand_j$	Plant forest harvest residue in period *j* (ODMT)
M	large number

4.3.3 Solver

For this study, a commercially available optimization model solver (Lingo® v16.0.28) was used. This solver allows importing volume and cost data to the Lingo platform from Microsoft Excel and the mathematical formulation can be written in Lingo language. The time to solve the problem will depend on the problem structure, number of integer variables, and the gap the analyst is willing to accept. The gap is the difference in objective function value between the best integer solution arrived at so far (known as the incumbent) and linear programming solution of the best leaf node still to be investigated.. The solution can be easily exported to a Microsoft Excel file. Approximately 2 minutes of computing time was necessary on an Intel Core 2 PC (Windows 7 Enterprise, 3 GHz, 8 GB RAM).

4.3.4 Moisture content

Finite element models to predict forest residue drying rates for four different climate regions in Oregon were generated and calibrated with samples in Chapter 2 of this dissertation. Those models focused on piled residue and calibrated with data collected in the field; however, moisture content data was also collected for scattered residue using samples of the same dimensions as the ones in the piles (30 cm long, approximately 3.8-4.3 cm in diameter).

Since the geographic location and species provided in the harvest data-set are similar to the Valley-East Douglas-fir unit used to build and calibrate the FEA model, this unit was used to determine the drying rates for the piled residue of the study area. In addition, the same model with a flat pile was used to estimate the drying rates for scattered residues. After running an initial model, it was calibrated with data obtained in the field. The piled residue geometry was a half ellipsoid of 12 m wide and 3 m high and the scattered residue a half ellipsoid 12m wide and 0.5 m high.

The original FEA models were set to run for only one year. However, since we wanted to have the residue available for one full year for each unit, independent from the harvesting date, the models were set to run for two years, starting at different months. The same weather data was used for the second year, assuming both years would have the same weather pattern. Since the starting date for storage provided in the data set is the date in which the loaded trucks were delivered, 50% moisture content was considered as the initial moisture on each month (Chapter 1). The material properties used in the model are summarized in the following table:

Table 4.2 Material properties

	Air	**Wood**	**Pile**
Porosity	1	0.67[1]	0.70[2]
Bulk density (kg/m^3)	1	500[3]	150
Thermal conductivity (W/m K)	0.025[4]	0.11[5]	0.05[6]
Heat capacity (J/kg K)	1,000[7]	1,250[3]	1,075[6]

[1]Based on 1,520 (kg/m^3) cell wall density (Bowyer *et al.*, 2003), [2]Hardy (1996), [3]Simpson and TenWolde (1999), [4]Monteith and Unsworth (2008), [5]TenWolde *et al.* (1988) Wilkes equation, [6]Nield and Bejan (1998), [7]Welty *et al.* (2008)

Some authors assume material loss and deterioration over time. However, since our drying curves and sampling only include solid wood and not needles and fines taken into account when sampling is performed after comminution, mass loss was not taken into account. Additionally, harvest residue samples were cut after 23 and 48 weeks of storage to determine changes in specific gravity. A two sample t-test showed no significant differences between the mean specific gravity of samples obtained at different times (t-test p-value = 0.2677).

4.3.5 Drying curves

Forest harvest residue dries rapidly during the first weeks in the harvest unit and then reaches equilibrium with ambient conditions. This is similar to what Pettersson and Nordfjell (2007) found, their harvest residue MC fell from 50 to 29% in only three weeks. Scattered residue left after a ground-based logging operation in this particular harvest unit (assumed typical of Valley East Douglas-fir) can reach moisture contents as low as 10% (wet basis) during the summer months, and can re-moisten up to 30% (wet basis) during the winter (Figure 4.2).

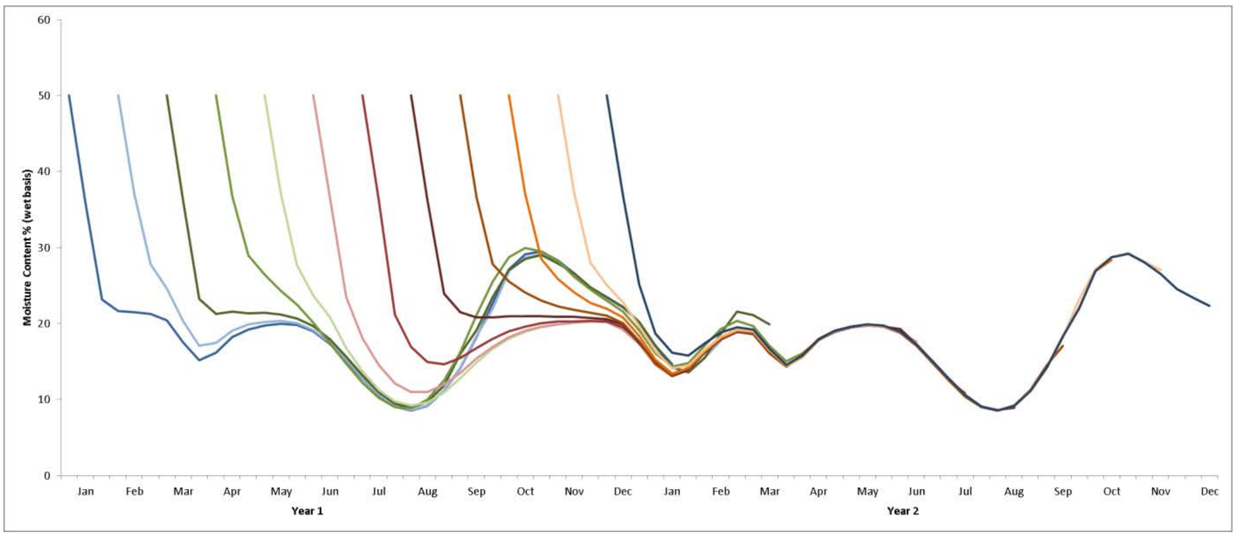

Figure 4.1 Drying curves for Douglas-fir scattered residue based on modeling of Valley East Douglas-fir empirical data

When residue is left piled at the landing on a cable logging operation, it does not reach as low moisture content as if it was scattered. Also, the piled residues gains moisture during the winter, the material has less moisture fluctuations over time compared to scattered residue (Figure 4.2).

