AN ABSTRACT OF THE THESIS OF

Christian F. W. Schmidt for the degree of Master of Science in Forest Engineering presented on June 6, 2011.
Title: Spatially-Explicit Prediction of Recoverable Harvesting Residues

Abstract approved:

__________________________________________________________________________

John Sessions

In order to decide whether or not to develop biomass energy facilities and where to best locate them, developers and investors need accurate assessments of fuel supply. This includes information about the distribution and concentration of fuel throughout the assessment area, the quality of fuel (form, moisture content, contaminant content, energy value, etc.), accessibility, and transportation distances to the facility. Including spatial detail about recoverable fuel densities and distribution allows planners to determine optimal choices for facility siting, fuel sourcing and transportation. Improving assessment accuracy increases the likelihood of project success and profitability.

In this thesis we demonstrate methods for predicting quantity, density and distribution of recoverable forest harvesting residues applied to a biomass assessment project in northwest Oregon and southwest Washington. Predicted vegetation maps, allometric equations, and information about landowner intentions were used to predict forest biomass during the inventory period. Riparian and wetland management zones were modeled in a Geographic Information System (GIS) and excluded from potential biomass yielding lands. Private industrial forests harvestable during the inventory and forecast periods were classified into groups by species composition and basal area. To
represent growth between inventory and forecast periods average biomass densities for inventory period harvestable forest groups were projected onto the groups in forecast period harvestable forests. On Oregon Department of Forestry (ODF) land, harvest plan data was used to determine harvest areas in the forecast period and how much biomass they would yield. This information was combined to make a GIS raster of recoverable harvest residue densities for the forecast period. The estimate of residues recoverable over the forecast period was 7,054,526 bone-dry tons (BDT), using the strictest residue criteria. A simulation was designed to quantify uncertainty caused by use of allometric equations in the inventory period private industrial forest biomass estimate. This uncertainty simulation generated an average recoverable biomass total of 6,412,049 BDT, only 0.4% less than the point estimate of 6,437,632 BDT. The maximum and minimum of 1170 simulation runs differed by only 392 BDT. This suggests that the allometric equations have a negligible contribution to the uncertainty of the total biomass estimate. Comparison of the point estimate, simulation outputs and rough estimates of biomass from harvest records and estimated BDT/MBF ratios led us to conclude the point estimate for the inventory period was reasonably accurate. This lent support to the forecast period estimate which relied on many of the same methods. Calculated average BDT/MBF ratios for the project area were comparable to other published figures. Promising subjects for future research include improving the gradient nearest neighbor (GNN) imputation method to predict recoverable biomass, developing methods for quantifying uncertainty of biomass assessments, and determining residue recovery rates for different forest types and harvest methods.
Spatially-Explicit Prediction of Recoverable Harvesting Residues

by
Christian F. W. Schmidt

A THESIS
submitted to
Oregon State University

in partial fulfillment of the requirements for the degree of
Master of Science

Presented June 6, 2011
Commencement June 2012
ACKNOWLEDGEMENTS

I would like to thank the members of my committee John Sessions, Kevin Boston, David Smith, Lisa Madsen, and Kate Field for all their help and support. Thank you to Temesgen Hailemariam and Quinn Payton for their assistance. Thank you to Ryan Miller, Liz Dent, Tod Haren and Rob Nall at the ODF. Thank you to Janet Ohmann, Matt Gregory and Heather Roberts with the LEMMA program. Many thanks to Rick Strachan, L.L. Stewart, Wes and Nancy Lematta, Alfred W. Moltke, the OSU Foundation, and the Oregon Office of Vocational Rehabilitation Services for giving me the opportunity to study at OSU.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Rationale and Significance</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Goals and Objectives</td>
<td>7</td>
</tr>
<tr>
<td>1.4 Researchable Questions</td>
<td>9</td>
</tr>
<tr>
<td>2 Literature Review</td>
<td>10</td>
</tr>
<tr>
<td>3 Materials and Methods</td>
<td>34</td>
</tr>
<tr>
<td>3.1 Overview</td>
<td>34</td>
</tr>
<tr>
<td>3.2 Materials / Data Sources and Assumptions</td>
<td>37</td>
</tr>
<tr>
<td>3.2.1 LEMMA Predicted Vegetation Map</td>
<td>37</td>
</tr>
<tr>
<td>3.2.2 Harvest Residue Criteria</td>
<td>40</td>
</tr>
<tr>
<td>3.2.3 Allometric Biomass Equations</td>
<td>42</td>
</tr>
<tr>
<td>3.3 Biomass Calculations for LEMMA FCID’s</td>
<td>44</td>
</tr>
<tr>
<td>3.4 Determining Biomass Producing Lands</td>
<td>46</td>
</tr>
<tr>
<td>3.4.1 Land Ownership</td>
<td>46</td>
</tr>
<tr>
<td>3.4.2 Landowner Groups Included in the Biomass Estimate</td>
<td>47</td>
</tr>
<tr>
<td>3.4.3 Management Intentions</td>
<td>50</td>
</tr>
<tr>
<td>3.4.4 Accuracy of LEMMA Dominant Forest Ages</td>
<td>51</td>
</tr>
<tr>
<td>3.5 Accounting for Riparian and Wetland Management Areas</td>
<td>52</td>
</tr>
<tr>
<td>3.6 Predicting Residue Biomass in the Forecast Period</td>
<td>60</td>
</tr>
<tr>
<td>3.6.1 Private Industrial Forests</td>
<td>60</td>
</tr>
<tr>
<td>3.6.2 ODF Forests</td>
<td>67</td>
</tr>
</tbody>
</table>
TABLE OF CONTENTS (Continued)

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7 Forecast Recoverable Forest Residue Biomass Map</td>
<td>69</td>
</tr>
<tr>
<td>3.8 Residues Left On-Site After PI Harvests</td>
<td>71</td>
</tr>
<tr>
<td>3.9 Assessing Accuracy of the Recoverable Biomass Estimate</td>
<td>72</td>
</tr>
<tr>
<td>4 Results</td>
<td>76</td>
</tr>
<tr>
<td>4.1 Recoverable Biomass Totals</td>
<td>76</td>
</tr>
<tr>
<td>4.2 Forecast Residue Densities and Ratios</td>
<td>79</td>
</tr>
<tr>
<td>4.3 Residues Left On-Site After PI Harvests</td>
<td>82</td>
</tr>
<tr>
<td>4.4 Forecast Period Biomass Landbase</td>
<td>83</td>
</tr>
<tr>
<td>4.5 Riparian and Wetland Management Zone Modeling</td>
<td>84</td>
</tr>
<tr>
<td>4.6 Allometric Equation and Imputation Error and Uncertainty</td>
<td>89</td>
</tr>
<tr>
<td>5 Discussion</td>
<td>90</td>
</tr>
<tr>
<td>6 Conclusion</td>
<td>100</td>
</tr>
<tr>
<td>References</td>
<td>103</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>107</td>
</tr>
<tr>
<td>Appendix A - Allometric equations and and biomass database calculations</td>
<td>108</td>
</tr>
<tr>
<td>Appendix B - Oregon RMZ Modeling Script</td>
<td>133</td>
</tr>
<tr>
<td>Appendix C - Washington R/WMZ Modeling Script</td>
<td>135</td>
</tr>
<tr>
<td>Appendix D – Allometric equation uncertainty simulation</td>
<td>148</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1. One-way travel time, minutes, to Forest Grove from the surrounding area (Sessions and others 2010)</td>
<td>6</td>
</tr>
<tr>
<td>1.2. Cumulative forest biomass (BDT) supply available to multiple destinations as a function of one-way travel distance (Sessions and others 2010)</td>
<td>7</td>
</tr>
<tr>
<td>3.1. Project area PI forest land age distribution (excluding R/WMZ's)</td>
<td>63</td>
</tr>
<tr>
<td>4.1. The recoverable harvest residue raster for the 10 year forecast period displayed over project area map</td>
<td>78</td>
</tr>
<tr>
<td>4.2. Frequency of recoverable forest residue densities in harvestable age PI forests</td>
<td>79</td>
</tr>
<tr>
<td>4.3. Projected tree biomass (BDT/Ac) left on-site during the forecast period after harvesting with current commercial harvesting methods</td>
<td>82</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Biomass quantities (BDT/Ac) by class and forest type for all ownerships</td>
<td>26</td>
</tr>
<tr>
<td>2.2. Percentage of biomass by class and forest type for all ownerships</td>
<td>26</td>
</tr>
<tr>
<td>3.1. Sequence of steps in creating the recoverable harvest residue forecast map</td>
<td>37</td>
</tr>
<tr>
<td>3.2. Forest residue specification groups</td>
<td>41</td>
</tr>
<tr>
<td>3.3. Washington riparian and wetland management zone GIS model parameters</td>
<td>58</td>
</tr>
<tr>
<td>3.4. Oregon riparian management zone GIS model parameters</td>
<td>59</td>
</tr>
<tr>
<td>3.5. Rules for classifying forests into species-basal area groups</td>
<td>64</td>
</tr>
<tr>
<td>4.1. Total recoverable forest biomass and generating acres for 2010-2019 for the six recoverable material criteria</td>
<td>76</td>
</tr>
<tr>
<td>4.2. Recoverable forest residues and generating landbase for 2010-2019 by county for OR and WA</td>
<td>77</td>
</tr>
<tr>
<td>4.3. Recoverable forest residue densities of harvestable age PI Forests by species-BA group for the six residue criteria</td>
<td>80</td>
</tr>
<tr>
<td>4.4. Recoverable forest residue to timber volume ratios of harvestable age PI forests by species-BA group for the six residue criteria</td>
<td>81</td>
</tr>
<tr>
<td>4.5. Acres by land ownership likely to be harvested during the forecast period</td>
<td>83</td>
</tr>
<tr>
<td>4.6. Distribution of harvestable age PI forest land among species-basal area groups for the forecast period</td>
<td>84</td>
</tr>
<tr>
<td>4.7. Recoverable biomass (BDT) from PI forests without accounting for riparian and wetland management zone restrictions</td>
<td>86</td>
</tr>
<tr>
<td>4.8. Recoverable biomass (BDT) from PI forests using the GIS model to account for riparian and wetland management zones</td>
<td>87</td>
</tr>
<tr>
<td>4.9. Recoverable biomass (BDT) from PI forests, subtracting 7.35% from the total in Oregon and 18.75% in Washington to account for riparian and wetland management zones</td>
<td>88</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
</tr>
<tr>
<td>-------</td>
<td>------</td>
</tr>
<tr>
<td>4.10. Point estimates, range estimates, and allometric equation uncertainty simulation averages, medians and prediction intervals of recoverable biomass (BDT) from PI forests in the project area during the ten years centered on the inventory period (1998-2007).</td>
<td>89</td>
</tr>
<tr>
<td>5.1. Comparison of recoverable residue to harvested timber ratios</td>
<td>91</td>
</tr>
</tbody>
</table>
DEDICATION

For Rachel Houtman and Pegge Erkenef.
This would have been impossible without your support and friendship. I am so lucky and so grateful to have you both in my life. Thank you.
Spatially-Explicit Prediction of Recoverable Harvesting Residues

1 Introduction

1.1 Background

Increasing interest in sources of domestic, renewable energy has brought forest biomass energy into the public spotlight. Electricity produced from woody biomass has a number of advantages that make it an attractive energy source for the United States as well as some other countries. There are a number of economic reasons why woody biomass energy is appealing. As a result of the decreasing supply of petroleum oil, the price of derived products, including electricity and liquid fuels, will continue to rise. Currently, prices for petroleum are unpredictable and this unpredictability is passed along to related energy products. The United States relied on other countries for 49% its supply of petroleum products in 2010 (EIA 2011) and relationships with some of these oil exporting countries are tenuous. Reducing the U.S.’s demand for oil imports would help reduce the effect this dependence has on our nation's foreign policy decisions. Development of biomass energy in the U.S. to move towards energy independence would also help create more domestic jobs and services throughout the biomass supply and energy conversion chain.

Environmental concerns also motivate the increased interest in forest bioenergy development. As the public has become more aware of the effects of climate change, the influence of anthropogenic factors has entered the national discussion. Generating electricity and usable heat from woody biomass instead of fossil fuels can reduce the net flux of greenhouse gases into the atmosphere under certain conditions (Marland and
Carbon emission reductions from woody bioenergy replacing fossil fuel energy can be marginal or even negative soon after development but increase with increasingly longer time frames (Schlamadinger and others 1995). Electricity and usable heat generated from wood waste such as harvesting residues has a lower greenhouse gas “footprint” than some dedicated woody energy crops or natural gas since wood waste will either decompose or be burned if it is not used for energy production (Johnson 2009). Using this material to generate electricity reduces emissions when compared to open-burning (CH2M Hill 2005) by burning this material under controlled conditions and routing the exhaust through pollution control devices.

Aside from preventing or reducing some environmental harm, development of forest bioenergy can have environmental benefits. Some of the common forest ecosystem types found in the Western United States are adapted to survive low to moderate intensity forest fires and even rely on this as a mechanism for nutrient cycling and reducing competition between trees for water, nutrients and sunlight. Widespread, intense, highly successful fire suppression efforts during the 20th century changed the forest profile, in terms of density, size and species composition, of many of these fire-adapted forests. More recently, efforts have been made to restore some of these forests to their pre-fire-suppression structure through the use of thinning and prescribed fire application. When thinning projects to achieve these lower forest densities or prepare for prescribed fire occur, they can produce significant quantities of woody residues. If broadcast burning can’t be applied, often the only affordable options to dispose of this material are landfills or pile burning. By creating a demand for woody biomass,
bioenergy projects can provide a more desirable and useful option for disposing of the residues from forest health thinning. In spite of the large area in the Western U.S. in need of forest health thinning treatments, relatively few acres have been treated due to the prohibitively high cost per acre. Sufficient development of biomass energy facilities could create a market for wood waste that would partially offset the high cost of forest restoration projects and allow more areas to benefit as a result of restoration programs with fixed budgets facing lower marginal treatment costs.

1.2 Rationale and Significance
The feasibility of a biomass energy project depends on reliable access to a sufficient yield of affordable feedstock of acceptable quality to fuel the proposed facility throughout its operational life. Woody biomass used for fuel is the lowest value wood product produced in the forest, with extremely low value to volume and value to weight ratios (Lord and others 2006). As a result, approximately half or more of the cost of fuel delivered to a power plant comes from transportation and handling costs (Fried and others 2003). Fuel acquired from distant locations can cost more than the revenues created from converting it to energy. If a biomass energy power plant runs out of fuel it cannot produce usable energy and therefore cannot generate revenue and accumulates significant financial losses with increasing down-time. Determining if there is reliable access to a sufficient yield of affordable, quality feedstock requires an understanding of the distribution of recoverable fuel across the potential catchment areas for candidate facility sites, and an evaluation of fuel sourcing, handling, and routing options and siting alternatives that together result in the lowest cost to acquire and transport the required quantity and quality of fuel to the facility throughout its lifespan.
The City of Forest Grove, Oregon is an example of an entity that is interested in the potential of woody biomass energy. The City of Forest Grove contracted with Oregon State University to perform an assessment of the potential for developing a biomass energy facility in northwest Oregon. The assessment includes three primary functions: A) to assess available sources of woody biomass to determine the type, location, quality and quantity of fuel produced annually; B) to develop recommendations for the handling and transportation of fuel to a biomass plant and obtain costs for each method; and C) to investigate costs of providing biomass to several alternative locations within northwest Oregon. The assessment of available woody biomass quantity and distribution across the project area (part A) for this contract was completed while conducting the work and analysis for this thesis using the methods described herein.

This project demonstrated a method for developing a spatially-explicit estimate of the quantity of forest harvesting residues available for recovery as energy feedstock across the project area over a ten year forecast period which can be used along with data on the local transportation network to analyze optimal facility siting, feedstock transportation methods and routing, and develop supply curves and cost predictions to facilitate determining the financial feasibility of the project. Examples of the analyses enabled by spatially-explicit predictions of recoverable biomass are maps of transportation time from different locations to candidate sites (Figure 1.1) and calculations of potential biomass supply to facility sites as a function of travel time (Figure 1.2) (Sessions and others 2010). The project area represented the catchment areas for a number of potential biomass power plant sites. Because this resulting map of estimated biomass densities
across the project area was intended to become an input in an economic analysis of supply costs for potential facility sites performed by other researchers, the spatial distribution of woody forest biomass quantities across the landscape was a fundamentally important characteristic of the biomass assessment.
Figure 1.1. One-way travel time (minutes) to Forest Grove from the surrounding area (Sessions and others 2010)
1.3 Goals and Objectives

There is significant interest in ensuring the accuracy of biomass energy feasibility assessments because of the high cost of developing a biomass energy power plant and the risk of financial losses if an adequate supply of affordable, quality fuel can’t be consistently delivered to such a facility throughout its operational life. One quote for the capital cost of a 25 MW stoker-fired biomass energy plant is $56,200,000 (McNeil Technologies 2003). Considerable research has been done on decision support systems for fuel sourcing and routing and facility siting for biomass energy projects (Noon and Daly 1996; Fried and others 2003; Domínguez and Amador 2007; Alfonso and others...
2009; Young and others 2009) but few studies have focused on improving the level of detail, spatial resolution and accuracy of project level biomass assessments. The challenge of developing an accurate estimate of the distribution of available fuel biomass densities over the project landscape has received less attention and is one of the main subjects of this thesis. Many of the published biomass estimates for energy development are limited in spatial detail, particularly regarding distribution of fuel quantities across the catchment areas. A significant proportion of published assessments base their estimates on hypothetical accelerated treatment scenarios for hazardous fuel reduction (HFR) projects, instead of current conditions and land management practices. While such assessments can be helpful in getting an estimate of the maximum potential available biomass if conditions change drastically, their applicability is contingent on these major changes in landowner behavior and biomass market demand taking place. These changes in management practices, behavior and market conditions could potentially occur if woody biomass energy projects were already established. Realistic estimates of woody biomass that is available under current conditions are necessary to inform current bioenergy facility development decisions and represent a necessary first step towards developing a thriving bioenergy market. For this reason, this thesis focuses on timber harvesting residues, which are currently available and being generated under present conditions. Not all biomass estimates have predicted the portion of potential fuel biomass that is practically recoverable. This thesis will demonstrate how detailed vegetation coverage predictions, knowledge of current dominant land management behaviors, allometric biomass equations and reasonable assumptions about biomass recovery and forest practice law applications can be used to develop estimates of available, recoverable timber harvesting residue quantities and their distributions over
the project area with higher detail and spatial resolution than current standards for such biomass assessments to enable more precise transportation and economic modeling and analysis.

1.4 Researchable Questions

- What effects do the inclusion of riparian and wetland management area regulations have on the recoverable biomass estimate?
- How significant is the error in this biomass assessment and how can it be estimated?
- How reasonable are these assumptions and generalizations compared to those made by other methods of assessment?
- How do this method's calculations of recoverable biomass rates in the project area compare with previously published rates for predicting available biomass?
- What are the strengths and weaknesses of this method of estimating available biomass distribution and total quantity when compared to other biomass estimates performed in the region?
- Is this approach to estimating available biomass replicable in areas outside of the region covered by the Landscape Ecology, Modeling, Mapping and Analysis (LEMMA) projects?
2 Literature Review

As the interest in forest biomass as a source of fuel has picked up again in the past decade, there have been a number of biomass estimates published with different spatial scales considered. A significant number of publications (Howard 1990; Walsh and others 1999; Jenkins and others 2003; Perlack and others 2005; USDA FS 2005) have described methods of estimating biomass or developed actual estimates of the total quantity of biomass in an area at a national or regional scale. Such assessment methods certainly serve a purpose, but are of little value when trying to determine the feasibility of specific biomass energy projects or predict the cost of supplying the necessary feedstock to potential facility sites. Determining project feasibility and supply cost to specific locations requires detailed prediction of the spatial distribution and variation in the biomass resource over the catchment areas. Multiple biomass assessments with some degree of relevance to this thesis will be presented here. Some of the estimates are more relevant to the topic of this thesis than others. Those that had a sub-state spatial scale, focused on logging residues, accounted for recoverability limitations, or were focused on private industrial timberlands were of particular interest. These assessments will be organized by spatial scale, similarly to Roger Lord’s paper in Biomass Energy & Biofuels from Oregon’s Forests (Lord and others 2006), starting with national and regional estimates and continuing to state level and sub-state level estimates. Also, the Gradient Nearest Neighbor (GNN) imputation method used by the LEMMA program, the results of which this thesis made extensive use of, will be discussed.
Walsh and others (1999) published a national level assessment that included logging residues and other forest biomass sources in the total. This assessment is noteworthy in the context of this thesis because the authors reduced their calculated totals to factor equipment limitations, site access and steep slopes into the recoverable total.

Perlack and others’ (2005) billion ton study used logging residue data from the USDA Forest Service (USDA FS) Forest Inventory Analysis (FIA) forest product output database to make its calculations at a national scale. It is one of many assessments to make use of FIA data (Howard 1990; Sampson and others 2001; USDA FS 2005; Lord and others 2006; PES and MB&G 2007).

The USDA Forest Service’s (2005) “Strategic Assessment” estimated potential biomass from forest health and hazardous fuel reduction thinnings that would implement National Fire Plan objectives. This assessment combined USDA FS FIA data and “coarse-scale” fire regime data for public and private land in 15 western states. Biomass was calculated separately for the merchantable volume and the “biomass volume”. The merchantable volume materials were from segments of trees that had a diameter at breast height (DBH) greater than or equal to 7 inches up to a minimum top diameter of 4 inches. Biomass volume material was that which had no commercial uses other than fuel. The fuel biomass volume included small trees, limbs, and tops. The assessment excluded from consideration lands incapable of producing at least 20 ft$^3$/ac/yr and lands not “operationally accessible” for hazardous fuel reduction.

Howard’s (1990) “Biomass Estimates for 5 Western States” for Oregon, Washington, southeast Alaska, Montana and Idaho had two primary goals, to identify major sources
of woody biomass for energy generation and provide estimates of annual logging residue biomass. Howard's estimates were developed from USDA Forest Service inventory data from 1970-1981. The data used for Oregon was from 1975-1977 and the Washington data was from 1979-1981. Because harvested tree sizes, harvesting practices and utilization rates in the Pacific Northwest have changed since the 1970's, some of the measurements of residue production may not be accurately representative of today's timberlands. Biomass calculations for merchantable, small, cull and dead trees and merchantable tree logging residue were presented separately. For merchantable trees and culls, merchantable biomass weight was calculated by converting volume from FIA inventories to weight based on the density for each species. Top biomass was taken from tariff tables from the FIA for the Pacific Northwest based on a 4 inch minimum top diameter. Published branch factors from multiple sources were used to estimate the branch biomass. These compartments were added together to get the Total Tree Biomass (TTB), which excluded bole bark, foliage and the material in a 1 foot stump. Small tree biomass was calculated by multiplying the average weight for small trees by the number of trees between 1 and 5 inches DBH. Because the author had no way of telling from the inventory data how much of the branches, bark and foliage were missing, dead tree biomass only includes bole biomass, which was calculated the same way as for merchantable and cull trees. Logging residue was estimated using factors developed in Howard's earlier work for residue weight per thousand board feet (MBF) of merchantable timber harvested. When determining the quantities of logging residue, only pieces larger than 3 inches diameter and 1 foot long were counted. Howard notes that additional material not meeting those specifications could exceed 20 bone-dry tons (BDT) per acre (Maxwell and Ward 1976, cited in Howard 1990). Small, cull and dead
trees combined made up 5-15% of the biomass in the areas studied. They also determined that the percentage of biomass in crowns varied little between areas or hardwoods and conifers, ranging from 12.7-21.8% and averaging 16.3%. In western Oregon forests, they found that average chippable harvest residues on private, public and National Forest ranged from 0.53-0.69 BDT/MBF for clearcut harvesting and 1.23-3.91 BDT/MBF for partial cut. In western Washington they ranged from 0.47-0.65 BDT/MBF for clearcut and 1.3-1.78 BDT/MBF for partial cut. The study didn't account for the recoverability of biomass, and the results were representative of the forest as it was at the time the source data was collected, as opposed to being a forecast of predicted future conditions. Culls and dead trees were concentrated in the older forests. Howard noted younger stands were more likely to have better recovery of biomass from the crowns because mechanized harvesting techniques are more common there and result in less breakage. He found that reliability and error were “difficult to assess” and included no error estimates. Howard concluded that biomass data need more “depth and precision” before the regional biomass resource can be effectively managed and that that is a “major issue faced by all woody biomass users and managers in the West”.

The “Western Forest Health and Biomass Energy Potential” report (Sampson and others 2001) combined a regional biomass assessment of 11 western states and a sub-state level assessment of Wallowa and Grant counties in Oregon, both of which were based on a hypothetical ten year region-wide expedited forest health treatment plan. The report also focused on describing the need to implement hazardous fuel reduction projects, the effects of fire exclusion, and the challenges and hurdles to implementing hazardous fuel reduction (HFR) projects. One of the environmental benefits cited in this study is the
reduction in air pollution that results from primary combustion energy conversion of
forest residues as an alternative to disposal by open burning. Their estimate of biomass
was based on the assumption that most of the overstocked forests in the assessment
area would undergo HFR treatments over the course of a decade in order to bring them
into acceptable condition. Because of this critical assumption, the assessment is an
estimate of potential biomass generation and not based on current conditions or
management plans. The authors made an effort to exclude lands that would be
unavailable for treatment by excluding National Park Service (NPS), and designated
Wilderness lands. Because the source data used was from the FIA, they were unable to
exclude Roadless Areas, which would also be unavailable for biomass recovery. They
attempted to address this shortcoming by including only some forest types in their
potentially treatable lands, specifically Ponderosa pine, Douglas-fir, and True Fir
dominated forest types. Douglas-fir dominated forests in Oregon and Washington were
entirely excluded however, because the data sources used didn't differentiate between
the drier Douglas-fir forests representative of those in the eastern parts of Oregon and
Washington which could benefit from fuel treatments, and the wetter Douglas-fir forests
usually found in the western parts of the states for which there is little justification for
such treatments. Their HFR scheme assumes an average of 15 BDT/Ac of fuel biomass
would be generated by these treatments, taken from the 5-11” DBH classes at varying
intensities of 60-80% removed. The need for catchment or project level biomass
assessments is supported by their observation that regional scale estimates of forest
biomass for fuel use “mean little or nothing in terms of any localized situation” but “are
useful in considering total resource supplies”. Determining if a local fuel supply is
sufficient for an energy project requires an assessment performed at the local level. The
sub-state scale section of the report estimated potential biomass that would be
generated in Wallowa and Grant counties in eastern Oregon if the proposed HFR
projects were executed. Unfortunately the authors failed to describe their methodology in
detail, limiting the ability to compare or repeat their methods. Their estimate grouped
together biomass from merchantable materials with biomass from non-merchantable
materials, only stating that “some of this material will likely go to higher uses”. The
estimate didn't include biomass that would be generated from private lands in these
counties due to the lack of sufficiently detailed forest inventory data on private
ownerships. From this two county estimate they concluded that it appeared there would
be enough total fuel in the area to fuel a power plant but they note “it is also clear that an
accurate quantification of fuel that is physically available and the amount that is feasible
to deliver to a facility is impossible to do at this time. The forest inventory data available
are simply not current or specific enough in terms of stand structure and condition to
make informed estimates”. A noted limitation of the report is that it does not address the
desire of private landowners or the capability of the federal landowners to implement the
proposed HFR treatments. On federal lands, they describe this as a “critical factor”
because of legal interference to almost any treatments. In order for the treatments to be
affordable some merchantable size trees would also have to be removed, but some
environmental groups have shown harsh resistance to this possibility claiming that
hazardous fuel reduction is just a cover story to justify old-fashioned exploitative logging.
Because of lawsuits and other resistance from environmental groups, on National
Forests, time in planning and appeals processes can run from 1.5-3 years and by the
time that is finished the prescription may not even be useful or applicable anymore.
The Western Governors’ Association Biomass Task Force report (WGA 2006) focused on 12 western states. It’s relevance to this thesis is limited due to the report’s exclusive consideration of biomass from HFR projects. It assumed 50% of residues were recoverable, compared to the 20-25% used in a number of other regional studies.

“Biomass Energy and Biofuels from Oregon’s Forests” (Lord and others 2006) was a two part publication, with part A being a collection of articles on topics relevant to forest biomass assessment and fuel recovery, and part B being an assessment of biomass fuel potential from Oregon's Forests. One of the articles in part A, “Biomass Energy and Biofuels Technology” by Dr. Mike Penner, notes the greater energy density of other solid fuel sources compared to forest residues. Forest residues have an energy density of 9.1 MJ/kg (wet,LHV) while coal has an energy density of 25.8 MJ/kg (wet,LHV) (Freeman and others 1997, cited in Lord and others 2006). Another article included in part A was “Estimates of Forest Biomass Supply at National, Regional, State, and Sub-State Scales” (Lord and others 2006), a review article by Roger Lord of Mason, Bruce and Girard, Inc. natural resource consultants. Lord did a good job of providing summary and comparison information of biomass estimates published at a variety of spatial scales in recent years, and his article was a useful resource for finding relevant publications for further review. He also includes various observations about the importance of different techniques and practices for making a useful biomass estimate. He notes that detailed supply info, transportation distance, and cost info is important for a useful and successful local assessment because of the low value of biomass. Lord pointed out that none of the state-level studies considered growth between the time the assessment was written and the first treatment was conducted. He stated that assessments that fail to take into
account this growth are effectively assessing current forest conditions, not providing a forecast of conditions at time of harvest, even if their assessments assume an accelerated fuel treatment program. This could result in underestimation of the biomass resource. Lord found McNeil Technologies’ (2003) report more detailed (“comprehensive”) and thorough than the other sub-state level reports he discussed. McNeil Technologies (2003) considered supply from non-commercial thinnings, timber stand improvement (TSI), HFR and timber harvest on federal, state, municipal, county and private lands, and wood product and agricultural residues. Many other reports Lord reviewed only considered HFR residues. Lord considers McNeil Technologies’ (2003) report conservative since it only considers fuel from current management plans, not accelerated fuel treatment scenarios. He points out that the McNeil Technologies and Sampson Group reports show a contrast of results from different assumptions. McNeil Technologies (2003) estimated 213,000 BDT for 3 counties, Sampson Group (Sampson and others 2001) estimated 950,000-1,421,000 BDT from 2 of those counties. Lord also notes that the percentage of non-merchantable biomass to total “removed” biomass (here he seems to use “removed” to mean “cut”, since it’s unlikely that much material was actually recovered) for Fried and others (2003), McNeil Technologies (2003), and USFS (2005) all fall in the 25-29% range.

Part B of “Biomass Energy and Biofuels from Oregon's Forests” (Lord and others 2006) discussed an assessment of biomass from potential HFR projects in Oregon. HFR projects were the only potential biomass source considered in their assessment. They used inventory data from 2002 for federal land and from 1992 for non-federal land and did not model growth. Because of this, the assessment was described as a “snapshot” of
conditions in the early to mid 1990’s as opposed to a prediction of future conditions. The USDA Forest Service Fuel Treatment Evaluator 3.0 (FTE 3.0), which was also used in the Western Governors’ Association taskforce report, was used to estimate biomass generated from a number of unique scenarios with different assumptions and fuel treatment options. FTE 3.0 uses FIA inventory data and user defined assumptions and constraints to model the effects of different fuel treatment scenarios on private and public lands. It excludes lands unsuitable for timber production, determines appropriate landbase based on user inputs and produces outputs which include estimates of effects on fire risk, total biomass, net biomass and merchantable timber generated, and treatment/harvesting costs. Dead and down biomass was excluded from the estimates. The forests included in the model included forest types with high-intensity, infrequent fires. HFR projects in these forest types are controversial because it is argued they have little utility in such forests and do not replicate conditions caused by natural disturbance regimes. For this reason biomass supply from these forest types was reported separately from supply from other forest types. Some of the criteria used for excluding areas from the landbase in some of the scenarios include slopes greater than 30%, designated Roadless Areas, areas with low fire hazard ratings, and plots with less than 300 ft³ of merchantable harvest (a restriction also used by the WGA task force). The estimates of biomass include potential HFR projects on private land, but only treatment options that are likely to pay for themselves with enough merchantable timber removals. This assumption may overestimate actual supply if private owners aren't willing to actually perform these thinnings. Western Oregon forests were excluded from the biomass assessment but the authors note that recovery of logging slash could contribute to the biomass supply. The average yield of biomass from merchantable and non-
merchantable material for HFR projects modeled in this assessment was 10.7 BDT/Ac. The average for the non-merchantable biomass portion was 5.3 BDT/Ac. Graf and Koehler's (2000) Oregon Cellulose-Ethanol study which similarly considered only biomass from HFR used a rate of 21 BDT/Ac, although it is unclear from either study whether or not Graf and Koehler's number included merchantable material.

“Phase II Biopower Market Assessment: Sizing and Characterizing the Markets for Oregon Biopower Projects” was a report prepared by CH2M Hill (2005) for Energy Trust of Oregon, Inc. The report considered multiple source of fuel biomass, including mill residues, forest residues, landfill gas, and sewage. Logging residues and potential biomass from thinning overstocked stands were both included. Biomass supply and minimum delivered cost were estimated for the state as a whole, with no finer detail or spatial distribution information included. They based their estimate of timber residues on 6.7 [billion] board feet of softwood lumber produced in Oregon in 2004. No details of biomass estimation methods were included, they simply state that “limbs left in the forest from these operations amount to about another 1,800,000 BDT/yr [in addition to the merchantable timber removed].” Almost no information on methods or data sources is included for the forest biomass section and it seems that the authors didn't perform an in-depth analysis of forest biomass, probably because they determined it to be uneconomical. Because the report is so vague, it provides little value or precedent for forest biomass assessment research. One of the benefits of forest biomass energy that they cite is the reduction of air pollution compared with open burning. They state that open burning produces 17 lbs/BDT of particulates while direct combustion for energy in the Biomass 1 powerplant in White City, OR produces only 0.7 lbs/BDT. One major
impediment to forest residue recovery on federal lands is that they consider the USDA Forest Service incapable of fulfilling any timber sale contract it writes because of the legal challenges to all proposed harvest plans, many of which are killed by court decision.