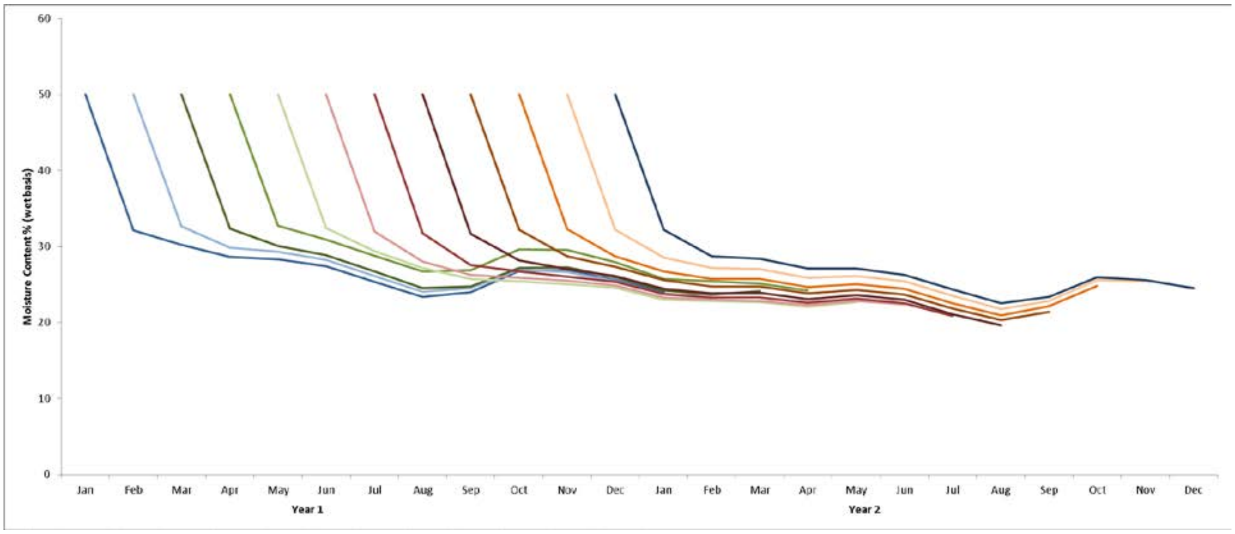

Figure 4.2 Drying curves for Douglas-fir piled residue based on modeling of Valley East Douglas-fir empirical data

4.3.6 Costs

For the purpose of this exercise, the cable logging operation consists of a horizontal grinder, an excavator loading the grinder and a 13.7m chip trailer for transportation. Both the grinder and excavator need to be mobilized with one lowboy trip each. The ground-based logging operation consists of a horizontal grinder, an excavator loading the grinder, two forwarders and a loader loading the forwarders. The productivity and cost effectiveness for this system was evaluated by Zamora-Cristales and Sessions (2016). The grinder and two excavators need to be mobilized with three lowboys. The mobilization cost was estimated in $1,000 per piece of equipment (Table 4.3).

Grinding cost was obtained from NARA (2016a) at 21 $/ODMT at 60% utilization and 3.54 $/gal for diesel and average productivity of 32 ODMT/PMH. Transportation cost was calculated based on a 13.7 m trailer with a volumetric capacity of 99 m^3, a maximum payload of 25 metric tons and a ground material dry bulk density of 160 kg/m^3 (Zamora-Cristales and

Sessions, 2015). These calculations are based under the assumption that conventional trailers can access ground-based units and self-steered trailers can access all cable units.As the moisture content of the material changes over time, the truck load was limited by either weight (when wet) or volume (when dry). Transportation hourly cost was calculated based on 8% of the time on dirt road, 15% on gravel road and 77% highway and different costs for travel loaded and unloaded. Additionally, $3.2 /ODMT, was added for an unloaded truck waiting for one hour in order to make sure there is sufficient truck capacity to maintain high grinder utilization (>60%). Truck shortages have been documented as the primary reason for low grinder utilization (Zamora-Cristales *et al.* 2013, Aman *et al.* 2011). Since we assume that all trucks can access all units, a rear steered axle trailer was used to transport residues from cable units at a higher cost, and a standard trailer for ground-based units. The total truck cost is then $103/hr for the standard trailers (NARA, 2016a) and $126/hr for the steerable rear trailers (Zamora-Cristales *et al.* 2015) with an average speed assumed at 30 mph. Daugherty and Sessions (personal communication) are currently documenting self-steering trailer mobility.

Collection cost was considered to be zero when the harvest units were yarded with a cable system and 24 $/ODMT on ground-based units (Zamora-Cristales and Sessions, 2016) using two forwarders and one loader with a harvest residue average distance to roadside of 156 m (Zamora-Cristales and Sessions, 2016).

Table 4.3 Cost summary per logging system

System	Mobilization ($)	Comminution ($/ODMT)	Collection ($/ODMT)	Truck waiting ($/ODMT)	Transportation ($/hr)
Cable	2,000	21	0	3.2	126
Ground	3,000	21	24	3.2	103

Distance from each harvest unit to the cogeneration plant was calculated from the centroid of each timber sale with the harvest units to Lyons, Oregon using ArcGIS.

4.3.7 Energy- based residue demand

Electricity output from a co-generation plant will depend upon many factors revolving around plant design that determine combustion efficiency in the boiler and turbine efficiency. In general, the lower the average moisture content of the feedstock, the less feedstock that will be required. Average energy rates per wood mass burned in a boiler were developed by Sessions (pers. communication) were used to generate a polynomial function that could be implemented in the optimization program (Figure 4.3). The energy rates were estimated assuming 33% conversion of net boiler output to electricity and recoverable Btu per green lb from Ince (1979) and Haygreen and Bowyer (1996) were scaled to approximately 1 MW-hr at 50% average moisture.

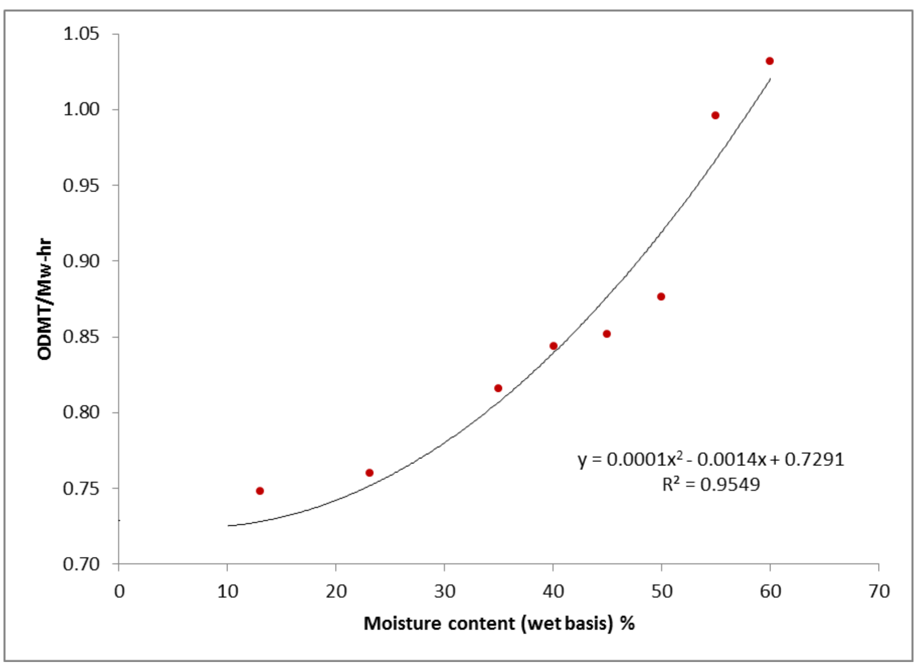

Figure 4.3 Rate of wood (ODMT) per MW-hr needed at the energy plant depending on wood moisture content

In order to implement this energy-based residue demand, the mathematical formulation of the problem needs to be modified as follows:

The first part is to be able to calculate average moisture content per period. A variable was created to calculate the amount of water contained in the wood per each period as follows:

$$\sum_i \left(\frac{volume_{ij}}{1-mc_{ij}}\right) * mc_{ij} = water_j, \forall\, i,j \in \mathbb{N} \qquad \text{(Eq. 8)}$$

Where mc_{ij} is the moisture content (wet basis) of harvest residue of unit *i* in period *j* and $water_j$ is the total amount of water contained in the residue in period *j*. The average moisture content per period was calculated dividing the amount of water on each period *j* by the green volume in the same period (Eq. 9).

$$\frac{water_j}{\sum_i \left(\frac{volume_{ij}}{1-mc_{ij}}\right)} = amc_j, \forall\, i,j \in \mathbb{N} \qquad \text{(Eq. 9)}$$

The function shown in Figure 4.1 was implemented as follows:

$$\sum_j 0.0001 * 100 * amc_j^2 - 0.0014 * 100 * amc_j + 0.7291 = d_j \;\; \forall\, i,j \in \mathbb{N} \qquad \text{(Eq. 10)}$$

Where d_j is the ODMT/MW-hr in period *j* at the average moisture content amc_j.

Finally, the original demand equation Eq. 2 needs to be modified to make the amount of ODMT demanded at each period vary, depending on the average moisture content of the delivered material.

$$\sum_i \frac{Volume_{ij}}{d_j} = Demand_j \;, \forall\, i,j \in \mathbb{N} \qquad \text{(Eq. 11)}$$

This energy-based demand scenario was implemented for only 6 periods (months) and compared with a 6 period original baseline scenario to demonstrate the effect in volume demand per period and changes in total cost. This decision was made to decrease computation time.

4.4 Results

4.4.1 Delivered volume by logging system

After economic optimization of the problem, the result indicates that all the residues from the previous year are used to help supply the power plant during the first four monthly periods (January to April of year 1). Then, the excess residue produced in May and June is left to dry to supply the deficit in August and September (Figure 4.4). A total of 75% of the available harvest residue is processed and delivered to the cogeneration plant in Lyons, Oregon. The average round-trip distance for the cable logging units is 72 km and for ground-based units 32 km.

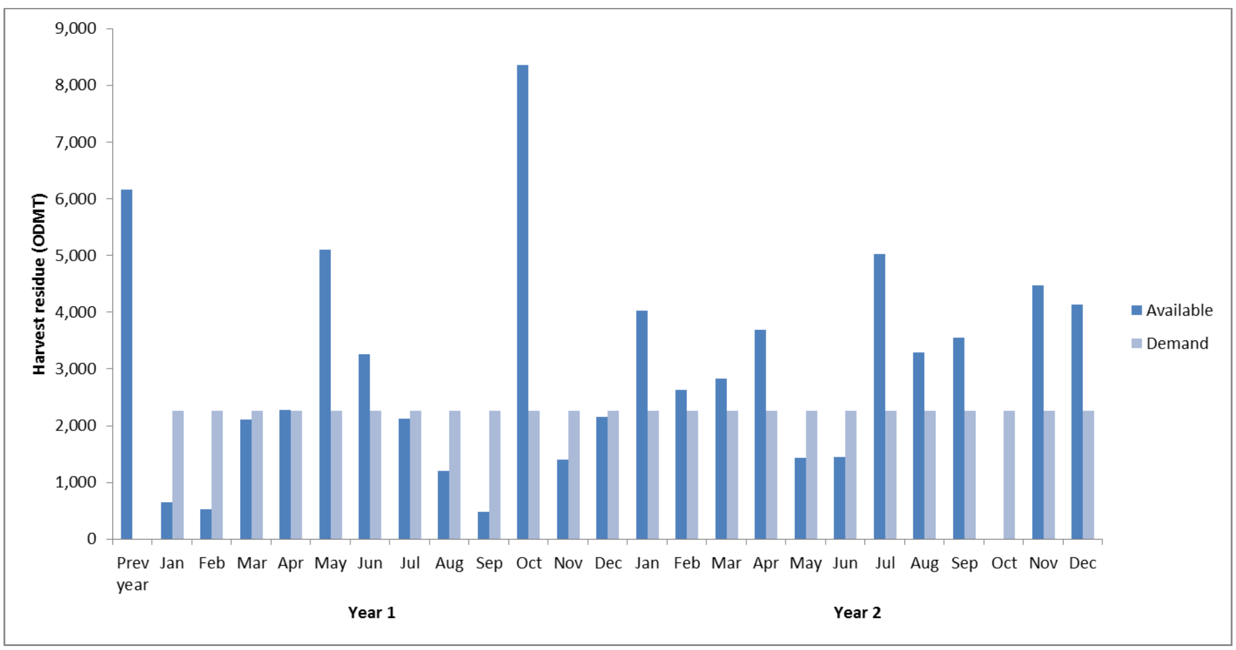

Figure 4.4 Harvest residue volume distribution over the two year period

4.4.2 Baseline scenario

In the base scenario, using a 13.7 m trailer and 160 kg/m^3 material bulk density, 98% of the volume harvested by cable system is processed and delivered to the plant, and only 56% of the volume harvested with a ground-based system is delivered to the plant (Figure 4.5). The average round trip distance of the material left in the harvest units is 87 km.