“Biomass Resource Assessment and Utilization Options for Three Counties in Eastern Oregon” was a report by McNeil Technologies (2003) prepared for the Oregon Department of Energy. The goal of the study was to “promote cost effective, sustainable use of biomass for power and/or ethanol manufacturing [in the area]”. The study's objectives were to estimate the amount of biomass generated, the amount available, its location, its physical and chemical properties, to determine the best facility location, to explore the economic and environmental impacts of biomass use, and to provide an overview of the relevant technologies, fuel requirements, and economic potential of development options. Forest biomass from harvesting residues, timber stand improvement (TSI), pre-commercial thinning (PCT), and hazardous fuel reduction (HFR) were included. Also considered were wood product processing residues and agricultural/orchard residues. The authors determined the fuel from potential thinning of Pinyon-Juniper cover type would have a low yield and that it “could serve as a supplemental source of biomass for a” […] “facility but they should not be considered as available for planning purposes.” The estimates provided were primarily based on current conditions and management practices, not on hypothetical accelerated treatment scenarios or potential future situations that formed the basis for a number of other biomass assessments previously mentioned. They contrast their assessment methods with those of those of the Sampson Group's “Western Forest Health and Biomass
Energy Potential” report (Sampson and others 2001) that assumed thinning would be performed on 50% of available forests land over 10 years (5% of available forest land per year) and generate between 10 and 15 BDT/Ac. McNeil Technologies (2003) estimated the timber harvest residue generation rate to be 2,099 green tons (GT) per million board feet (approximately 2.1 GT/MBF). Harvest levels were assumed to be the same as in recent history, taken from harvest records. Thinning and harvest levels from USDA FS land were taken from their planning and monitoring data. A conservative estimate was used for thinning on overstocked private lands. In an attempt to represent site-specific variability, biomass generation rates of 5, 10 and 15 GT/Ac were applied to the combined landbase for fuel reduction, TSI and non-commercial thinning, generating three estimates of total biomass yield from the combined treatment types. In order to reflect an assumption of no biomass recovery on slopes greater than 30%, for each county they divided the portion of forest land with slopes over 30% by the total forest land area and used that percentage as a reduction factor on the total biomass calculated for the county. Forest residue collection cost was estimated to range between $30-46/GT, which includes cutting, processing and yarding to roadside for transport. It's unclear if this represents the costs for timber harvesting, for fuel reduction, or an average of the two, or if different yarding systems were considered in this estimate. They state that a 25 MW stoker-fired biomass energy plant has a $56,200,000 capital cost, operates 7,884 hrs/yr, and requires 54.5 GT/hr. Before biomass energy development, they recommend a more detailed investigation for the specific project, including closer communication and work with fuel and energy buyers and suppliers, reporting and tracking of fuel recovery and effects, community education and outreach efforts and programs to acquire and maintain public support, and communication with potential
suppliers to encourage practices that improve recovery, reduce costs and assure them it will be worth the effort.

Pacific Energy Systems and Mason, Bruce and Girard's (2007) Hood River County biomass report estimated biomass available for energy generation in the area of and surrounding Hood River County, Oregon. The study estimated forest biomass from thinnings and harvest residues. Forest biomass was divided into three compartments: aboveground biomass (AGB), merchantable tree biomass, and non-merchantable tree biomass. Foliage was excluded from all biomass calculations. AGB was defined as all non-foliage biomass in live trees greater than or equal to 1” DBH. Merchantable biomass included non-foliage biomass in live trees greater than or equal to 5” DBH from a 1 ft stump up to a 4” diameter top. It is unclear if merchantable biomass includes bark. Non-merchantable biomass was calculated as AGB minus merchantable biomass for merchantable trees and all AGB in trees with DBH greater than or equal to 1” and less than 5”. Federal, state and private lands were included in the estimate. Only biomass from “timberlands” was counted. Timberlands were defined as forest lands capable of producing greater than or equal to 20 ft³/ac/yr of “industrial wood” and not off-limits to harvesting by statute or administrative regulation. Estimates of BDT/Ac and percentage of yielding acres acquired from interviews with land managers, the most applicable BDT/MBF ratios from publications and interviews, local BDT/MBF ratios calculated from the proportion of non-merchantable biomass to AGB from FIA statistics, the proportion of harvests using whole-tree yarding, and the residue recovery percentages quoted by local land managers were all used to determine recoverable residues from harvest for the different ownership types in the assessment area. The authors note that while Howard
1990 published forest residue production ratios for various ownerships, forest types and harvest types, they believe that average tree sizes, harvesting systems and utilization rates have changed significantly enough since the data for Howard's study were collected that his numbers are likely no longer accurate. They used a residue recovery rate of 1.2 BDT/MBF, based on FIA data for the area showing 30% of AGB was non-merchantable biomass. They do no specify whether they measured MBF in long log or short log scale. Timberlands in the study area averaged 77 BDT/Ac of live woody biomass. For Washington Department of Natural Resources (WADNR) and westside USDA FS lands in the study area they assumed 10% of logging residues were recoverable. Eastside USDA FS residues were included in the estimate of biomass from HFR. A 50% recovery rate for logging residues from harvests on county and municipal timberlands was used as estimated by the county forester. Local forest managers said that approximately 70-90% of harvest operations in the area are whole-tree yarded, where residues are piled at the landing and easier to recover, and in these operations about 70% of total residues make it to the landing. For their assessment, MB&G assumed 60% residue recovery on private industrial logging units. WADNR lands in the study area are mostly partial cut. They note that partial cut harvesting usually includes in-woods processing where slash is scattered in small piles in the woods because whole-tree yarding would do too much damage to the residual stand. WADNR estimated that 2 Tons/Ac were available from roadside piles on 50% of their harvested lands. The authors distributed the annual residue yields among owners and area proportionally to the FIA inventory for each ownership and area based on the assumption that over time, harvest volumes are proportional to the inventory levels in a given area. The study mentions the Coordinated Resource Offering Protocol, a system to help coordinate the
sale offerings of biomass from public land restoration projects as a potential aid to making the biomass markets and biomass energy feasible. Also, the Oregon Biofuel Act of 2007 (HB2210) provides a $10/GT incentive for “collectors” of biomass fuel that could help make biomass energy economical. The authors state that their report is only a preliminary assessment in analyzing the potential for biomass energy in the area and that further in-depth analysis would be required before deciding to develop a bioenergy facility.

Oneil and Lippke’s (2009) “Eastern Washington Biomass Accessibility” study developed new estimates for post-harvest residues across a range of ownerships and forest types in eastern Washington. This included analyses and comparisons for different owner groups, forest types, harvest methods, silvicultural regimes and management objectives. Some of the sites they sampled were cut primarily for HFR and some primarily for timber production. They also looked at the “available” portions of total harvest residues and the proportion that was actually “recoverable” under current technical and economic constraints. Their resulting biomass rates were very close to the results of a 2009 central Washington study that interviewed landowners and equipment operators to estimate biomass residue rates. The authors separately measured biomass in slash piles and dispersed slash in treatment/harvest units. Dispersed slash was grouped into pieces less than 1” diameter were the pieces crossed line transects, pieces between 1” and 7” diameter grouped into 2” size classes (ie. 1-3” class, 3-5” class, 5-7” class), and pieces greater than 7” diameter tallied into groups to the nearest inch. For a subsample of slash piles, individual pile biomass was estimated using common equations used by WADNR procedures and then compared to direct measurements of biomass when those piles
where chipped, weighed and sampled for percent moisture content. The difference between estimated and actual pile volumes from these sample piles was used to calibrate the estimates of biomass in the other slash piles in the study to eliminate the bias from the pile biomass estimation equations. Dispersed slash was divided into two groups, one of pieces less than 5” diameter and the other group of pieces greater than 5” diameter. This diameter division between groups was chosen because it corresponds with common cruise and sale volume minimum top diameters which range from 4-5.5”, and is thought to represent the pieces that can be recovered with conventional machinery versus material that would require specialized equipment to recover. Sample residue quantities were compared with inventory/sale volumes to estimate residue per merchantable volume harvested. Because some inventory data was lower quality (had lower sampling intensities), the outputs were discussed but not included in the study’s results section. The terminology in the report can be slightly misleading as the authors use the term “harvested” when they seem to refer to material that was cut but not necessarily recovered, use the term “removals” to refer to harvested material that was recovered, and use “residuals” to refer to material left on site. This ambiguous, possibly confusing terminology reflects a larger tendency in biomass assessment literature of a lack of precise, standardized terminology necessary to reflect nuance and communicate findings and results clearly.

The results of Oneill and Lippke’s (2009) comparison between slash pile biomass estimation equations and actual slash pile biomass measurements led the authors to conclude that the current estimation procedures for pile biomass from field measurements regularly underestimate actual pile biomass substantially. They note that
this could partially be because of different utilization standards (such as stronger pulp markets) which result in different proportions of cut material left in slash piles. The breakdown of total cut biomass among different biomass classes for all ownership and harvest types combined is detailed in Tables 2.1 and 2.2, taken from Oneil and Lippke’s report. The proportion of residues to total biomass cut ranged from 33-62% for the three forest types across all ownerships, management intentions, site groups and harvest methods. Approximately 2/3 of residual biomass across all samples was piled slash or dispersed slash with diameters greater than 5”. With appropriate economic incentives, the authors estimated that 50% of dispersed slash greater than 5” diameter and all piled material could be recovered. This equates to 54-64% of all slash in piles and dispersed greater than 5” diameter being recoverable given appropriate economic conditions.

<table>
<thead>
<tr>
<th>Forest Type</th>
<th>Douglas Fir</th>
<th>Mixed Conifer</th>
<th>Grand Fir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removals</td>
<td>62</td>
<td>44</td>
<td>51</td>
</tr>
<tr>
<td>Piles</td>
<td>4</td>
<td>12</td>
<td>5</td>
</tr>
<tr>
<td>Dispersed &gt; 5”</td>
<td>12</td>
<td>30</td>
<td>56</td>
</tr>
<tr>
<td>Dispersed &lt; 5”</td>
<td>16</td>
<td>18</td>
<td>20</td>
</tr>
<tr>
<td>Total cut</td>
<td>94</td>
<td>104</td>
<td>132</td>
</tr>
</tbody>
</table>

Table 2.1. Biomass quantities (BDT/Ac) by class and forest type for all ownerships

<table>
<thead>
<tr>
<th>Forest Type</th>
<th>Douglas Fir</th>
<th>Mixed Conifer</th>
<th>Grand Fir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Removals</td>
<td>66%</td>
<td>42%</td>
<td>38%</td>
</tr>
<tr>
<td>Piles</td>
<td>4%</td>
<td>12%</td>
<td>4%</td>
</tr>
<tr>
<td>Dispersed &gt; 5”</td>
<td>14%</td>
<td>29%</td>
<td>44%</td>
</tr>
<tr>
<td>Dispersed &lt; 5”</td>
<td>16%</td>
<td>17%</td>
<td>14%</td>
</tr>
</tbody>
</table>

Table 2.2. Percentage of biomass by class and forest type for all ownerships
Using a General Linearized Model in R, Oneill and Lippke (2009) attempted to determine the most significant predicting factors of residual biomass across the different ownership, treatment, forest, and site types and harvest/yarding methods. They found harvested material quantity was the only significant predictor of residual biomass (95% confidence level). Owner group and forest type were not predictors. Site group was weakly predictive (90% confidence level). The resulting model still only resulted in 14% Deviance Explained (DE). The authors concluded that “These results highlight how difficult it is to arrive at reliable estimates of available biomass across a broad region without many hundreds of units to sample and many dozens of samples within each unit”. They go on to further analyze availability, recovery and retention rates, but these are of limited applicability to this thesis since it deals with forests that will primarily undergo whole-tree yarding, which has a significantly higher recovery percentage than the yarding methods used in Oneil and Lippke’s sites. An additional finding of the study was that the levels of material left on the sample sites indicate more residues are usually left behind after biomass recovery than are needed for ecological purposes. Small diameter residuals and foliage from the forest treatments have higher nutrient content (Hagen-Thorn and others 2004), are less desirable for biomass energy conversion because of their chemical makeup (Mohan and others 2006), and are more difficult to collect. Oneill and Lippke (2009) suggest this makes them an ideal choice for the material to leave on site for ecological purposes, especially needles, leaves and small twigs.

Fried and others (2003) modeled fuel treatments in northern California and western Oregon and combined these with plot data from six inventories and harvest and haul
cost estimates in a GIS to produce a spatially-explicit biomass map of supply and identify biomass concentration “hot-spots”. Like a number of previous studies they excluded from consideration areas were harvest or biomass recovery was prohibited by statute or administrative policy. Also excluded were steep areas more than 2000 ft from roads. HFR biomass yield was estimated by running a sample of inventory plots from the area through the Forest Vegetation Simulator – Fire and Fuels Extension (FVS-FFE). The biomass estimate was based on material from trees on gentle slopes with DBH between 3.5” and 7”, the limbs and tops of merchantable trees, and all cut hardwoods. They found that the average haul cost was nearly ½ the delivered market value and the rest of the market value was met or exceeded by harvesting costs. They concluded that “biomass rarely pays its way out of the woods”. One factor affecting availability of biomass that was overlooked in the study was riparian area restrictions on harvesting.

Parikka (1996) presented a computer program, Biosims, for estimation of woody forest biomass in “Methodology and Techniques for the Appraisal of Wood Fuel Balances in Sweden”. Biosims can calculate available biomass in either of two ways, the regression method, in which woody biomass inventory is calculated using regression equations for the four dominant local tree species, and the ratio method, in which biomass inventory is based on forest inventories and the ratios between merchantable volume and residue biomass. Woody biomass from both timber harvest residues and direct fuel wood harvesting are considered by the program and it can be used at a forest stand level or at a regional level. The program incorporates a model to represent the effects of the National Board of Forestry restrictions for soil productivity protection and it includes functions to facilitate mapping of the results in a GIS. Modular program design, flexible
parameters, and standardized ASCII output files allow the program to be tweaked for use in other countries and on various computing platforms or to be expanded with more code. Parrika’s (2000) paper described a number of tests performed and scenarios modeled using Biosims. Dalarna County, Sweden was the study region used for the modeling and calculations. The objectives were to test the program’s ability to calculate the quantity of woody biomass while incorporating the National Board of Forestry ecological restrictions on harvesting, to calculate the effects of stricter ecological restrictions on harvesting on the quantity of wood fuel in the study region, to test a method of analyzing the consequences of ecological restrictions, and to describe the wood fuel balance in the region.

One of the key sources of data we used in this thesis was the LEMMA program. Ohmann and Gregory’s (2002) paper “Predictive Mapping of Forest Composition and Structure with Direct Gradient Analysis and Nearest Neighbor Imputation in Coastal Oregon, USA” describes the methods and concepts behind the data produced by the LEMMA program. Their research and the development of the predictive mapping method they refer to as Gradient Nearest Neighbor (GNN) was motivated by the need for spatially-explicit information on forest composition and structure at broad spatial scales. GNN is a predictive vegetation mapping method that combines direct gradient analysis and nearest neighbor imputation and produces spatially-explicit, regional maps with a high level of forest structure and composition detail. They are careful to emphasize throughout their paper that vegetation maps produced with GNN are appropriate for use in “regional level planning, policy analysis, and research”, but not for “local management decisions”. Their goal was to “characterize, both quantitatively and spatially, the current
patterns of forest vegetation in the OR Coastal province” Specific objectives included quantifying the relationship between multiple mapped factors/inputs (environmental, spectral and disturbance, etc.) and “regional gradients of tree species composition and structure”, to develop a GIS-based model to predictively map vegetation by integrating field inventory plot data, remote-sensing, and mapped environmental data, and to produce predicted vegetation maps using the model they built. Their method mapped multiple continuous vegetation attributes simultaneously in order to maintain realistic forest structure and composition results. Inventory plot sources included USDA FS FIA, Bureau of Land Management Natural Resource Inventory, Siskiyou and Siuslaw National Forest Current Vegetation Surveys, and USDA FS Old Growth Study data. Some of the inventory plots consisted of nested subplots. Plots with clear mismatches between ground and remotely-sensed data and those “that straddled distinct boundaries in forest condition” were excluded from the collection of sample plots. Input variables used were: Landsat 5 TM data for both 1988 and 1996 (Specifically bands 1, 2, 3, 4, 5, and 7; ratios of bands 4/3, 5/4 and 5/7; tassel cap brightness, greenness, and wetness axes; and number of years since clearcut harvest), ownership class, topographic variables (elevation, aspect, slope, relative position on the slope, and solar radiation), soil type and composition variables, climate variables (mean annual ppt, May-September ppt, variation between mean ppt in December and July, moisture stress during growing season, mean annual temp, August mean maximum temp, difference between mean August maximum and December minimum temps, and proportion of total hours in July with stratus clouds), and latitude and longitude. Because data from two Landsat TM years were used, for the gradient analysis they used the TM data from the year that most closely matched the date the data for each inventory plot was collected. The model was
only applied to forested areas. The GNN process followed a series of steps. First, for each inventory plot they recorded the explanatory/input variables for that location. Second, they developed a stepwise Canonical Correspondence Analysis that mathematically related the inventory plot conditions (response variables) as a function of the explanatory/input variables or transformations thereof. Third, for each pixel on the map they used the explanatory variables for that location as inputs to the model and got an output value in eight-dimensional gradient space. Fourth, for each pixel they identified the sample plot whose model output value in eight-dimensional gradient space was the nearest neighbor to the model output for that pixel. Fifth, they imputed the ground attribute values for the nearest neighbor sample plot to that pixel on the map. The authors performed accuracy assessments of their method at the aggregate level and site level. For the aggregate level accuracy assessment they compared the relative proportions of mapped (predicted) vegetation classes with the estimated proportions from the inventory data. They also compared overall means and ranges of variability of the mapped predictions to those of the plot data for a number of vegetation attributes to test GNN’s ability to preserve the variability present in the inventory (observed) data. For the site level accuracy assessment the authors compared the 823 plot locations with the second nearest neighbor plot predictions (because the nearest neighbor of a sample plot would be the plot itself). By constructing nine additional models were they left out different groups of 10% of the sample plots they found that “the CCA model is robust to changes in plot input data”. The procedure was repeated leaving out different groups of 25% of the sample plots. In all cases the results were “nearly identical” to the full second-nearest neighbor analysis. Dividing the sample plots into ten different classes (open; broadleaf; small, medium, large and very large mixed conifer/broadleaf; and
small, medium, large and very large conifer) the second-nearest neighbor predictions for the individual sample sites had an overall accuracy of 45%, with accuracy ranging from 0-54% better than chance for the individual classes. They found that “most misclassification errors were minor: Overall classification was 87% correct within one class”, with accuracy within one class deviation ranging from 70-98% better than chance. While these accuracy numbers may seem low taken out of context, it is necessary to recognize that the GNN method’s intended function is to accurately reflect the forest structure and composition at the watershed level or greater when multiple pixel predictions for the area are taken in aggregate as opposed to determining the structure and composition of an individual site on the map, which the site level accuracy tests measured. Correlations between observed and predicted values at the site level were 0.53 for species richness, 0.80 for quadratic mean diameter, and 0.71 for stand age. The GNN method tended to overpredict continuous vegetation attributes at low values and underpredict at high values. The authors note that “the subset of plots used in GNN was not selected randomly or systematically and, thus, had potential to yield biased results”. They note that it may be possible to optimize the model for prediction of specific attributes, but “improving model accuracy for some attributes may come at the cost of reduced accuracy for others”. There is a risk that the high resolution and small pixel size will lead some people to assume a greater degree of precision (particularly at the stand or pixel level) than actually exists and the authors emphasize that the results are for “strategic-level planning and policy analysis”, not local management decisions. This raises the question of where the line between “local” and “strategic-level” drawn, however that subject is not addressed in detail. Ohmann and Gregory suggest that the GNN method could probably be applied to other regions with representative samples of
inventory plots with accurate location data, GIS maps of input variables and remotely-sensed data.