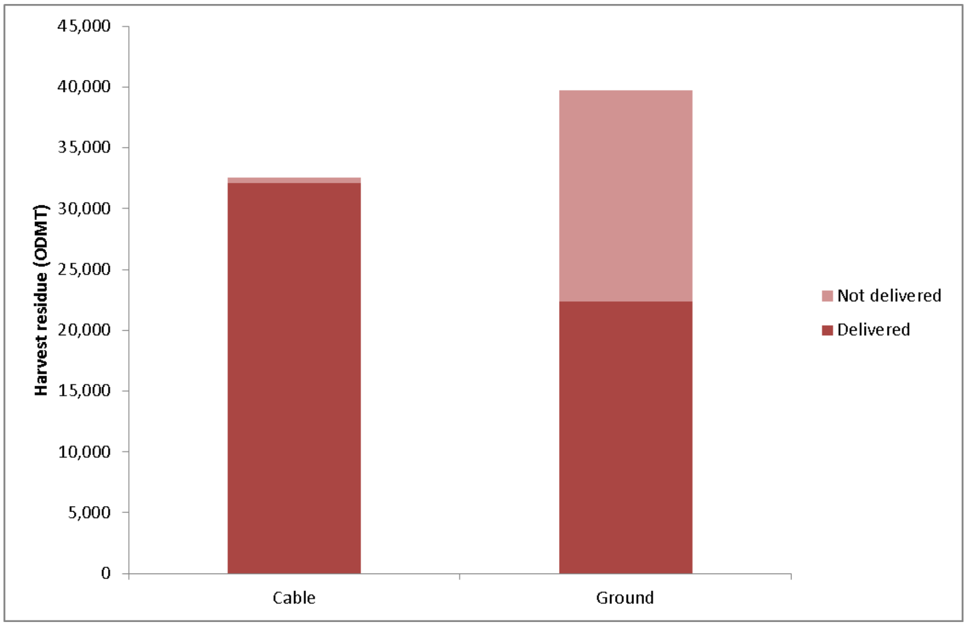

Figure 4.5 Delivered residue volume by harvest system

The average moisture content (wet basis) of the residue for both cable and ground-based harvest systems for the two year period is 34%.

4.4.3 Energy-based demand scenario

After implementing the harvest residue demand depending on its energy content for six periods, the amount of volume delivered to the plant is reduced by 13% (1,805 ODMT) without affecting the energy needs to keep the plant generating electricity at the same level as the baseline scenario. In terms of harvest systems, the ground-based system volume delivered to the plant is reduced by 36% and the cable system by 8% (Figure 4.6).

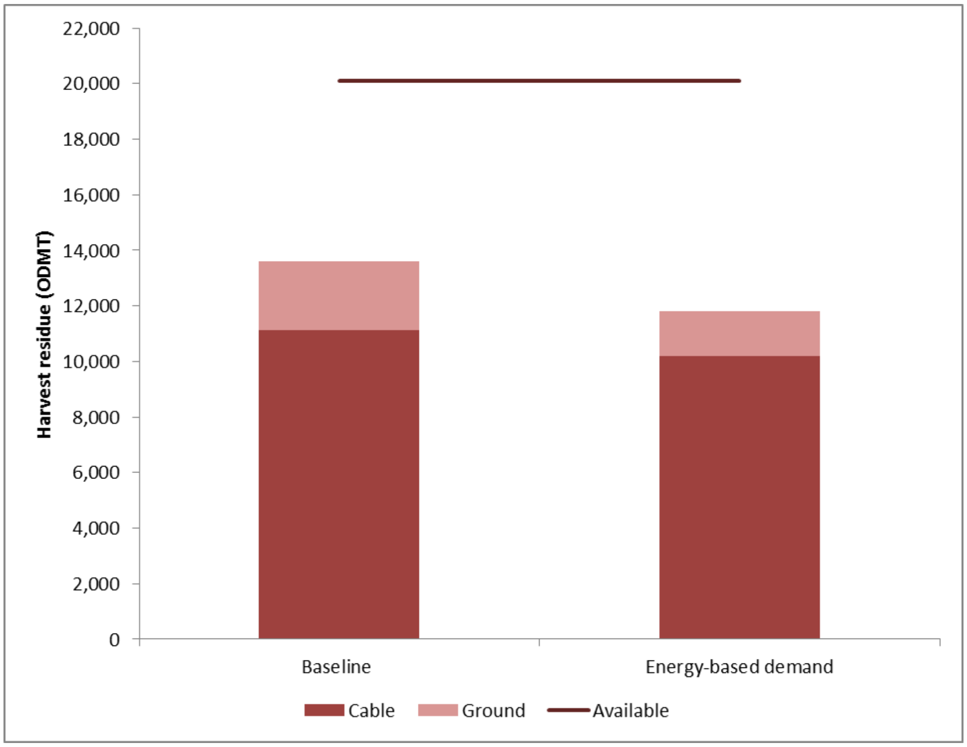

Figure 4.6 Available and delivered residue volume by harvest system during 6 periods

4.4.4 Storage time

4.4.4.1 Baseline scenario

The majority of the residue is left to dry for one month, especially the material harvested with a cable system. Very little volume is left to dry for more than four months (Figure 4.7). Probably because the single trailer becomes volume limited and there is not an advantage to let the material dry for much longer. Additionally, material is needed to cover volume gaps in preceding periods.

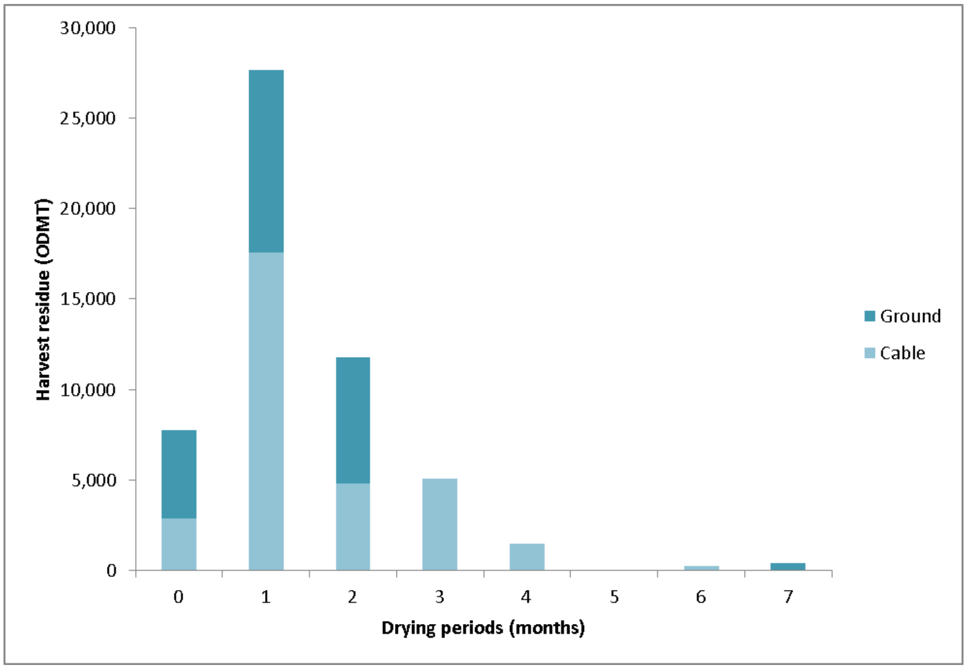

Figure 4.7 Number of dying periods for delivered harvest residue volume by harvesting system

4.4.4.2 Energy-based demand scenario

The amount of volume delivered to the plant is not only reduced when the demand for harvest residues is based on energy content. It also changes the number of drying periods of the residues in the field, shifting towards longer drying times. In Figure 4.8 b) is shown that are no residues processed and transported immediately after harvesting and residue volume is shifted towards 2 and 3 drying periods compared to the baseline scenario (Figure 4.8 a).