Wimberly and others’ (2003) paper, “A Multivariate Approach to Mapping Forest Vegetation and Fuels Using GIS Databases, Satellite Imagery, and Forest Inventory Plots”, demonstrated the feasibility of using the GNN method to map the forest fuels of the Coast Range in Oregon. Their work provides an example of one of the potential specialized applications of the GNN method. The GNN method was used to develop a GIS raster map of fuel characteristics in the area. They observed coarse-scale (large area) patterns in their output that were consistent with the boundaries between different ownership classes and with past forest management actions in those ownerships. Making independent predictions of fuel variables showed advantages over tying all indicator variables to a single classification scheme. The GNN method will always result in some uncertainty and, as with Ohmann and Gregory (2002), uncertainty was considerable at the individual pixel level but the authors concluded that potential exists for reliable modeling when viewing and using the resulting maps at the wider project level and considering the pixels of an area in aggregate. At time of publication, the authors were continuing their efforts to better tailor their multivariate statistical model for use with the GNN method to improve precision and better quantify uncertainty and error propagation.
3 Materials and Methods

3.1 Overview

In order to create a spatially-explicit prediction of recoverable harvest residues for the project area, we chose to apply allometric equations to inventory tree lists for a predicted vegetation map. The LEMMA predicted vegetation maps were the only spatial vegetation dataset with individual tree measurements, consistent records and sampling standards, and high resolution we could find that covered our entire project area. Predicted residue biomass maps can also be created by applying residue BDT/Ac values to the different forest types of a map of specific forest types for the area, or by applying an average residue biomass to aboveground biomass (AGB) ratio to a vegetation map with spatially-explicit AGB estimates like the LANDFIRE dataset. A disadvantage of the BDT/Ac method is that it fails to account for local factors such as site index and precipitation that can change the average residue biomass densities for an area. BDT/Ac values can vary significantly between stands. The second method doesn’t consider how the residue/AGB ratio may vary between forest types. Both of these alternative methods have weaknesses which can bias estimates of residue biomass levels over a contiguous area which can significantly change transportation and supply analysis outputs even if it doesn’t substantially change the recoverable residue total for the project area.

Using LEMMA inventory data for each sampling plot or subplot with a unique Forest Class ID (FCID) and a collection of allometric biomass equations for all of the prominent tree species in the study area, we calculated the biomass densities (BDT/Ac) for each FCID. These calculated biomass densities for each FCID were then joined to the LEMMA predicted vegetation raster map by the imputed FCID for each cell to create a
map of predicted biomass densities over the project area representative of the conditions from 2000 to 2006 (the years the inventory data used by the LEMMA raster was collected).

The biomass yielding landbase for the 10 years centered around the inventory period was determined by combining information on land ownership, behavior and probable future management actions of forest landowners, specifications of Oregon Forest Practice Rules, estimates of the effects of riparian and wetland management zones on availability of timber, and predicted stand dominant age. We then determined the biomass yielding landbase for the 10 year forecast period in the same way.

The biomass densities initially calculated for the forecast period landbase with inventory data are not representative of the densities on those areas in the forecast period because they are based on inventories from the sample collection period. In order to estimate the forest residues that would be present during the forecast period on forest lands that would be harvested during the forecast period, the biomass rates from the inventory data needed to be adjusted for the effect of growth. Instead of running all of the inventory data through a growth simulator and recalculating biomass densities based on growth simulations for private industrial forest lands we represented growth of the biomass densities between the sample collection period and the forecast time period by projecting the biomass densities of available, harvestable age stands on private industrial (PI) forests (the PI landbase) for the inventory period onto the stands of similar forest types in the forecast period PI landbase. Specifically, we did this by grouping forests in the inventory period and forecast period PI landbases into 6 forest type groups,
calculating the average biomass densities for each forest type in Oregon and Washington of all harvestable age PI forest land and projecting these biomass densities onto the matching forest type groups and states in the forecast period PI landbase. For ODF lands, we calculated the cumulative removal intensities for each harvest unit from all harvests that are scheduled during the forecast period and multiplied these cumulative removal intensities by the biomass densities calculated for the inventory period. Because the proportion of residue generation to proportion of volume removed can vary greatly based on the selection procedure for partial-cut harvests, our estimates of recoverable biomass from the ODF harvests are likely less accurate than those from PI forests.

The generated biomass raster maps for the forecast period for PI and ODF land were merged and forecast harvest residue densities were adjusted by a fixed recovery factor across the entire project area. The result was a spatially-explicit map of predicted recoverable harvest residue densities for the entire harvestable ODF and PI landbase for the forecast period. Table 3.1 outlines the main steps in the biomass prediction process. We then calculated summary statistics for the recoverable biomass forecast and performed analyses of different methods of modeling the effect of riparian and wetland areas on total predicted recoverable residue biomass. Lastly, a simulation was designed in an attempt to quantify uncertainty in the recoverable biomass estimate for the 10 years centered on the inventory period resulting from the use of allometric equations and imputed vegetation data.
Table 3.1. Sequence of steps in creating the recoverable harvest residue forecast map

- Collect allometric equations for species in project area tree
- Calculate biomass for every FCID and merge with raster of FCID's
- Determine land ownership and major landowners in the project area
- Predict management intentions of landowner groups
- Consult with major landowners to check accuracy of age data and estimate model parameters (breakage/defect rates, utilization rates, etc)
- Determine biomass yielding landbase for the inventory and forecast period
- Adjust the landbase for riparian and wetland management zones
- Divide the PI landbase into six forest groups by species composition and basal area
- Calculate average residue rates for the forest groups in the inventory period
- Project these rates onto the PI forest groups for the forecast period
- Use ODF harvest plans to make a map of forecast period removal intensities
- Combine ODF harvest intensity map with residue biomass raster
- Merge ODF and private industrial biomass forecast maps and adjust by a biomass recovery rate

3.2 Materials / Data Sources and Assumptions

3.2.1 LEMMA Predicted Vegetation Map

The Landscape Ecology, Modeling, Mapping and Analysis (LEMMA) program applies a supervised classification process called the Gradient Nearest Neighbor method (GNN) to remote sensing, environmental and vegetation inventory plot data to generate a GIS raster map of predicted vegetative cover for all individual raster cells on the map. The
GNN method uses a number of location-specific landscape, ecological, vegetative, and other characteristics available for specific points on the map as input variables to predict the characteristics of the areas which lack collected data, based on their similarity according to multivariate functions (Ohmann and Gregory 2002). The GNN method takes inventory data for a set of sample points, and using multiple predictive variables for the know sample plots and the unknown areas on the map it assigns each unknown pixel on the map the inventory data of the sample plot determined by the multivariate equations to most closely resemble it, or in other words, its nearest neighbor in the equation's multidimensional solution space. By assigning unknown pixels the inventory data of known sample plots, the GNN method maintains realistic combinations of vegetative characteristics (covariances). While the uncertainty of predictions for individual pixels is relatively high, the aggregate accuracy of the groups of pixels that make up larger areas on the landscape are more certain. As the creators have repeatedly emphasized, the resulting predicted vegetation maps are appropriate for use in strategic-level planning and research uses, not for smaller area site-specific predictions.

The researchers with the LEMMA program have undertaken a number of specific analysis projects using the GNN method. The LEMMA database of vegetation data for inventory plots in the area and the predicted vegetative cover rasters the LEMMA program generated to assist in evaluating the effectiveness of the Northwest Forest Plan (NWFP) were used in the analysis described in this thesis (LEMMA [no date]). The LEMMA program aggregates data from multiple inventories performed by a number of different organizations in various locations across the modeling areas into a single database. Ohmann and Gregory (2002) note that “the subset of plots used in GNN was
not selected randomly or systematically and, thus, had potential to yield biased results”. This fact limits the ability to use this collection of sample plots itself as a representation of the frequency of occurrence of forest cover types in coastal Oregon and Washington although the study implicitly assumes that the collection of plots does represent the diversity of forest types. Inventory plots or subplots in the LEMMA database are assigned a unique Forest Class Identification number (FCID). Each FCID in the database lists the trees contained in the corresponding inventory plot and their measurements. The GNN method assigns each raster cell an FCID which most closely represents the expected land cover at that location. In addition to FCID’s, the attribute table of the LEMMA rasters includes dominant forest age and basal area for each tree species. A few of the FCID’s represent non-forest cover types (eg. Open water, developed land, urban areas, shrubland, grassland, etc.) although the GNN method was not designed to accurately identify between non-forest cover types (Ohmann and Gregory 2002). The majority of the FCID’s represent forested land.

The inventory and remote sensing data used for LEMMA’s NWFP project were collected between 2000 and 2006. From the data available we were unable to determine the applicable data age for individual raster cells. For our purposes, when performing calculations related to forest age with this data, we assumed the data in all raster cells was collected in 2003.
3.2.2 Harvest Residue Criteria

Calculations of quantity of forest harvesting residues available in an area are dependent on the specifications for what materials and components are included in the calculations. Our biomass calculations considered only live trees because the biomass in dead and down trees is hard to predict with allometric equations since many have broken off limbs or tops (Howard 1990). Because dead and down trees tend to be concentrated in older forests (Howard 1990), it is likely that they are a less significant factor in the relatively short-rotation private industrial forests than in longer-rotation “natural” forests or those found on federal land. Additionally, partially decomposed dead and down woody material can be difficult to recover because it may break apart during yarding and sound dead and down trees that aren’t being retained in the stand are more likely to go to higher value uses than biomass fuel (Howard 1990). The specifications of what residues are recoverable depend on the harvesting system used, field conditions during harvest and recovery, and the economic incentives for recovery of forest residues. The most easily recovered forest residues are the branches, tops, and broken or defective stem sections, excluding any foliage, from harvested live merchantable trees. For our calculations, trees are considered merchantable if they are a commercial species and meet or exceed a specified minimum DBH. These residues collect and are piled at the landing in harvesting systems such as whole-tree yarding where harvested trees are processed at the landing and merchantable log lengths produced. These forest harvesting residues were our primary focus because they are currently being produced by common harvesting practices. We referred to this specification as “merchantable slash, no foliage”, abbreviated “MS-NF”. We also calculated recoverable biomass for five other biomass criteria (Table 3.2). Although small-diameter trees can be difficult to yard,
biomass from some non-merchantable trees can be recovered if larger diameter non-
merchantable stems are yarded to the landing along with merchantable stems. Biomass
from all cut trees can also be recovered if the slash on the harvest area is gathered into
piles and equipment is sent into the harvest unit to recover the biomass in these piles.
Both of these alternatives require significant additional time and cost and the low value
of forest residues often does not justify such additional expense. Allowing forest residues
to field dry before collection can improve value by reducing residue weight for
transportation and improving combustion and energy yield when burned for energy
generation (Oneil and Lippke 2009). Field drying fuel also results in the loss of some or
all of the foliage. This can be beneficial in multiple ways. Foliage has less desirable fuel
characteristics than the woody portion of forest residues (Mohan and others 2006) and
higher nutrient content (Hagen-Thorn and others 2004). Leaving foliage on site by field
drying allows more nutrients to be returned to the forest soil, a consideration for long
term site productivity.

Table 3.2. Forest residue specification groups

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merchantable tree slash</td>
<td>No Foliage</td>
</tr>
<tr>
<td>Merchantable tree and Large Non-merchantable tree slash</td>
<td>No Foliage</td>
</tr>
<tr>
<td>Merchantable tree and all Non-merchantable tree slash</td>
<td>No Foliage</td>
</tr>
<tr>
<td>Merchantable tree slash</td>
<td>With Foliage</td>
</tr>
<tr>
<td>Merchantable tree and Large Non-merchantable tree slash</td>
<td>With Foliage</td>
</tr>
<tr>
<td>Merchantable tree and all Non-merchantable tree slash</td>
<td>With Foliage</td>
</tr>
</tbody>
</table>
3.2.3 Allometric Biomass Equations

A number of studies have been conducted to generate allometric biomass equations for specific tree species or species groups. These allometric equations predict individual tree biomass using measurements and characteristics such as species, species group or genus, diameter at breast height (DBH), and tree height. We reviewed publications on allometric tree biomass equations in order to find allometric equations for all of the species on this list. A number of tree species had multiple published equations from separate studies and for a few of the less common species no allometric biomass equations could be found. Priority was given to finding the best equations for merchantable tree species and species that were known to be very abundant in the timber lands of northwestern Oregon and southwestern Washington. Even though the frequency with which a species occurred in the database was not necessarily proportional to its abundance in the project area since some FCID’s were much more common in the LEMMA predicted vegetation raster than others, species which occurred very frequently in the database were generally given higher priority. For the merchantable species, it was necessary to gather allometric equations which calculated component biomass (such as foliage, branches and bole) as opposed to equations that only calculated above-ground or above-the-stump biomass. For non-merchantable species, above-the-stump or above-ground biomass equations were useful, because they required less calculation over the dataset and avoided the risk that has been observed by Parrasol (2001) of magnifying the errors from the equations when adding the products of multiple component equations together. Foliage component equations for non-commercial species were also desired so that the woody biomass could be calculated without foliage. Where foliage equations were unavailable, it was assumed
that foliage comprised 4% of above-ground biomass by dry weights. This number was chosen based on observations of the foliage to above-ground biomass ratios for other trees in the database. When multiple equations were available for a species, a single equation was selected and preference was given to equations that were developed from larger sample populations, had wider diameter ranges for the sample population, used fewer predicting variables, had a larger coefficient of determination ($R^2$), and were developed from studies done in the coastal Pacific Northwest or places with similar climate, soils and growing environment. Occasionally a species specific equation wasn't available. In such cases, we tried to select allometric equations for related species, species with similar growth forms, average mature height, diameter and density, or an equation for a genus or species group that best matched the species of interest. Because the final units of the recoverable biomass map were to be in dry weight per unit area, when multiple equations of similar quality were available an effort was made to select functions that yielded an output of biomass in dry weight to avoid converting from volume of wood to weight, since this density can vary substantially throughout an individual tree, and between different regions. Out of the 54 different species found in the inventory tree lists for the unique FCID's of the project area, 5 species occurred very infrequently in the FCID tree lists and lacked a satisfactory equation. 4 of the 5 were non-commercial species. They were left without equations. We believe that their effect on the biomass estimates over the project area is minimal because of their likely scarcity and because the residue criteria we were most interested in counts only merchantable tree slash.
3.3 Biomass Calculations for LEMMA FCID's

Individual LEMMA predicted vegetation raster maps of different modeling regions were merged to create a larger raster map covering the entire extent of the project area. Querying the merged raster that covered the extent of the project area, we extracted a list of each unique FCID that was represented in at least one cell of this combined raster. We used this list of FCID's to reduce the size of the inventory database by excluding records with FCID's that were not predicted to be found in the project area in order to decrease the computation time necessary to perform calculations on all records. We extracted a list of all the species present in the predicted vegetation map of the project area.

The database of sample trees for all FCID's in the project area was copied so that two sets of calculations could be performed; one for biomass quantities including foliage, and another for biomass quantities excluding foliage. The allometric equations were applied to the two databases to determine the component and total biomass of the individual sample trees. We were ultimately interested in calculating biomass densities (in bone-dry tons per acre, BDT/Ac) for the six forest residue criteria, gross merchantable wood, net merchantable wood, and above-ground biomass. Intermediate calculations were performed on all the trees until the final fields of interest were calculated. The series of calculations performed to get the final biomass numbers for each FCID is listed in Appendix A. The final quantities of interest for every sample tree in each FCID were summed to get the totals for each FCID. All conifer species except for Pacific Yew (Taxus brevifolia) and Western Juniper (Juniperus occidentalis) were considered commercial species. Red Alder (Alnus rubra) was the only hardwood species considered
commercial. Commercial conifer species over 5" DBH and Red Alder over 6" DBH were considered merchantable. It was assumed that merchantable stems were cut-off at a 4” top diameter, since this was commonly used in other assessments (PES and MB&G 2007) (USDA 2005). If a tree of non-commercial species had a DBH greater than or equal to 6” it was considered “Large Non-Merchantable” biomass, otherwise it was considered “Small Non-Merchantable” biomass. This “Large Non-Merchantable” criteria was used to reflect additional biomass that could be potentially recovered if sufficient economic incentives were added as discussed in Oneil and Lippke (2009) and would roughly fit the description of “chunkwood” from PES and MB&G (2007). Stem portions of non-merchantable tops were calculated using the stem wood and stem bark equations for the trees. Because diameter at breast height (4.5 ft) is the expected input for these equations, using the diameter at the base of the non-merchantable top could bias the calculation of biomass in the stem portion of non-merchantable tops by effectively calculating an extra 4.5 ft of length below the base. To address this concern, an estimate of diameter 4.5 ft up from the bottom of the non-merchantable tops was used as the input (Briggs 2009). These diameters were calculated using some rough estimates of top taper based on 10-20 sample trees for both conifers and hardwoods (Hailemariam 2010). For conifers tops, diameter at the top of a 4.5 foot section was 86.5% of the diameter of the bottom of the section. For hardwood tops it was 88.75%. A stump height of 6” was assumed, and the biomass in the stump left behind was estimated to be 2.5% of above-ground biomass based on similar assumptions made in Jenkins 2003. It was assumed that 3% of gross merchantable stem biomass would be lost to breakage and defect. This proportion was chosen based on rough estimates of breakage and defect rates from three large timber companies in the area. The final
calculations for these fields were indexed by FCID and exported to a spreadsheet. This spreadsheet was joined by FCID value to the LEMMA raster, yielding a raster map with an attribute table containing calculated biomass densities from the years the LEMMA inventory and remote sensing data was collected (2000 - 2006) for every forested cell in the project area.

### 3.4 Determining Biomass Producing Lands

#### 3.4.1 Land Ownership

Determining what lands would yield forest harvesting residues required predicting landowner management intentions for different areas. Individual landowners have different goals and management plans, and it was unrealistic to interview all of the landowners in the project area about their management intentions over the next decade. However, landowner groups tend to have similar goals and management regimes. These goals and management tendencies influence when the woody biomass on forest lands becomes available. An up-to-date GIS map of land ownership was required to estimate the influence these different management priorities have on when different forested areas in the project area will likely be harvested. Since no current digital map was available, we used a current paper map provided by Atterbury Associates to update the most recent GIS ownership map available (ORGEO [no date]) to reflect all major changes in land boundaries and ownership.

Forest land ownership in the project area can be divided into five major landowner groups: private industrial forest landowners, private non-industrial landowners, Oregon Department of Forestry, other state agencies, and federal agencies.
3.4.2 Landowner Groups Included in the Biomass Estimate

Management intentions, harvesting systems used, size of average harvests, proximity of ownership areas to potential facility sites, and predictability of harvests were all considered in determining which land owners could be significant contributor of recoverable harvesting residues. Management intentions of different ownership groups were used in this study to predict which lands might generate timber harvesting residues. In general the primary concern of the private industrial forest owners is sustainable timber production. The state and federal agencies have multiple concerns, some of which are maintaining environmental quality, habitat conservation, recreational opportunities, timber production, research and preservation of cultural resources. Oregon Department of Forestry's plans for timber production are described in their harvest plan. The primary interests of private non-industrial forest owners can vary from one individual owner to the next. Individual private non-industrial owners may have one or multiple primary concerns, which may include timber production, aesthetic values, recreation, environmental quality or habitat protection.

Although private non-industrial forest land owners made up a significant proportion of the forest land in the project area, the management intentions of this group are much more difficult to characterize reliably over an area the size of the project area than the other groups. Because private non-industrial landowners own smaller acreages individually compared to the other landowner types, there are many more individual landowners of this category in our area of interest. Unlike private industrial forest owners, these landowners have a diverse array of reasons for owning forest land and management
objectives. While some government agencies that own forest land also have multiple ownership objectives, most of these small landowners don’t have published and publicly accessible management plans. Indeed, some landowners of this class may not have even considered what their specific management objectives are or have strategies and time-lines for achieving them. For small forest landowners who have specific management goals, those intentions may change rapidly over a short period of time, whether due to changing knowledge and attitudes or the land itself changing hands.

Our digital map didn’t show the boundaries of individual parcels in this ownership group or list names or contact information of individual landowners. Interviewing enough private non-industrial forest owners to cover a significant proportion of this ownership type would have been unreasonable because of the difficulty of differentiating individual ownerships on the map, identifying owners, acquiring their contact information, conducting a multitude of interviews and accurately characterizing their diverse forest management goals over the entire project area. Harvests on private non-industrial forest land are typically smaller acreage-wise than timber harvests on PI forest and government lands. Whereas timber harvesting on private commercial forest land in northwest Oregon is almost exclusively clear-cut harvesting and 70-90% of the harvests use whole-tree yarding methods (PES and MB&G 2007), a significant proportion of harvests on private non-industrial forest use partial-cut systems. Depending on the proportion and selection of trees removed in a partial-cut system, the amount of economically recoverable woody biomass from the harvest will be reduced. WADNR officials in the Hood River County biomass report area stated that on average only 2 BDT/Ac were recoverable from roadside piles on 50% of their lands where they use
partial-cut systems (PES and MB&G 2007). As Oneil and Lippke found, quantity of harvested material was the only significant indicator of residual biomass, meaning as acreage or intensity of a harvest decreases, so does the quantity of biomass made available. When there is less woody biomass per site the cost of harvesting, loading and transporting the woody biomass from the operation often increases in relation to the quantity of fuel recovered. With harvest, loading and transport costs often meeting or exceeding delivered market price of fuel (Fried and others 2003), it's clear that any increase in these costs can quickly push a biomass recovery operation into the red. Less-than-truckload shipments, longer wait times between available loads, and insufficient operating room for larger, more efficient equipment can all contribute to higher marginal costs in these smaller harvests. For these reasons, private non-industrial forest lands where not included in our calculations of recoverable biomass fuel supply.

The federal land management agencies face a number of the same challenges to reliable woody biomass supply that the private non-industrial forest owners do. While local districts and regions of federal land management agencies like the USDA Forest Service have clearly documented, regularly reviewed, and carefully planned management objectives and strategies, a number of their planned timber harvests don’t occur on schedule or at all as lawsuits can temporarily sideline or permanently eliminate a project (Sampson and others 2001). The CH2M Hill (2005) report goes as far as saying that the USDA Forest Service is incapable of fulfilling any timber contract that it writes because of legal challenges. Although the intentions of the local forest managers may remain fairly constant throughout the planning horizon, changes in policy or funding at a regional or national level can force a change of plans. In order to meet more diverse
and equally weighted management objectives, government land management agencies perform more thinning and partial-cut harvests and less regeneration harvests when compared to timber harvests on private industrial forest lands. These influences result in less predictable or reliable woody biomass yields and potentially higher recovery costs. As a result, government land, other than Oregon Department of Forestry, was excluded from the calculations of recoverable woody biomass.

Due to the numerous challenges in accurately estimating harvests from Private Non-Industrial and federal government forest land, they were excluded from the recoverable forest biomass calculations. Both of these landowner groups may provide sources of supplemental biomass fuel for the forecast period, but they should not be relied on as primary sources for planning purposes. Only the Oregon Department of Forestry and Private Industrial forest lands were included in the recoverable biomass estimate.

3.4.3 Management Intentions

In order to estimate the acres that will be cut in any given time period, it is necessary to know the likely harvest ages of the lands being considered, and the distribution of forest ages across the landscape. Determining biomass yield from the areas that will be cut then requires knowledge of how much biomass is present immediately before harvest, the harvest intensity on the harvested acres, and what components and percentages of the cut material are economically recoverable based on the equipment and methods used. Building a biomass power plant is a large investment and a reliable, sufficient supply of fuel is necessary for it to cover its costs and be profitable. The determination of how many acres will be cut, what area will be cut, and how (in terms of techniques and
equipment) it will be cut in the future is clearly more subjective than applying a series of equations to measured and imputed forest cover data. Realizing this, we tried to err on the conservative side in these determinations to prevent significantly overestimating the future available biomass fuel resource.

The management goals and strategies of most private industrial forest land owners in the area were fairly similar, consisting predominantly of regeneration harvests followed by replanting with a 40-50 year average rotation age. The Oregon Department of Forestry was also a significant forest landowner in the project area, and they provided us with GIS maps of their likely harvest units and a database of the harvest schedule for the following 20 years indexed by harvest unit numbers including planned harvest period, current wood volume, and harvesting intensity in terms of proportion of volume to harvest.

3.4.4 Accuracy of LEMMA Dominant Forest Ages

From the updated ownership map we determined the five largest private industrial (PI) forest landowners in the area. As a rough test of the accuracy of the age data in the LEMMA predicted vegetation raster we generated a histogram for each of the five large PI forest landowners of acres owned in each 10 year forest age class and interviewed them regarding the accuracy of predicted dominant forest age distribution across their properties. Our primary interest was for the 30-50 year age classes which would provide harvesting residues. Overall, the companies confirmed the general age class proportional breakdowns with the exception of 0-9 year age class and the age classes greater than 60 years old which were all overrepresented. Approximately 15% of the
total forest acres were predicted in all age classes over 60 years, but the 0-9 year age class was the largest single predicted age class at 21% of the total area and had the largest discrepancy between predicted proportion of total acres and company estimates. After reviewing a map of predicted dominant forest age spatial distribution across their properties, company representatives stated that they didn’t notice any significant inaccurate trends in the spatial predictions of dominant forest ages other than some small areas classified as greater than 80 years old that they believed were likely younger. The responses we received to the age class data seemed to indicate that for our project area the method for determining age used when making the LEMMA NWFP raster had difficulty differentiating the ages of the stand 0-15 or 0-20 years old, and somewhat overestimated the number of acres over 60 year old, but was generally accurate in determining the dominant age distribution patterns over the landscape otherwise.

3.5 Accounting for Riparian and Wetland Management Areas

In both Oregon and Washington, legal restrictions require leaving a certain number of trees per acre for wildlife habitat and limit timber harvesting in or near riparian and wetland areas. To accurately determine what areas can be harvested and as a result, yield woody biomass, these restrictions must be taken into account. None of the biomass assessments we reviewed have modeled the effect of these regulations, although Fried and others (2003) did mention it was a potential source of inaccuracy. A number of options exist in both Oregon and Washington for selective removal of a limited proportion of the basal area of trees from parts of these zones. The decision to avoid harvesting in these areas altogether or selectively remove some trees within operational
restrictions is a decision that must be made by the manager in charge of the timber harvest and is something that we are unable to predict accurately for all commercial timber lands across the project area. Likewise, the wildlife tree retention requirements provide some flexibility in location and selection of trees to leave behind. Sometimes these trees are located in the riparian or wetland management areas and they are often grouped together instead of being dispersed evenly among every harvested acre in order to protect forest workers from the hazards presented by standing dead trees. To account for this choice that we cannot predict and to simplify our models of riparian and wetland management zones, we assumed that all wildlife trees would be placed within riparian/wetland management zones (R/WMZ's). In our model, no harvesting occurs in the R/WMZ's and no trees are left behind in harvest units outside of these zones.

Riparian management zones and wetland management zones were both modeled for Washington. Only riparian management zones were modeled in Oregon, as there was no GIS layer of “significant wetlands” for the Oregon portion of the project area with high enough resolution and accuracy. GIS files representing river and stream locations and classifications for Oregon were acquired from ODF (ODF 2009). GIS files representing watercourse and wetland locations and classifications, and site class information for Washington were acquired from the Washington Department of Natural Resources (WADNR [no date]). The size of riparian management zones in Washington depends on watercourse classification and soil site class. Wetland management zone size in Washington depends on wetland size and classification. In Oregon, RMZ size depends on stream classification and fish presence designation.
Oregon Stream Classes Considered (All combinations of Size and Fish Presence):

<table>
<thead>
<tr>
<th>Size</th>
<th>Fish Presence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large</td>
<td>Fish (fish observed or determined to be present)</td>
</tr>
<tr>
<td>Medium</td>
<td>Non-fish (fish determined not to be present)</td>
</tr>
<tr>
<td>Small</td>
<td>Unknown</td>
</tr>
<tr>
<td>Uncategorized</td>
<td></td>
</tr>
</tbody>
</table>

Washington Stream Classes Considered:

- Np (No fish, perennial)
- Ns (No fish, seasonal)
- Nu (No fish, unknown p or s)

...and five classes for each Site Class (1 to 5) for each of the following groups...

- S (Shorelines of the state), Site Class #
- F (Fish-bearing), Site Class #

Washington Wetland Classes Considered:

- A, Large
- A, Medium
- B, Large
- B, Medium
- FW (Forested Wetland)
A number of challenges were encountered while developing the R/WMZ models. A significant number of the stream segments lacked classifications in both Oregon and Washington and some areas on the site class map had additional classifications not included in the Washington regulations. Also, while the location of the stream lengths was detailed in GIS files, the stream widths were not listed for any of the watercourses. Because the boundaries of riparian management zones are determined by distance from bank-full width of the streams and rivers, not from the center of the streams, and the GIS features representing the watercourses are lines (with no width) representing the centers of the streams, it was necessary to estimate stream width for each classification in the model in order to avoid consistently under-representing riparian management zone areas over the project area. Another confounding factor to an exact delineation of R/WMZ’s was slope. The width of these zones is defined by slope distance from the bank-full width. Although it would have been possible to calculate slopes for the project area, the locations of the streams in the GIS layer lacked enough precision when compared to the widths of some of the smaller riparian zones, that we would have been unable to tie together slope calculations and stream centerlines with enough confidence to justify it. Also, the added computational complexity of calculating variable buffer widths within every stream segment based on slope calculations would likely have increased solution time immensely. Although using horizontal distance instead of slope distance can make a significant difference in the width of riparian zones, it is questionable how much benefit such a possible increase in bank to zone-edge width precision would have when the widths of the streams themselves were unknown and had to be estimated as an average for entire stream classifications. With no known bounds on stream widths, unknown changes in actual zone width due to slope and with a significant number of
watercourses unclassified, there were countless combinations of parameter choices that could be used when modeling the riparian and wetland management zones. To help determine if a parameter set was reasonable, we used guidelines of how much of the total land area was to be designated as riparian or wetland management zones. At the time the R/WMZ models were being developed a literature search for proportions of total forest land in riparian and wetland zones for north west Oregon and southwest Washington yielded no published measurements. The only estimates available of the proportion of forest land in riparian and wetland management zones were second-hand information from personal communication with forestry professionals. A professor of forest hydrology stated estimates he had heard ranged from 6-10% for Oregon, and 18-22% for Washington, although he was unable to verify those values (Skaugset 2010, personal communication). Because of the lack of published measurements, these were the estimates used when building the model. The actual proportion of forest land in R/WMZ’s will vary by drainage density (miles of stream per square mile of land) and the degree of overlap of adjacent riparian and wetland management zones in addition to stream classification (Ice and others 2006). Because the area calculations for the models in GIS do not differentiate between the area of the watercourses and wetlands themselves and forest land at the edges of the watercourses, another 0.75% was added to these target ranges to account for the area covered by the actual watercourses and wetlands. GIS scripts for modeling the R/WMZ’s were created in ArcGIS ModelBuilder and Python programming language (Appendices B and C). With those proportional area ranges as a guide, trial and error was used, combining parameters that seemed reasonable and checking the proportion of total land covered. The final parameter sets for Washington and Oregon are shown in Tables 3.3 and 3.4. The ODF harvest data
already accounted for the effects of these zones, so it was only necessary to adjust the PI forest landbase. When we were satisfied with the R/WMZ GIS layer we ran another script which eliminated those areas from the map of the PI forest landbase in the project area. The Riparian and Wetland Management Zones GIS layer that we generated with these parameters covered 8.1% of the Private Industrial forest land in Oregon and 19.5% in Washington.
Table 3.3. Washington riparian and wetland management zone GIS model parameters. Widths are combined watercourse and management zone half-width in feet.