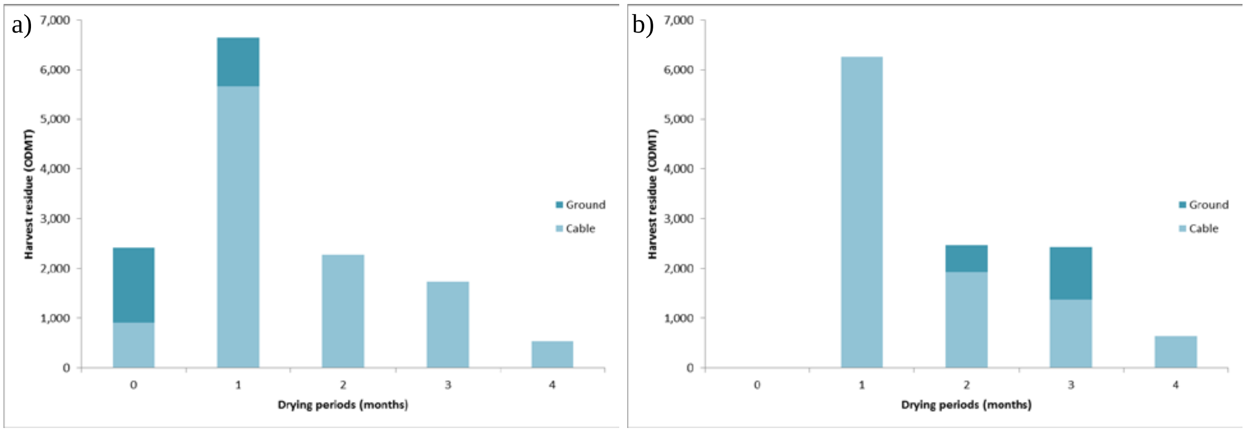

Figure 4.8 Number of dying periods for delivered harvest residue volume by harvest system, a) baseline scenario, b) energy-based demand scenario

4.4.5 Delivered harvest residue moisture content

4.4.5.1 Baseline scenario

Even when the optimization program is set to reduce cost, there are months in which moisture content is still high due to re-wetting of the material that is already being stored in the field or fresh material from fresh units. These high moisture peaks are observed mostly during the winter (Figure 4.9). However, most of the year the material stays at 30-35% moisture content.

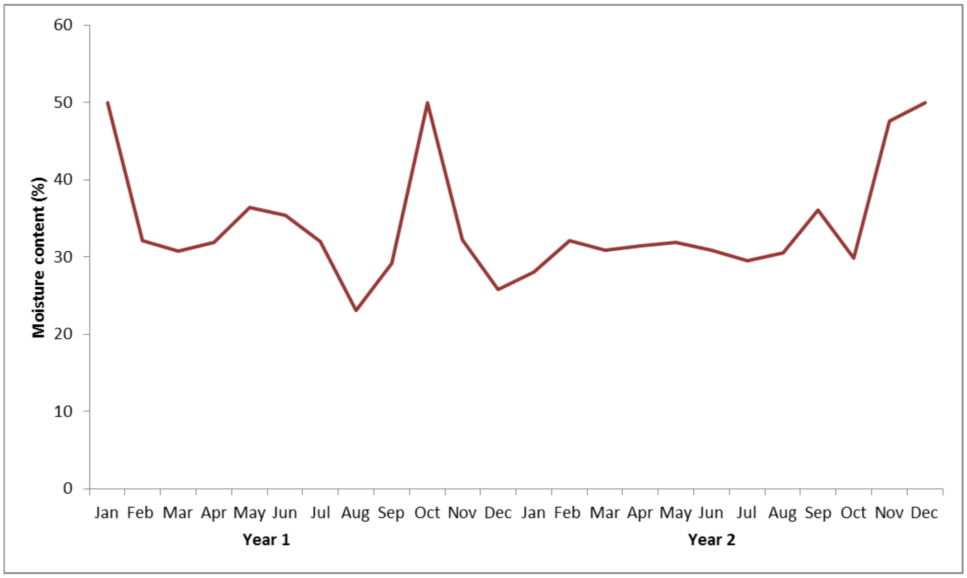

Figure 4.9 Average moisture content (wet basis) of delivered harvest residue per period

4.4.5.2 Energy-based demand scenario

By recognizing the value of drier material the problem shifts towards delivering material with lower moisture content. In the first two periods, the average moisture content is the same for both cases, probably because there is a smaller pool of units to choose from. However, as more units become available, the average moisture content starts decreasing, especially in the last two warmer months (Figure 4.10).

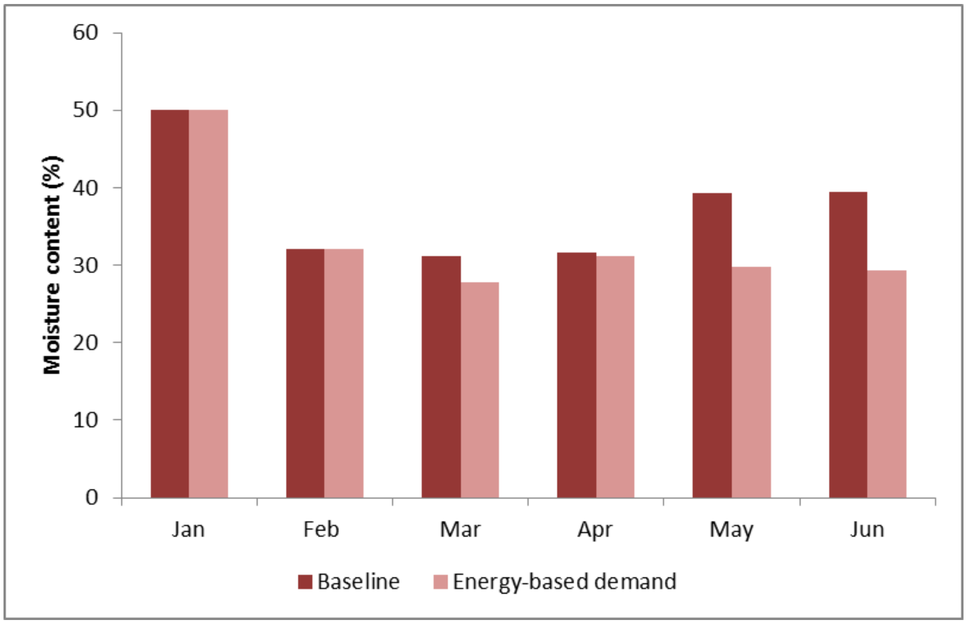

Figure 4.10 Average moisture content (wet basis) of delivered harvest residue per period for both baseline and energy-based demand scenario

4.4.6 Cost analysis

4.4.6.1 Baseline scenario

At the ground-based units, the largest proportion of the variable cost is collection (24.3 $/ODMT) which can be avoided in a cable unit because the material is already at the landing (Figure 4.11). Even when the average truck transportation cost for the cable system is 17.6$/ODMT and ground-based harvesting system is 9.5 $/ODMT, the higher residue drying rates achieved on a ground-based system are not enough to offset the transportation cost. The difference between both systems is 16.2$/ODMT.

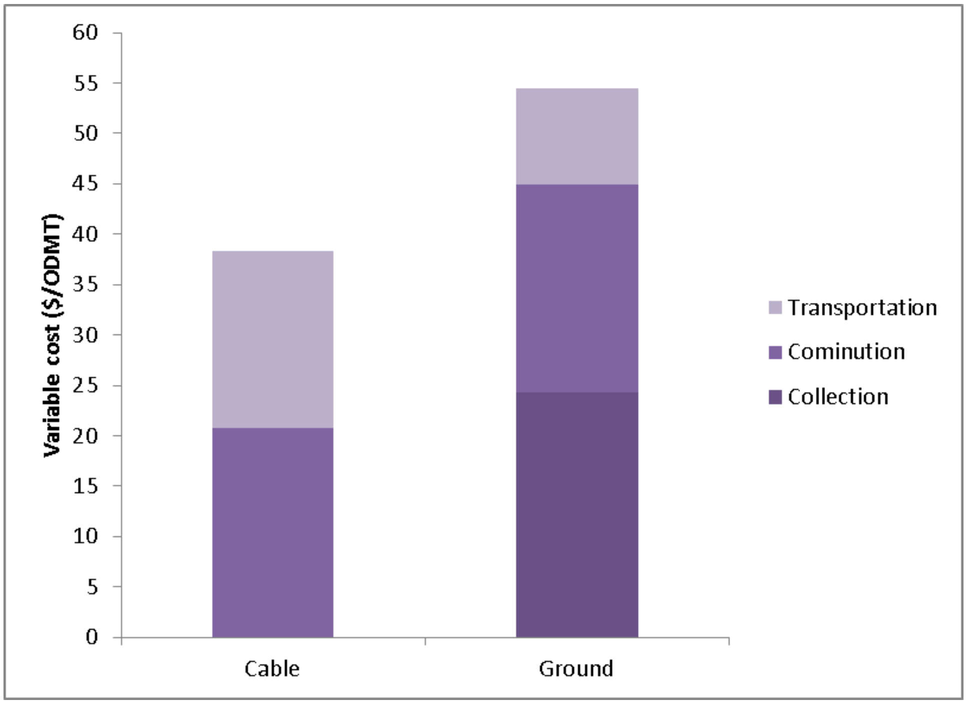

Figure 4.11 Variable cost by logging system

The total cost for the operation is $2,700,326 (50 $/ODMT) over the two year period. This is the objective function value with 0.7% gap. The upper bound is our integer solution associated with the objective function, $2,700,326, and the lower bound is the minimum of the optimal objective function values of all the current leaf nodes.

4.4.6.2 Energy-based demand scenario

The only difference in variable costs for the energy-based demand scenario is transportation. Comminution and collection are assumed to be constant (Zamora-Cristales *et al.* (2016)) and the handling within the mill is assumed to be unaffected. Since the amount of residue volume and harvest units that are chosen change, transportation cost is reduced on average by 1.4 $/ODMT. When the cost is separated by harvesting system, the cost reduction is 1.1 $/ODMT for the cable system and 1.7 $/ODMT on the ground-based system (Figure 4.12).

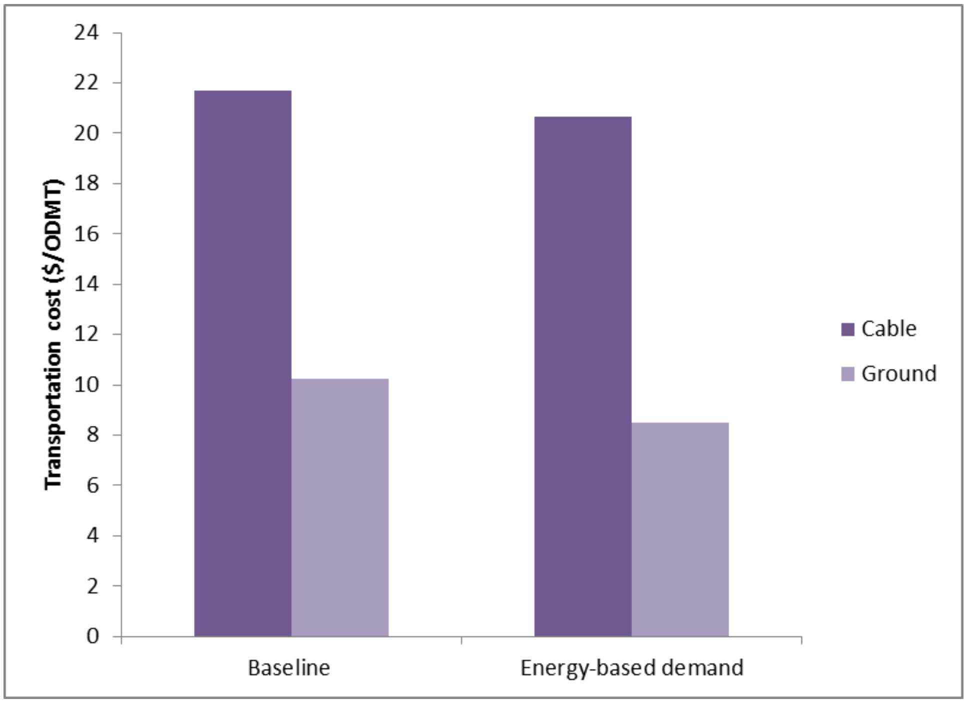

Figure 4.12 Transportation cost by logging system for the two scenarios

When compared with the baseline scenario, the total cost of the operation during the 6 periods is reduced by 16.5% ($100,297 lower).

4.5 Discussion

Drying rates for piled and scattered residues are quite different. Scattered residue is more sensitive to changes in the environment than residue stored in piles. It will reach lower moisture content and dry faster during the summer months but also will get wetter during the rainy season. So if residue is to be stored in the field, it is best to store scattered residue over the summer and process it before it gets wet. But if the residue is piled, it will get less wet over the rainy season when compared with scattered residue, that is, if residue needs to be processed in the wet season it is better to do so with material that has been previously piled.

The amount of forest residue available for this case study is enough to supply 63% of feedstock for a 6 MW-hr cogeneration plant in Lyons, OR. The majority of the residue coming from a cable system operation is delivered to the plant (98%), even when the cable units are further from the plant and have a lower drying rate. The ground system units are closer to the plant but the collection cost is too high to have those units be more cost effective than the cable units.