<table>
<thead>
<tr>
<th>Watercourse Class</th>
<th>Site Class</th>
<th>Width</th>
<th>Watercourse Class</th>
<th>Site Class</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>1</td>
<td>175</td>
<td>U</td>
<td>1</td>
<td>97</td>
</tr>
<tr>
<td>S</td>
<td>2</td>
<td>153</td>
<td>U</td>
<td>2</td>
<td>84</td>
</tr>
<tr>
<td>S</td>
<td>3</td>
<td>130</td>
<td>U</td>
<td>3</td>
<td>71</td>
</tr>
<tr>
<td>S</td>
<td>4</td>
<td>108</td>
<td>U</td>
<td>4</td>
<td>57</td>
</tr>
<tr>
<td>S</td>
<td>5</td>
<td>93</td>
<td>U</td>
<td>5</td>
<td>49</td>
</tr>
<tr>
<td>S</td>
<td>NCM*</td>
<td>93</td>
<td>U</td>
<td>NCM*</td>
<td>49</td>
</tr>
<tr>
<td>S</td>
<td>Not Determined</td>
<td>100</td>
<td>U</td>
<td>Not Determined</td>
<td>53</td>
</tr>
<tr>
<td>S</td>
<td>Red Alder</td>
<td>153</td>
<td>U</td>
<td>Red Alder</td>
<td>84</td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>156</td>
<td>Np</td>
<td></td>
<td>52</td>
</tr>
<tr>
<td>F</td>
<td>2</td>
<td>134</td>
<td>Nu</td>
<td></td>
<td>42</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>111</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>4</td>
<td>89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>5</td>
<td>74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>NCM*</td>
<td>74</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Not Determined</td>
<td>81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>Red Alder</td>
<td>134</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wetland Type</th>
<th>Buffer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A, Large</td>
<td>100</td>
</tr>
<tr>
<td>Type A, Medium</td>
<td>50</td>
</tr>
<tr>
<td>Type B Large</td>
<td>50</td>
</tr>
<tr>
<td>Type B, Medium</td>
<td>25</td>
</tr>
<tr>
<td>Cut Forested Wetlands?</td>
<td>Yes</td>
</tr>
</tbody>
</table>

*NCM: Non-Commercial/Marginal
Table 3.4. Oregon riparian management zone GIS model parameters. Widths are combined watercourse and management zone half-width in feet.

<table>
<thead>
<tr>
<th>Class</th>
<th>Width</th>
<th>Class</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large, fish present</td>
<td>125</td>
<td>Small, fish present</td>
<td>51</td>
</tr>
<tr>
<td>Large, no fish present</td>
<td>95</td>
<td>Small, no fish present</td>
<td>13</td>
</tr>
<tr>
<td>Large, unknown</td>
<td>125</td>
<td>Small, unknown</td>
<td>26</td>
</tr>
<tr>
<td>Medium, fish present</td>
<td>77</td>
<td>Uncategorized size, fish present</td>
<td>55</td>
</tr>
<tr>
<td>Medium, no fish present</td>
<td>57</td>
<td>Uncategorized size, no fish present</td>
<td>20</td>
</tr>
<tr>
<td>Medium, unknown</td>
<td>69</td>
<td>Uncategorized size, unknown</td>
<td>28</td>
</tr>
</tbody>
</table>

To test the impact of excluding the areas in the riparian and wetland management zones GIS model, the predicted available biomass for the forecast period was compared for three different scenarios, using the GIS model to exclude the R/WMZ's, reducing unbuffered biomass totals by 8.1% in Oregon and 19.5% in Washington (the same percentages of the available private industrial landbase excluded in the GIS model and thought to represent the percentage of that land in the R/WMZ's and watercourses themselves), and without accounting for the R/WMZ's at all (no buffers). The percentage difference in predicted available biomass between the GIS model and the No buffers calculations and between the GIS model and fixed percentage model calculations were calculated and compared. We performed a random permutation test to identify if there was a statistically significant difference in predicted available biomass between using the GIS model to eliminate R/WMZ's from the landbase and selecting a random combination of raster cells of equal total area to exclude from the available landbase. The random selection process was repeated for 1000 iterations. Because some of the cells near larger watercourses were identified as water in the predicted vegetation raster and would
yield no biomass even if R/WMZ's were not accounted for, the random permutation test was run for both the estimated percentage of available landbase in the R/WMZ's and watercourses combined (8.1% in OR, 19.5% in WA) and for the estimated percentage of the available landbase in the R/WMZ's alone (7.35% in OR, 18.75% in WA), excluding the watercourses themselves. Since the true proportion of total area covered by streams and rivers is unknown (we used 0.75% as an estimate) and the proportion of total area covered by the R/WMZ's themselves is simply an educated guess based on a “rule-of-thumb” estimate for the project area, these were confounding factors and reduced the number of conclusions that could be reached from the analysis.

3.6 Predicting Residue Biomass in the Forecast Period

3.6.1 Private Industrial Forests

To accurately calculate the available forest biomass during the forecast period it was necessary to identify which areas will yield biomass in that period and to predict the recoverable biomass densities on those lands in that period. The calculations of forest biomass density for all FCID’s in the project area from the LEMMA inventory database were based on data acquired from 2000-2006. Using biomass densities and locations for forests thought to be 40-50 years old in 2003 as an estimate of available biomass from 2010-2019 would be spatially-inaccurate as those stands would likely have been harvested already and not cut again until approximately 2043-2052. This would result in inaccurate biomass quantities as well as inaccurate locations (which are important for transportation analysis). Using locations of forests that will reach the likely harvesting age during the forecast period with the biomass calculations for those areas based on
data taken from the LEMMA inventory period would also yield inaccurate results, as the biomass densities for those locations would not account for growth that occurred between the years inventory and remote sensing data were collected and the forecast period. In order to update the biomass calculations for the areas harvestable on PI forests during the forecast period, we chose to select the forests harvestable during the inventory period and the forests harvestable during the forecast period, group them both by proportional species composition and high or low relative basal area, calculate average biomass numbers for each group in the forests from the LEMMA inventory period, then apply those group biomass numbers to the appropriate groups in the forests harvestable during the forecast period. This method was not used on ODF lands because we had access to their likely harvest plan information which included harvest periods, removal intensities, volumes and boundaries for each likely harvest unit.

To represent the private industrial forest lands that were likely to be harvested during the ten year period centered around the time the LEMMA data was collected, we aimed to select those forests that were 40 to 49 years old at that time. Figure 3.1 and Table 3.6 detail the breakdown of PI forest acres outside of RMZ's by age. Based on responses from the timber companies we spoke to, the published number of acres harvested per year from PI forest lands in the area and the irregular distribution of acres among the age classes, we determined that the forests with a dominant age from the LEMMA raster between 40 to 59 years were probably more representative of the actual 40 to 49 year PI forest lands than the lands with a LEMMA dominant age between 40 and 49 years. Ohmann and Gregory (2002) describes some of the uncertainty in stand dominant age that could account for this effect. The PI forests with a LEMMA dominant age between
28 and 37 years were believed to best represent forests that will have an actual age between 40 and 49 years in the middle of the ten year forecast period of 2010 to 2019. The raster cells for PI forest land outside of the riparian and wetland management zones with a LEMMA dominant age of 40 to 59 and 28 to 37 were selected for Oregon and Washington and their FCID's and basal area by species were each exported to a spreadsheet. The percentage of total forest basal area for each tree species was calculated from the inventory data for each FCID present in these areas. All FCID's in the age selections were assigned to one of six groups based on this species composition data and relative basal area. The six species-basal area groups were: Douglas-fir, Hemlocks, Red Alder, Non-Commercial species (NC), Commercial species Mix – Low basal area (CommMix-L) and Commercial species Mix – High basal area (CommMix-H). The criteria for determining what group an FCID belonged to are described in Table 3.5.
Figure 3.1. Project area PI forest land age distribution (excluding R/WMZ's)
### Table 3.6. Private industrial forest land age distribution (excluding R/WMZ’s)

<table>
<thead>
<tr>
<th>Age Class</th>
<th>Oregon Acres</th>
<th>Wash. Acres</th>
<th>TOTAL Acres</th>
<th>Ages 0-14 Averaged</th>
<th>Ages 0-35 Averaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-4</td>
<td>384,779</td>
<td>98,657</td>
<td>483,436</td>
<td>183,577</td>
<td>206,391</td>
</tr>
<tr>
<td>5-9</td>
<td>0</td>
<td>5,134</td>
<td>5,134</td>
<td>183,577</td>
<td>206,391</td>
</tr>
<tr>
<td>10-14</td>
<td>3,505</td>
<td>58,655</td>
<td>62,160</td>
<td>183,577</td>
<td>206,391</td>
</tr>
<tr>
<td>15-19</td>
<td>152,148</td>
<td>102,304</td>
<td>254,452</td>
<td>254,452</td>
<td>206,391</td>
</tr>
<tr>
<td>20-24</td>
<td>121,682</td>
<td>82,720</td>
<td>204,403</td>
<td>204,403</td>
<td>206,391</td>
</tr>
<tr>
<td>25-29</td>
<td>151,051</td>
<td>80,396</td>
<td>231,447</td>
<td>231,447</td>
<td>206,391</td>
</tr>
<tr>
<td>30-34</td>
<td>110,885</td>
<td>92,824</td>
<td>203,709</td>
<td>203,709</td>
<td>206,391</td>
</tr>
<tr>
<td>40-44</td>
<td>82,782</td>
<td>66,677</td>
<td>149,459</td>
<td>149,459</td>
<td>149,459</td>
</tr>
<tr>
<td>45-49</td>
<td>65,200</td>
<td>33,766</td>
<td>98,965</td>
<td>98,965</td>
<td>98,965</td>
</tr>
<tr>
<td>50-54</td>
<td>75,660</td>
<td>26,421</td>
<td>102,080</td>
<td>102,080</td>
<td>102,080</td>
</tr>
<tr>
<td>55-59</td>
<td>30,068</td>
<td>13,072</td>
<td>43,140</td>
<td>43,140</td>
<td>43,140</td>
</tr>
<tr>
<td>60-64</td>
<td>37,276</td>
<td>15,685</td>
<td>52,962</td>
<td>52,962</td>
<td>52,962</td>
</tr>
<tr>
<td>65-69</td>
<td>23,495</td>
<td>4,190</td>
<td>27,685</td>
<td>27,685</td>
<td>27,685</td>
</tr>
<tr>
<td>70-74</td>
<td>25,433</td>
<td>8,312</td>
<td>33,744</td>
<td>33,744</td>
<td>33,744</td>
</tr>
<tr>
<td>75-79</td>
<td>18,465</td>
<td>8,207</td>
<td>26,673</td>
<td>26,673</td>
<td>26,673</td>
</tr>
<tr>
<td>80+</td>
<td>123,019</td>
<td>25,149</td>
<td>148,167</td>
<td>148,167</td>
<td>148,167</td>
</tr>
<tr>
<td><strong>TOTAL:</strong></td>
<td><strong>1,506,587</strong></td>
<td><strong>784,538</strong></td>
<td><strong>2,291,126</strong></td>
<td><strong>2,291,126</strong></td>
<td><strong>2,291,126</strong></td>
</tr>
</tbody>
</table>
Table 3.5. Rules for classifying forests into species-basal area groups

1. If 40% or more of the total basal area of the FCID is non-commercial species, it is classified as NC.

2. If 50% or more of the basal area is Douglas-fir, Hemlocks, or Red Alder, it is classified PSME, Hemlock, or ALRU2 accordingly.

3. The remaining FCID’s are classified as Commercial Mix. For forests with a LEMMA dominant age of 40 to 59 years, the Low basal area class has a basal area of less than 40 m²/Ha and the High class has 40 or more m²/Ha. For forests with a LEMMA dominant age of 28 to 37 years, the Low basal area class has a basal area of less than 35 m²/Ha and the High class has 35 or more m²/Ha.

*If an FCID meets multiple criteria, the higher numbered rule takes precedence. (eg. An FCID with 54% Douglas-fir and 43% non-commercial species is classified NC).
Using the harvesting residue, merchantable biomass and aboveground biomass density calculations associated with each FCID we calculated the average biomass densities and ratios for each of the forest type groups for PI forests with a LEMMA dominant age of 40 to 59, those determined to be harvestable during the 10 year period centered around the inventory period. Based on the assumptions of 26 green tons (GT) of net merchantable log biomass per log truck, 4.0 MBF per log truck, and a wet basis moisture content of 40% for the net merchantable log biomass on the trucks, we also calculated ratios of forest residue biomass to net merchantable log biomass for all of the forest residue criteria. These ratios of forest residue biomass weight to merchantable log volume provided a means of comparison to BDT/MBF ratios published in other studies and reports.

The average biomass densities for the forest groups from the PI forest lands harvestable during the inventory period in Oregon and Washington were then applied to the same forest groups from the PI forest lands expected to be harvestable during the forecast period. These average biomass numbers for each forest group were assigned to the PI forest areas harvestable during the forecast period whose FCID’s had been classified in the same forest group. We attached this table of FCID’s and their associated forecast period biomass densities to a GIS raster map of FCID’s of the project area. This map represented the PI forest lands that will likely be harvested during the 2010-2019 time period and the biomass densities associated with forests of harvestable age of the same group from the inventory period. The purpose of this was to represent accurate biomass densities, locations and total acreages for the forecast period in the forecast biomass raster map for PI forest lands.
3.6.2 ODF Forests

There are three Oregon Department of Forestry districts in the project area; Astoria, Tillamook, and Forest Grove. The ODF harvest plan data included a GIS map of the individual harvest units in each district and a spreadsheet that had entries for each harvest scheduled for all harvest units over a 20 year period. The spreadsheet rows described the target unit, the harvest intensity (in percent of merchantable volume removed), the period when the harvest would occur, the standing volume of the unit before the cut, and the standing volume remaining in the unit after the cut. There were four periods of five years each spanning the 20 year period of the ODF plans. Periods 2 and 3 corresponded most closely to our forecast period of 2010-2019. A few units were scheduled for partial cuts in both period 2 and 3. Unlike the Private Industrial forest land biomass prediction, we did not use the species-basal area grouping method on the ODF forests. Recent work by Stander (2011) describes a bias in the ODF’s harvestable volume estimates for the Tillamook district, but we used the estimates as we received them.

To determine the forest residue biomass available on ODF forest lands during the forecast period, we created a raster map of the cumulative removal intensities for all the harvests in each of the ODF harvest units for the forecast period and multiplied it with the raster map of biomass densities created by applying allometric equations to the LEMMA inventory data. We estimated the total removal intensities for each unit for the forecast period by simply adding the intensities of all harvests in each unit for periods 2
and 3. These total removal intensities were assigned to the areas of the corresponding harvest units to create the raster map of total removal intensities. In some units, our total removal intensity for a harvest unit would be greater than 100%. This was allowed to account for growth between harvest periods and growth between the time the LEMMA inventory data was collected and the harvest would occur. Multiplying the raster of total harvest intensities for periods 2 and 3 by a raster of biomass calculations for the inventory period yielded a raster representing the quantities of forest residue biomass generated from harvests on ODF land from 2010-2019.

There were a number of challenges and sources of uncertainty in predicting the forecast biomass available from the ODF units. The method of selecting trees for the partial-cuts could significantly affect the biomass yield since relationship between tree DBH in centimeters and tree biomass in kilograms or tons is not linear for most of the allometric equations used to predict individual tree biomass. For example, if the proportion of total volume harvested came from the largest or smallest trees in the unit, the proportion of the unit's forest residue biomass that was cut would probably be skewed higher or lower than that same proportion. Also, summing harvest intensities from multiple entries probably doesn't adequately account for growth between the time the LEMMA data was collected and the time the harvest occurred and for units that had multiple harvests throughout the forecast period it is not possible to accurately model the growth of the remaining stand without information about the selection process for which trees were cut initially.
3.7 Forecast Recoverable Forest Residue Biomass Map
The raster maps of predicted forest residue biomass generated on Private Industrial forest land outside of riparian and wetland management zones and on Oregon Department of Forestry land from 2010-2019 were combined into a single raster map. While this map represents the spatially-explicit distribution and densities of forest residue generated from forest harvests during the forecast period, it does not address the issue of gathering the resulting residues so they can be loaded for transport. Not all forest residue generated from harvest can practically or economically be recovered. While the proportion of total harvesting residues recovered for fuel vary greatly depending on the harvesting system, the primary methods used in commercial timber production in the Pacific Northwest lend themselves to recovery rates in the higher end of the observed range. While Hakkila (2004) stated that current average recovery rates in Finnish forests are as low as 10% of what is technically recoverable, local forest managers cited in Hood River County biomass report said that about 70% of residues make it to the landing in whole-tree yarding operations, which make up approximately 70-90% of commercial harvest operations in that area (PES and MB&G 2007), which is similar to our project area. While they applied a logging residue recovery rate of 60% to the total residue biomass on private industrial lands in their study area, we were primarily concerned with slash from merchantable trees only excluding foliage, which is more likely to make it to the landing with whole tree yarding than other residues. Because of this, our 70% residue recovery rate seems comparable to the rate used by PES and MB&G, at least for our estimate for private industrial lands of recoverable residues from merchantable trees excluding foliage. Gan and Smith (2006) also used a 70% recovery rate in their estimate of quantity and regional distribution of recoverable logging residue biomass.
biomass annual yields in the US. Oneil and Lippke (2009) found that across all samples in their study, which included a variety of harvesting and yarding systems, residues averaged 50% of total cut material (ranging from 33-63% for different samples), the rest being merchantable timber removals. Two-thirds (67%) of all residues are in piled slash and dispersed slash > 5" diameter and the remaining one-third is dispersed slash < 5" diameter. With appropriate economic incentives they estimated most of the piled slash and dispersed slash > 5" could be recovered, however once restrictions on biomass removal for ecological sustainability are accounted for most of the piled slash and only half of the dispersed slash > 5" diameter would likely be recovered. Currently, for the samples and region of northeastern Washington that they studied, residues recoverable for fuel made up 20% of the total cut biomass. With merchantable timber removals and total residues each averaging 50% of total cut biomass, the amount of recoverable residues was equal to 40% of the merchantable timber removed or 40% of total residues. Oneill and Lippke’s use of the term “recoverable” is somewhat different than how it is used in this thesis. While we use it to refer to the amount or proportion of biomass that can be collected and delivered under technical limitations of the equipment used on the harvesting sites, they use the term “recoverable” to refer to the biomass that can be technically collected and delivered economically assuming there are incentives in place to encourage utilization. This is a more restrictive use of the term “recoverable” than we are using in this thesis. The six different residue criteria we used in our biomass estimate were intended to represent some of the variation in levels of biomass supply that could occur if market conditions justified collecting the materials that required greater cost or time to collect, such as biomass from small non-merchantable trees. There are other factors that would also cause their estimate of recoverable rate to differ
from ours. They included foliage and slash from non-merchantable trees in their total residue numbers while foliage was only included in 3 of our 6 different residue criteria and slash from non-merchantable trees was included to varying degrees in 4 of our 6 residue criteria. A 70% recovery rate applied to merchantable tree slash excluding foliage would represent a recovery rate for all residues including foliage that is lower than 70%. Also, we are dealing mostly with whole-tree yarding in regeneration harvests while their study included various harvesting systems. To represent the biomass losses that occur during the recovery process, the combined forecast period forest residue densities raster was multiplied by a constant of 0.7 to create a recoverable forest residue raster map.