For both cases, piled and scattered residue, moisture drops fast during the first month. For that reason most of the residue is left to dry for the first month. This result is different from what Acuna *et al.* (2012) found. Their results indicate that they should leave the residues to dry from 7 to 8 months. However, they have multiple products to supply the plant with higher storage costs than harvest residues. Currently, since harvest residues are usually left to dry for burning in the fall, storage cost was not considered in this study.

In terms of variable cost, the ground-based units are 158% higher compared to units harvested with cable system. The main reason for this difference is the collection cost that needs to be incurred when the residue is scattered over the unit. The lower drying rates in the piled residues and the higher transportation cost of the cable units are not such a high cost compared with collection cost.

When the plant demand is based on a constant harvest residue energy content (0.91 ODMT=1 MW-hr), the amount of material needed to obtain the same output of energy is reduced by 13%. This is caused by energy losses due to the vaporization of water contained in the wood during the combustion process (Bowyer *et al.*, 2003). For that reason, drier residues make energy production more efficient.

Most of the ODMT reduction occurred in the ground-based units (36% reduction). Mainly because collection cost makes those units more expensive and because those units had less volume, making the mobilization cost very large in relation with the cable units.

As expected, when drier material becomes more attractive from the demand point of view, there is an additional incentive to let material dry in the field for longer time. As seen in Figure 4.8, no fresh material is taken to the plant in the energy-based demand scenario. It is all left to dry for at least one period, and as more units become available, material start shifting towards more drying periods. Since there is no cost considered to let the material dry, this is a good alternative to recognize the value of drier material.

The changes in moisture content, quantity and origin of the harvest residues delivered to the plant result in a cost reduction in transportation averaging 1.4 $/ODMT. This cost could be reduced even further if a double trailer could be used in harvest units further from the plant. These trailers present an advantage compared with single trailers since they have larger volumetric capacity (Zamora-Cristales and Sessions, 2015).The total cost reduction of the operation during the 6 periods is 16.5%. This is result of having the plant demand being driven by the harvest residue energy content as a function of its moisture content instead of assuming a fixed 0.91 ODMT/MW-hr at 50% moisture. If we were to express the total cost reduction in terms of energy production (2,268 MW-hr per month), the feedstock cost is reduced from 41 to 34 $/MW-hr.

4.6 Conclusions and Future Work

In this case study, it is more cost effective to process and transport forest harvest residues from cable logging units rather than ground-based logging units. This was true despite the greater average distance from those units to the plant (30% greater) compared to the ground-based system. In all the scenarios evaluated in this study, 98% of the harvest residue originated by a cable logging system is processed and delivered to the plant.

With the models developed in Chapter 3 we were successfully able to predict drying rates for piled and scattered residues being stored at different times of the year. It is a tool that provides key information for decision making in the forest harvest residue management.

For the baseline scenario (24 periods), the longest residue storage period in the units was seven months. Most of the material is stored for one month followed by two months. Under the circumstances of this study, letting the material dry for a longer time does not seem beneficial.

Since fuel value is inversely related to moisture content, grindings with lower moisture content are more valuable at the plant. In our case study, 13.3% fewer ODMT of residues are required to generate a fixed power output. This approach incentivizes longer drying times in the field and can result in a cost reduction of 16.5% in the total cost on a 6 year planning horizon. These cost differences consist of 92% variable cost and 8% fixed cost (mobilization).

The conclusions are limited to a specific area. However, drying rate schedules can be derived for other climate regions in the Pacific Northwest and can be used to investigate the effects of forest residue. We assumed that all cable harvest units required use of the more expensive self-steering trailer. Not all cable units will require self-steering trailers and 6 x 6 truck tractors. However, as cable harvest units were chosen over ground-based units, using less expensive trucks on some cable units probably would not have affected the biomass utilization schedule for this example.

This study assumed residue recovery of 0.82 ODMT/MBF for both cable and ground-based harvest units. Changing the residue recovery assumption of 0.82 ODMT/MBF to recognize different recovery coefficients will change the outcome of the results and would make the supply estimates and cost analysis more accurate.

The addition of the average moisture content as part of the relationship between fuel value and mill demand results in a nonlinear mixed integer program. Adding periods (variables) to the problem increases solving time exponentially. Future work could include solving the 24 period problem.

Finally, needle loss over time was not considered in this work. Needles increase ash content and are not desirable for combustion. It is an aspect that could potentially be included in the analysis in the future since it would increase the value of the harvest residue as a fuel and benefit the nutrient retention in the harvest unit. Our example used forest residues as feedstock for cogeneration. The trade-offs between feedstocks from cable units and ground-based units may change if the feedstocks are used for liquid fuels, particularly when polysaccharide content of aged versus fresh residues is considered (Zamora-Cristales *et al.* 2015b)

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5 General Conclusions

Forest harvest residues are a widely available renewable energy source in the Pacific Northwest. Several researchers, private and governmental entities have directed their efforts in making this product cost effective for energy production. In the presented studies, we have learned how its moisture content changes from the beginning of the drying process through storage time in the forest. It has been demonstrated that there are ways to manage these residues to improve their natural drying and increase the cost effectiveness of its processing and transport for energy production. Specifically, on each chapter, the conclusions are the following:

5.1 Seasonal changes in live branch moisture content of three forest species in the Pacific Northwest, USA

Seasonal branch average moisture content was determined for four major commercial forests areas in the Pacific Northwest. After data was analyzed, the main conclusions include the following:

- In the study, only ponderosa pine averaged 50 ± 1% during the winter, all other site averages are below this MC although a few individual branches exceeded 55%.
- In terms of seasonal variation, higher initial moisture content can be expected in ponderosa pine residues during the winter. MC can be from 1.6% to 9.8% higher compared with other seasons. For Douglas-fir, initial moisture content can be expected to be lowest when water supply is limited during summer drought. MC can be from 0.8% to

3.9% lower when compared with other seasons. Western hemlock and Douglas-fir growing with a secured water supply do not present significant differences in MC.

- Branch height and heartwood content have a strong correlation with branch average MC. Branch height explains up to 74% of branch moisture content by a simple regression. These equations can be used as a non-destructive method to estimate live branch moisture content. Using a sampling destructive method to measure heartwood diameter does not improve the coefficient of determination, making the branch height the simplest and most accurate predictor to estimate average branch moisture content.

5.2 Finite element analysis to predict in-forest stored harvest residue moisture content

Finite element models were developed for four sites representing the main climatic regions in Oregon and their respective commercialized forest species. These models are able to sufficiently predict piled forest residue drying rates with weather data input such as precipitation, wind, ambient temperature and relative humidity. Conclusions include:

- Piled residue moisture content responds to the environmental conditions greatly. The selection of pile shape or size can be beneficial or detrimental towards the rate of drying depending on ambient conditions, namely precipitation.
- A berm (windrow) presents the best option for expedient drying due to its large surface area. Drying is the fastest in this shape during dry summer months; however, the pile also re-wets the fastest during winter months.