This final product showed the spatial distribution of recoverable residue densities for PI and ODF forests in the project area that will be generated during the forecast period. The final map was an attempt to represent locations, densities, and total landbase of recoverable fuel for the desired forecast period, which enabled others to perform detailed analyses of transportation costs and optimal sourcing strategies for the required fuel for multiple candidate power plant locations.

### 3.8 Residues Left On-Site After PI Harvests

One of the concerns about recovery of forest biomass for energy generation is its effect on long-term site productivity and nutrient cycling. Although that matter is outside the scope of this thesis, we made some rough calculations of the concentrations of residue biomass left on-site after timber harvest on PI forest lands during the forecast area. These numbers were generated by subtracting the recovered residue and gross
merchantable biomass averages from the total aboveground biomass averages for the
different Species-BA forest groups during the forecast period. These estimates do not
include the additional biomass that is left on-site in the form of dead and down woody
material and non-woody vegetation. Oregon Department of Forestry has its own policy
for the minimum quantity of woody biomass to leave on-site, so they were not included in
these calculations.

3.9 Assessing Accuracy of the Recoverable Biomass Estimate

Because of the multi-stage nature of this biomass forecasting method, there are a
number of different potential factors that could contribute error, uncertainty and bias to
the final estimate of recoverable harvesting residues. These include:

- Allometric equations
- The GNN imputation method used by LEMMA
- The modeling and exclusion of riparian and wetland management zones
- The estimated residue recovery rate
- The estimated defect and breakage rate
- The methods of representing growth for both PI and ODF forests
- Various other assumptions necessary to develop the overall biomass estimate

One source of uncertainty in the final biomass estimate that can be analyzed with the
data currently available is the use of allometric equations to predict individual tree
biomass for all sample trees in the FCID’s. In order to quantify the uncertainty resulting
from this sources, a series of simulations were conducted on the allometric equations
that were applied to the inventory data.
To reflect the uncertainty in the biomass densities predicted for the FCID’s, prediction distributions of total plot residue biomass were created for each FCID by using the standard errors of estimate (SEE’s) for the allometric equations to draw predictions from the prediction distributions of the regression models for individual trees then adding up the biomass represented by each sample tree to get a total residue biomass prediction for the plot (FCID). By randomly drawing predictions for each tree in each FCID from the prediction distributions of the allometric regression equations, totaling the biomass predictions for all the trees in each FCID and repeating this process multiple times, we were able to develop prediction distributions for the total biomass of each FCID.

To represent the effect of the uncertainty in the biomass totals for each FCID when applied to the predicted vegetation map another simulation was designed. The simulation went cell by cell through a raster map of private industrial forests of harvestable age during the inventory period. For each cell the program read the FCID assigned to that cell by the GNN imputation method. As the program went cell by cell through the raster, it kept track of how many times each FCID had been assigned to a cell in the raster. After all the cells were read, for each FCID that appeared in the raster, for each cell that it had been assigned to a new biomass prediction from the list of predictions for that FCID was chosen at random. Each new cell biomass value was adjusted by a 70% residue recovery factor and then added to the recoverable biomass total for the raster. This process was repeated over 1000 times to create predictions of recoverable biomass from private industrial forests of harvestable age during the inventory period that incorporated the uncertainty from the allometric equations. A 95%
The prediction interval was determined by the value from these predictions that was higher than 97.5% of the others and the value that was lower than 97.5% of the others. The simulation was run for each of the three residue criteria that excluded foliage.

As a check of these predictions, a point estimate was made for the recoverable forest residues from private industrial forest lands of harvestable age during the inventory period for each of the three residue criteria that excluded foliage. This set of point estimates was made using similar methods to those outlined above for estimating the recoverable harvest residues from PI forests during the forecast period. We assigned biomass calculations for each FCID to the cells of the LEMMA predicted vegetation map to get a map of biomass values for each cell if it were harvested. These BDT/Ac values for the map were multiplied by 70% and rounded to reflect the recovery rate. We then combined this recoverable biomass density map with a map of private industrial forest lands outside of R/WMZ’s that had LEMMA dominant forest ages between 40 and 59 (thought to best represent harvestable age) to get the biomass values for areas likely to be harvested during the ten years centered on the inventory period.

To the same end, we also generated rough range estimates of quantity of these residues by applying the lowest and highest of the average recoverable BDT/MBF rates from our six species-BA forest groups to Adams and Latta’s (2007) PI timber harvest records and predictions for the counties in the project area during the ten years centered on the inventory period. Because our project area included a number of partial counties, and the timber harvest records and projections were presented as totals for each county, we generated a pair of low and high estimates that included only the 12 counties that were
fully within the project area boundaries and a pair of estimates that included all 18 counties that had any area within the project area boundaries. These range estimates were made only for the residues from merchantable trees excluding foliage.
4 Results

4.1 Recoverable Biomass Totals

During the forecast period of 2010-2019, an estimated 7,055,000 BDT of forest harvest residues from merchantable trees without foliage would be recoverable from ODF and Private Industrial forest lands in the project area, under our assumptions. Larger quantities of woody biomass will be recoverable if extra time and expense is invested in gathering other harvesting residues that are generated such as those from non-merchantable trees. This is reflected in the higher recoverable biomass totals for the other forest residue criteria (Table 4.1).

Table 4.1. Total recoverable forest biomass and generating acres for 2010-2019 for the six recoverable material criteria.

<table>
<thead>
<tr>
<th>Forest Residue Specification</th>
<th>Total Acres</th>
<th>Total BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merch Slash</td>
<td>482,144</td>
<td>7,054,526</td>
</tr>
<tr>
<td>Merch and Large Non-Merch</td>
<td>482,426</td>
<td>8,385,931</td>
</tr>
<tr>
<td>All Slash</td>
<td>482,785</td>
<td>8,793,026</td>
</tr>
<tr>
<td>Merch Slash</td>
<td>482,287</td>
<td>8,575,902</td>
</tr>
<tr>
<td>Merch and Large Non-Merch</td>
<td>482,524</td>
<td>9,911,141</td>
</tr>
<tr>
<td>All Slash</td>
<td>482,809</td>
<td>10,324,063</td>
</tr>
</tbody>
</table>
Table 4.2. Recoverable forest residues and generating landbase for 2010-2019 by county for OR and WA. Residues from merch. trees only, excluding foliage; * indicates only part of the county was included in assessment.

<table>
<thead>
<tr>
<th>Counties</th>
<th>Producing Landbase (Ac)</th>
<th>Recoverable Fuel (BDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benton *</td>
<td>2,689</td>
<td>32,583</td>
</tr>
<tr>
<td>Clackamas</td>
<td>17,876</td>
<td>234,672</td>
</tr>
<tr>
<td>Clatsop</td>
<td>81,496</td>
<td>1,202,769</td>
</tr>
<tr>
<td>Columbia</td>
<td>22,826</td>
<td>293,730</td>
</tr>
<tr>
<td>Lincoln *</td>
<td>25,394</td>
<td>330,247</td>
</tr>
<tr>
<td>Linn *</td>
<td>45,198</td>
<td>588,838</td>
</tr>
<tr>
<td>Marion</td>
<td>8,420</td>
<td>108,564</td>
</tr>
<tr>
<td>Multnomah</td>
<td>887</td>
<td>11,328</td>
</tr>
<tr>
<td>Polk</td>
<td>17,250</td>
<td>219,105</td>
</tr>
<tr>
<td>Tillamook</td>
<td>66,222</td>
<td>744,811</td>
</tr>
<tr>
<td>Washington</td>
<td>19,722</td>
<td>202,069</td>
</tr>
<tr>
<td>Yamhill</td>
<td>12,677</td>
<td>162,879</td>
</tr>
<tr>
<td>TOTAL</td>
<td>320,658</td>
<td>4,131,595</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Counties</th>
<th>Producing Landbase (Ac)</th>
<th>Recoverable Fuel (BDT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clark</td>
<td>3,322</td>
<td>41,860</td>
</tr>
<tr>
<td>Cowlitz</td>
<td>68,008</td>
<td>1,192,573</td>
</tr>
<tr>
<td>Lewis *</td>
<td>29,037</td>
<td>500,979</td>
</tr>
<tr>
<td>Pacific *</td>
<td>41,411</td>
<td>839,188</td>
</tr>
<tr>
<td>Skamania *</td>
<td>7,452</td>
<td>118,821</td>
</tr>
<tr>
<td>Wahkiakum</td>
<td>12,203</td>
<td>228,562</td>
</tr>
<tr>
<td>TOTAL</td>
<td>161,434</td>
<td>2,921,982</td>
</tr>
</tbody>
</table>
Figure 4.1. The recoverable harvest residue raster for the 10 year forecast period displayed over project area map.
4.2 Forecast Residue Densities and Ratios

Predicted recoverable residue densities from merchantable trees, excluding foliage on PI and ODF forests in the forecast period ranged from 0 to 39 BDT/Ac with the majority of the area having densities between 10 and 19 BDT/Ac (Figure 4.2). The recoverable residues for PI forests by Species-BA group are shown in Figure 4.3 per acre and Figure 4.4 per thousand board-feet of merchantable timber harvested.

Figure 4.2. Frequency of recoverable forest residue densities in harvestable age PI forests. Residues from merchantable trees only, excluding foliage. 70% recovery rate.
Table 4.3. Recoverable forest residue densities of harvestable age PI Forests by species-BA group for the six residue criteria. (at a 70% recovery rate) (M: merchantable tree slash, M_LNM: merchantable and large non-merchantable tree slash, A: slash from all trees).

<table>
<thead>
<tr>
<th>Group</th>
<th>BDT/Ac, no foliage</th>
<th>BDT/Ac, with foliage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>M_LNM</td>
</tr>
<tr>
<td>OREGON</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALRU2</td>
<td>11.5</td>
<td>13.4</td>
</tr>
<tr>
<td>CommMix-H</td>
<td>17.8</td>
<td>18.9</td>
</tr>
<tr>
<td>CommMix-L</td>
<td>11.7</td>
<td>17.5</td>
</tr>
<tr>
<td>Hemlock</td>
<td>18.3</td>
<td>18.7</td>
</tr>
<tr>
<td>NC</td>
<td>3.5</td>
<td>49.0</td>
</tr>
<tr>
<td>PSME</td>
<td>13.2</td>
<td>15.8</td>
</tr>
<tr>
<td>WASHINGTON</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALRU2</td>
<td>11.7</td>
<td>11.9</td>
</tr>
<tr>
<td>CommMix-H</td>
<td>23.7</td>
<td>24.2</td>
</tr>
<tr>
<td>CommMix-L</td>
<td>9.9</td>
<td>14.4</td>
</tr>
<tr>
<td>Hemlock</td>
<td>25.3</td>
<td>25.5</td>
</tr>
<tr>
<td>NC</td>
<td>3.5</td>
<td>94.8</td>
</tr>
<tr>
<td>PSME</td>
<td>16.9</td>
<td>17.0</td>
</tr>
</tbody>
</table>
Table 4.4. Recoverable forest residue to timber volume ratios of harvestable age PI forests by species-BA group for the six residue criteria. (at a 70% recovery rate) (M: merchantable tree slash, M\_LNM: merchantable tree and large non-merchantable tree slash, A: slash from all trees).

### OREGON

<table>
<thead>
<tr>
<th>Group</th>
<th>BDT/MBF, no foliage</th>
<th>BDT/MBF, with foliage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>M_LNM</td>
</tr>
<tr>
<td>ALRU2</td>
<td>0.739</td>
<td>0.929</td>
</tr>
<tr>
<td>CommMix-H</td>
<td>0.739</td>
<td>0.777</td>
</tr>
<tr>
<td>CommMix-L</td>
<td>0.878</td>
<td>1.359</td>
</tr>
<tr>
<td>Hemlock</td>
<td>1.077</td>
<td>1.105</td>
</tr>
<tr>
<td>NC</td>
<td>0.455</td>
<td>6.194</td>
</tr>
<tr>
<td>PSME</td>
<td>0.510</td>
<td>0.629</td>
</tr>
</tbody>
</table>

### WASHINGTON

<table>
<thead>
<tr>
<th>Group</th>
<th>BDT/MBF, no foliage</th>
<th>BDT/MBF, with foliage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>M</td>
<td>M_LNM</td>
</tr>
<tr>
<td>ALRU2</td>
<td>0.785</td>
<td>0.816</td>
</tr>
<tr>
<td>CommMix-H</td>
<td>0.803</td>
<td>0.823</td>
</tr>
<tr>
<td>CommMix-L</td>
<td>0.913</td>
<td>1.356</td>
</tr>
<tr>
<td>Hemlock</td>
<td>1.098</td>
<td>1.104</td>
</tr>
<tr>
<td>NC</td>
<td>0.921</td>
<td>72.275</td>
</tr>
<tr>
<td>PSME</td>
<td>0.607</td>
<td>0.612</td>
</tr>
</tbody>
</table>
4.3 Residues Left On-Site After PI Harvests

Our estimates for densities of residue biomass left on-site after harvest on PI forests during the forecast period are displayed in Figure 4.3. The majority of the harvestable area is predicted to have between 5 and 20 BDT/Ac of residues left on-site, while a few areas will have densities less than 5 BDT/Ac or greater than 45 BDT/Ac.

Figure 4.3. Projected tree biomass (BDT/Ac) left on-site during the forecast period after harvesting with current commercial harvesting methods. This estimate is in addition to standing dead or down trees and other live or dead vegetation.
4.4 Forecast Period Biomass Landbase

As shown in Table 4.5, the number of acres of biomass generating landbase varies slightly with the forest residue specifications. A few acres across the project area will yield mostly residues that meet the looser criteria and less than 0.5 BDT/Ac of residues meeting the stricter criteria. Because cell values in the raster of biomass densities are integers, as the specifications for forest residues get stricter lands such as those will not be included as a result of rounding.