- It is best to reduce pile volume if storage will occur through summer and increase size if it will occur through winter.
- Significant reduction in drying times can be achieved if the material is cut and left to dry during the dry, warm summer months. This reduction can be up to 1/3 of the time versus starting the process in the winter.

Future work can include a sensitivity analysis of changes in slope and aspect of piled harvest residue and refine the models by changing the porosity with pile depth.

5.3 Economic implications of moisture content and logging system in forest harvest residue delivery for energy production: a case study

For the case study evaluated in this manuscript, scheduling of harvest residue delivery was achieved in order to supply a hypothetical cogeneration plant of 6 MW-hr by 63%. A total of 75% of the available forest harvest residue is utilized to supply the plant. Analysis of the results indicates the following conclusions:

- It is more cost effective to process and transport forest harvest residues from cable logging units rather than ground-based logging units. This was true despite the greater average distance from those units to the plant (30% greater) compared to the ground-based system. In all the scenarios evaluated in this study, 98% of the harvest residue originated by a cable logging system is processed and delivered to the plant.
- For the baseline scenario (24 periods), the longest residue storage period in the units was seven months. Most of the material is stored for one month followed by two months. Under the circumstances of this study, letting the material dry for a longer time does not seem beneficial.

- Since fuel value is inversely related to moisture content, grindings with lower moisture content are more valuable at the plant. In our case study, 13.3% fewer ODMT of residues are required to generate a fixed power output. This approach incentivizes longer drying times in the field and can result in a cost reduction of 16.5% in the total cost on a 6 year planning horizon. It also represents a more accurate method to determine supply and cost estimates of harvest residue delivery for power generation.
- The conclusions are limited to a specific area. However, drying rate schedules can be derived for other climate regions in the Pacific Northwest and can be used to investigate the effects of forest residue. We assumed that all cable harvest units required use of the more expensive self-steering trailer. Not all cable units will require self-steering trailers and 6 x 6 truck tractors. However, as cable harvest units were chosen over ground-based units, using less expensive trucks on some cable units probably would not have affected the biomass utilization schedule for this example.

The average moisture contents, models and economic analysis were made with local data and inferences are generally specific to these locations. However, the main concepts, results and sensitivity analyses still present a general understanding for drying conditions and economic advantages in many different climates and geographic locations. Future work can include cost analysis of forest harvest residues for liquid fuel production, refine harvest residue estimates and including needle loss over time to recognize its value in terms of feedstock quality and harvest unit nutrient retention.

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APPENDICES

Appendix A Regression output and ANOVA to predict sample moisture content by its heartwood diameter

Call:

```
lm(formula = Sam_MC ~ poly(Heart_Sam, 2, raw = TRUE))
```

Residuals:

```
     Min       1Q   Median       3Q      Max
-1.64825 -1.23514 -0.00006  0.78452  2.85806
```

Coefficients:

```
                                 Estimate Std. Error t value Pr(>|t|)
(Intercept)                     44.154777   1.483284  29.768 1.94e-15 ***
poly(Heart_Sam, 2, raw = TRUE)1 -0.178920   0.114750  -1.559    0.139
poly(Heart_Sam, 2, raw = TRUE)2 -0.001732   0.001921  -0.902    0.381
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 1.444 on 16 degrees of freedom
Multiple R-squared:  0.8969,    Adjusted R-squared:  0.884
F-statistic: 69.61 on 2 and 16 DF,  p-value: 1.274e-08
```

Appendix B Regression output and ANOVA to predict branch average moisture content by its first sample heartwood diameter

Call:

```
lm(formula = Branch_MC ~ Heart_1st)
```

Residuals:

```
    Min      1Q  Median      3Q     Max
-1.8990 -0.6696 -0.2897  0.5887  3.1350
```

```
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 48.57535    0.62846  77.292  < 2e-16 ***
Heart_1st   -0.12928    0.01751  -7.385 5.38e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.288 on 19 degrees of freedom
Multiple R-squared:  0.7416,    Adjusted R-squared:  0.728
F-statistic: 54.54 on 1 and 19 DF,  p-value: 5.382e-07

Analysis of Variance Table

Response: Branch_MC
          Df Sum Sq Mean Sq F value    Pr(>F)
Heart_1st  1 90.423  90.423   54.54 5.382e-07 ***
Residuals 19 31.500   1.658
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
```

Appendix C Statistical tests

VDL, Valley Douglas-fir

Wilcoxon signed rank test

data: A$Model and A$Samples

V = 23, p-value = 0.1272

alternative hypothesis: true location shift is not equal to 0

Spearman's rank correlation rho

data: A$Model and A$Samples

S = 6, p-value < 2.2e-16

alternative hypothesis: true rho is not equal to 0

sample estimates: rho 0.9835165

Kendall's rank correlation tau

data: A$Model and A$Samples

T = 75, p-value = 1.416e-07

alternative hypothesis: true tau is not equal to 0

sample estimates: tau 0.9230769

CWH Coast Western hemlock

Wilcoxon signed rank test

data: A$Model and A$Samples

V = 13, p-value = 0.02148

alternative hypothesis: true location shift is not equal to 0

Spearman's rank correlation rho

data: A$Model and A$Samples

S = 36, p-value < 2.2e-16

alternative hypothesis: true rho is not equal to 0

sample estimates: rho 0.9010989

Kendall's rank correlation tau

data: A$Model and A$Samples

T = 69, p-value = 7.03e-05

alternative hypothesis: true tau is not equal to 0

sample estimates: tau 0.7692308

VDH, Valley-East Douglas-fir

Wilcoxon signed rank test

data: A$Model and A$Samples

V = 33, p-value = 0.4143

alternative hypothesis: true location shift is not equal to 0

Spearman's rank correlation rho

data: A$Model and A$Samples

S = 98, p-value = 0.006323

alternative hypothesis: true rho is not equal to 0

sample estimates: rho 0.7307692

Kendall's rank correlation tau

data: A$Model and A$Samples

T = 61, p-value = 0.006677

alternative hypothesis: true tau is not equal to 0

sample estimates: tau 0.5641026

EPP, East Ponderosa pine

Wilcoxon signed rank test

data: A$Model and A$Samples

V = 2, p-value = 0.0007324

alternative hypothesis: true location shift is not equal to 0

Spearman's rank correlation rho

data: A$Model and A$Samples

S = 16, p-value < 2.2e-16

alternative hypothesis: true rho is not equal to 0

sample estimates: rho 0.956044

Kendall's rank correlation tau

data: A$Model and A$Samples

T = 73, p-value = 1.808e-06

alternative hypothesis: true tau is not equal to 0

sample estimates: tau 0.8717949