Table 4.5. Acres by land ownership likely to be harvested during the forecast period

<table>
<thead>
<tr>
<th>Ownership Group</th>
<th>Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon Industrial</td>
<td>223,342</td>
</tr>
<tr>
<td>Washington Industrial</td>
<td>161,437</td>
</tr>
<tr>
<td>Oregon Dept. Forestry</td>
<td>98,030</td>
</tr>
</tbody>
</table>

The PSME (Douglas-fir dominated) Species-BA group was the most common forest group in both Oregon and Washington on biomass producing PI forest lands for the forecast period (Table 4.6). 51% of the PI forests in Oregon, 73% in Washington and 60% in both states combined were classified in the PSME group. The Hemlock group was the second most common in both states and the project area overall. This is reflective of the fact that Douglas-fir and Western Hemlock are the dominant commercial timber species in the project area.
Table 4.6. Distribution of harvestable age PI forest land among species-basal area groups for the forecast period

<table>
<thead>
<tr>
<th>Group</th>
<th>Oregon</th>
<th>Washington</th>
<th>OR &amp; WA</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALRU2</td>
<td>6.9%</td>
<td>1.7%</td>
<td>4.8%</td>
</tr>
<tr>
<td>CommMix-H</td>
<td>3.6%</td>
<td>4.6%</td>
<td>4.0%</td>
</tr>
<tr>
<td>CommMix-L</td>
<td>10.7%</td>
<td>1.2%</td>
<td>6.8%</td>
</tr>
<tr>
<td>Hemlock</td>
<td>25.5%</td>
<td>16.7%</td>
<td>21.8%</td>
</tr>
<tr>
<td>NC</td>
<td>2.2%</td>
<td>2.8%</td>
<td>2.5%</td>
</tr>
<tr>
<td>PSME</td>
<td>51.1%</td>
<td>73.1%</td>
<td>60.1%</td>
</tr>
</tbody>
</table>

4.5 Riparian and Wetland Management Zone Modeling

The GIS model of riparian and wetland management zones and stream areas created for this project covered 8.1% of the PI forest land in Oregon and 19.5% in Washington. Those GIS buffers included the area taken up by the watercourses themselves as well as the management zones around them. Assuming the watercourses cover approximately 0.75% of the total PI forest land, the GIS buffers represented management zones that covered 7.35% of the PI forest land in Oregon and 18.75% in Washington. Incorporating this GIS model of R/WMZ’s into the recoverable biomass forecast decreased the recoverable biomass from merchantable trees without foliage by an average of 7.71% in Oregon and 20.67% in Washington. The second method considered to estimate the effect of riparian and wetland management zones on recoverable biomass was simply subtracting a percentage of the totals for Oregon and Washington equal to the proportion of area in R/WMZ’s in each of those states. Assuming the proportion of PI forest land covered by the watercourses themselves is 0.75%, the GIS model for R/WMZ’s reduced the recoverable biomass by 0.36% and 1.92% more than the percentage reduction method in Oregon and Washington, respectively.
Random permutation tests were used to determine if using the GIS buffers we created to model R/WMZ’s resulted in significantly different estimates of recoverable biomass than randomly selecting biomass bearing raster cells to exclude. Using a probability of exclusion of 8.1% for each cell in Oregon, the recoverable biomass with the GIS R/WMZ model was less than with the random cell exclusion model in 0 out of 1000 iterations. Using a probability of exclusion of 7.35% (the proportion of land thought to be in the R/WMZ’s only) in Oregon the recoverable biomass with the GIS R/WMZ model was less than with the random cell exclusion model in 1000 out of 1000 iterations. In Washington, with a probability of cell exclusion of 19.5%, the recoverable biomass with the GIS R/WMZ model was less than with the random model for 1000 out of 1000 iterations. Recoverable biomass with the GIS model was also less than with the random model for 1000 out of 1000 iterations for Washington at a cell exclusion rate of 18.75%.

If the exact proportion of land covered in watercourses was known for Oregon, the test of R/WMZ GIS modeling versus random area exclusion could tell us whether spatially-explicit modeling of riparian and wetland management zones has a significant effect on estimates of recoverable biomass beyond chance in harvestable age PI forests in the project area. However, because it’s uncertain how much of the buffered area is really covered in water, it’s not possible to compare equal exclusion areas. In Oregon, the results of the random permutation test reversed dramatically when the estimated watercourse proportional area was factored in. In Washington, if it’s correct that 0.75% or less of the land is covered by watercourses, the results would indicate that spatially-explicit modeling of R/WMZ’s results in a greater reduction in estimated recoverable
biomass than random selection of the same amount of area. Considering the effect of R/WMZ's on recoverable biomass is something that has been neglected in many of the biomass assessments that we reviewed and is a subject that may warrant further investigation.

Table 4.7. Recoverable biomass (BDT) from PI forests without accounting for riparian and wetland management zone restrictions. Data are for the ten years centered on the inventory period, for 6 residue criteria.

<table>
<thead>
<tr>
<th>County</th>
<th>AS</th>
<th>MLNMS</th>
<th>MS</th>
<th>AS-NF4</th>
<th>MLNMS-NF4</th>
<th>MS-NF4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benton, OR</td>
<td>65,206</td>
<td>61,341</td>
<td>41,677</td>
<td>56,932</td>
<td>53,270</td>
<td>34,276</td>
</tr>
<tr>
<td>Clackamas, OR</td>
<td>457,284</td>
<td>431,780</td>
<td>301,329</td>
<td>403,130</td>
<td>379,451</td>
<td>251,171</td>
</tr>
<tr>
<td>Clatsop, OR</td>
<td>1,293,155</td>
<td>1,232,834</td>
<td>1,182,545</td>
<td>1,117,840</td>
<td>1,057,551</td>
<td>968,990</td>
</tr>
<tr>
<td>Columbia, OR</td>
<td>453,216</td>
<td>429,989</td>
<td>353,109</td>
<td>388,872</td>
<td>366,003</td>
<td>288,441</td>
</tr>
<tr>
<td>Lincoln, OR</td>
<td>574,740</td>
<td>540,318</td>
<td>430,639</td>
<td>493,659</td>
<td>459,396</td>
<td>355,602</td>
</tr>
<tr>
<td>Linn, OR</td>
<td>1,025,868</td>
<td>969,613</td>
<td>748,219</td>
<td>890,390</td>
<td>836,151</td>
<td>623,852</td>
</tr>
<tr>
<td>Marion, OR</td>
<td>188,443</td>
<td>176,173</td>
<td>135,453</td>
<td>163,419</td>
<td>151,310</td>
<td>115,262</td>
</tr>
<tr>
<td>Multnomah, OR</td>
<td>21,276</td>
<td>20,165</td>
<td>14,534</td>
<td>18,640</td>
<td>17,605</td>
<td>12,092</td>
</tr>
<tr>
<td>Polk, OR</td>
<td>408,872</td>
<td>385,884</td>
<td>301,351</td>
<td>351,163</td>
<td>328,539</td>
<td>247,164</td>
</tr>
<tr>
<td>Tillamook, OR</td>
<td>471,099</td>
<td>445,945</td>
<td>392,815</td>
<td>406,234</td>
<td>381,119</td>
<td>322,684</td>
</tr>
<tr>
<td>Washington, OR</td>
<td>182,749</td>
<td>173,303</td>
<td>133,364</td>
<td>157,277</td>
<td>148,138</td>
<td>108,444</td>
</tr>
<tr>
<td>Yamhill, OR</td>
<td>291,361</td>
<td>275,920</td>
<td>217,686</td>
<td>250,218</td>
<td>235,104</td>
<td>177,652</td>
</tr>
<tr>
<td>Clark, WA</td>
<td>162,530</td>
<td>162,433</td>
<td>59,527</td>
<td>148,801</td>
<td>147,523</td>
<td>48,165</td>
</tr>
<tr>
<td>Cowlitz, WA</td>
<td>2,078,956</td>
<td>2,042,864</td>
<td>1,749,569</td>
<td>1,741,323</td>
<td>1,702,012</td>
<td>1,425,776</td>
</tr>
<tr>
<td>Lewis, WA</td>
<td>956,399</td>
<td>944,361</td>
<td>792,461</td>
<td>803,643</td>
<td>789,896</td>
<td>645,323</td>
</tr>
<tr>
<td>Pacific, WA</td>
<td>1,456,808</td>
<td>1,388,483</td>
<td>1,365,731</td>
<td>1,192,959</td>
<td>1,124,612</td>
<td>1,122,756</td>
</tr>
<tr>
<td>Skamania, WA</td>
<td>191,204</td>
<td>190,181</td>
<td>168,231</td>
<td>159,032</td>
<td>157,800</td>
<td>136,481</td>
</tr>
<tr>
<td>Wahkiakum, WA</td>
<td>388,862</td>
<td>377,984</td>
<td>372,776</td>
<td>317,812</td>
<td>306,908</td>
<td>304,703</td>
</tr>
<tr>
<td>OR Total</td>
<td>5,433,269</td>
<td>5,143,265</td>
<td>4,252,721</td>
<td>4,697,774</td>
<td>4,413,637</td>
<td>3,505,630</td>
</tr>
<tr>
<td>WA Total</td>
<td>5,234,759</td>
<td>5,106,306</td>
<td>4,507,295</td>
<td>4,363,570</td>
<td>4,228,751</td>
<td>3,683,204</td>
</tr>
<tr>
<td>OR &amp; WA TOTAL</td>
<td>10,668,028</td>
<td>10,249,571</td>
<td>8,760,016</td>
<td>9,061,344</td>
<td>8,642,388</td>
<td>7,188,834</td>
</tr>
</tbody>
</table>
Table 4.8. Recoverable biomass (BDT) from PI forests using the GIS model to account for riparian and wetland management zones. Data are for the ten years centered on the inventory period, for 6 residue criteria.

<table>
<thead>
<tr>
<th>County, OR</th>
<th>AS</th>
<th>MLNMS</th>
<th>MS</th>
<th>AS-NF4</th>
<th>MLNMS-NF4</th>
<th>MS-NF4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benton, OR</td>
<td>61,248</td>
<td>57,620</td>
<td>39,428</td>
<td>53,422</td>
<td>50,535</td>
<td>32,583</td>
</tr>
<tr>
<td>Clackamas, OR</td>
<td>415,642</td>
<td>392,335</td>
<td>279,412</td>
<td>365,798</td>
<td>346,345</td>
<td>234,672</td>
</tr>
<tr>
<td>Clatsop, OR</td>
<td>1,181,552</td>
<td>1,126,703</td>
<td>1,086,141</td>
<td>1,020,921</td>
<td>968,806</td>
<td>889,753</td>
</tr>
<tr>
<td>Columbia, OR</td>
<td>423,333</td>
<td>401,719</td>
<td>332,520</td>
<td>362,770</td>
<td>342,051</td>
<td>271,655</td>
</tr>
<tr>
<td>Lincoln, OR</td>
<td>526,536</td>
<td>494,846</td>
<td>400,234</td>
<td>451,179</td>
<td>425,647</td>
<td>330,247</td>
</tr>
<tr>
<td>Linn, OR</td>
<td>957,805</td>
<td>905,140</td>
<td>703,834</td>
<td>830,510</td>
<td>783,476</td>
<td>588,838</td>
</tr>
<tr>
<td>Marion, OR</td>
<td>173,481</td>
<td>162,062</td>
<td>127,413</td>
<td>150,021</td>
<td>141,461</td>
<td>108,564</td>
</tr>
<tr>
<td>Multnomah, OR</td>
<td>19,618</td>
<td>18,594</td>
<td>13,516</td>
<td>17,179</td>
<td>16,224</td>
<td>11,328</td>
</tr>
<tr>
<td>Polk, OR</td>
<td>359,057</td>
<td>339,013</td>
<td>267,174</td>
<td>307,939</td>
<td>290,360</td>
<td>219,105</td>
</tr>
<tr>
<td>Tillamook, OR</td>
<td>410,383</td>
<td>388,543</td>
<td>346,482</td>
<td>353,403</td>
<td>334,374</td>
<td>284,485</td>
</tr>
<tr>
<td>Washington, OR</td>
<td>170,030</td>
<td>161,267</td>
<td>124,165</td>
<td>146,321</td>
<td>138,026</td>
<td>101,220</td>
</tr>
<tr>
<td>Yamhill, OR</td>
<td>264,082</td>
<td>250,147</td>
<td>199,411</td>
<td>226,426</td>
<td>213,485</td>
<td>162,862</td>
</tr>
<tr>
<td>Clark, WA</td>
<td>150,317</td>
<td>150,232</td>
<td>51,978</td>
<td>137,100</td>
<td>137,012</td>
<td>41,860</td>
</tr>
<tr>
<td>Cowlitz, WA</td>
<td>1,705,608</td>
<td>1,677,916</td>
<td>1,464,074</td>
<td>1,427,703</td>
<td>1,393,113</td>
<td>1,192,573</td>
</tr>
<tr>
<td>Lewis, WA</td>
<td>731,682</td>
<td>723,879</td>
<td>616,057</td>
<td>613,269</td>
<td>603,912</td>
<td>500,979</td>
</tr>
<tr>
<td>Pacific, WA</td>
<td>1,089,342</td>
<td>1,038,595</td>
<td>1,021,111</td>
<td>907,374</td>
<td>840,538</td>
<td>839,188</td>
</tr>
<tr>
<td>Skamania, WA</td>
<td>168,015</td>
<td>167,125</td>
<td>146,509</td>
<td>139,762</td>
<td>138,868</td>
<td>118,821</td>
</tr>
<tr>
<td>Wahkiakum, WA</td>
<td>291,605</td>
<td>283,434</td>
<td>279,666</td>
<td>240,456</td>
<td>229,954</td>
<td>228,562</td>
</tr>
<tr>
<td>OR Total</td>
<td>4,962,767</td>
<td>4,697,989</td>
<td>3,919,730</td>
<td>4,285,889</td>
<td>4,050,790</td>
<td>3,235,312</td>
</tr>
<tr>
<td>WA Total</td>
<td>4,136,569</td>
<td>4,041,181</td>
<td>3,579,395</td>
<td>3,465,664</td>
<td>3,343,397</td>
<td>2,921,983</td>
</tr>
<tr>
<td>OR &amp; WA TOTAL</td>
<td>9,099,336</td>
<td>8,739,170</td>
<td>7,499,125</td>
<td>7,751,553</td>
<td>7,394,187</td>
<td>6,157,295</td>
</tr>
</tbody>
</table>
Table 4.9. Recoverable biomass (BDT) from PI forests, subtracting 7.35% from the total in Oregon and 18.75% in Washington to account for riparian and wetland management zones. Data are for the ten years centered on the inventory period, for 6 residue criteria.

<table>
<thead>
<tr>
<th>County</th>
<th>AS</th>
<th>MLNMS</th>
<th>MS</th>
<th>AS-NF4</th>
<th>MLNMS-NF4</th>
<th>MS-NF4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benton, OR</td>
<td>60,413</td>
<td>56,832</td>
<td>38,614</td>
<td>52,747</td>
<td>49,355</td>
<td>31,757</td>
</tr>
<tr>
<td>Clackamas, OR</td>
<td>423,674</td>
<td>400,044</td>
<td>279,181</td>
<td>373,500</td>
<td>351,561</td>
<td>232,710</td>
</tr>
<tr>
<td>Clatsop, OR</td>
<td>1,198,108</td>
<td>1,142,221</td>
<td>1,095,628</td>
<td>1,035,679</td>
<td>979,821</td>
<td>897,769</td>
</tr>
<tr>
<td>Columbia, OR</td>
<td>419,905</td>
<td>398,385</td>
<td>327,155</td>
<td>360,290</td>
<td>339,102</td>
<td>267,241</td>
</tr>
<tr>
<td>Lincoln, OR</td>
<td>532,497</td>
<td>500,605</td>
<td>398,987</td>
<td>457,375</td>
<td>425,630</td>
<td>329,465</td>
</tr>
<tr>
<td>Linn, OR</td>
<td>950,467</td>
<td>898,346</td>
<td>693,225</td>
<td>824,946</td>
<td>774,694</td>
<td>577,999</td>
</tr>
<tr>
<td>Marion, OR</td>
<td>174,592</td>
<td>163,224</td>
<td>125,497</td>
<td>151,408</td>
<td>140,189</td>
<td>106,790</td>
</tr>
<tr>
<td>Multnomah, OR</td>
<td>19,712</td>
<td>18,683</td>
<td>13,466</td>
<td>17,270</td>
<td>16,311</td>
<td>11,203</td>
</tr>
<tr>
<td>Polk, OR</td>
<td>378,820</td>
<td>357,522</td>
<td>279,202</td>
<td>325,353</td>
<td>304,391</td>
<td>228,997</td>
</tr>
<tr>
<td>Tillamook, OR</td>
<td>436,473</td>
<td>413,168</td>
<td>363,943</td>
<td>376,376</td>
<td>353,107</td>
<td>298,967</td>
</tr>
<tr>
<td>Washington, OR</td>
<td>169,317</td>
<td>160,565</td>
<td>123,562</td>
<td>145,717</td>
<td>137,250</td>
<td>100,473</td>
</tr>
<tr>
<td>Yamhill, OR</td>
<td>269,946</td>
<td>255,640</td>
<td>201,686</td>
<td>231,827</td>
<td>217,824</td>
<td>164,595</td>
</tr>
<tr>
<td>Clark, WA</td>
<td>132,056</td>
<td>131,977</td>
<td>48,366</td>
<td>120,901</td>
<td>119,862</td>
<td>39,134</td>
</tr>
<tr>
<td>Cowlitz, WA</td>
<td>1,689,152</td>
<td>1,659,827</td>
<td>1,420,712</td>
<td>1,414,825</td>
<td>1,382,885</td>
<td>1,158,443</td>
</tr>
<tr>
<td>Lewis, WA</td>
<td>777,074</td>
<td>767,293</td>
<td>643,875</td>
<td>652,960</td>
<td>641,791</td>
<td>524,325</td>
</tr>
<tr>
<td>Pacific, WA</td>
<td>1,183,657</td>
<td>1,128,142</td>
<td>1,109,656</td>
<td>969,279</td>
<td>913,747</td>
<td>912,239</td>
</tr>
<tr>
<td>Skamania, WA</td>
<td>155,353</td>
<td>154,522</td>
<td>136,688</td>
<td>129,214</td>
<td>128,213</td>
<td>110,891</td>
</tr>
<tr>
<td>Wahkiakum, WA</td>
<td>315,950</td>
<td>307,112</td>
<td>302,881</td>
<td>258,222</td>
<td>249,363</td>
<td>247,571</td>
</tr>
<tr>
<td>OR Total</td>
<td>5,033,924</td>
<td>4,765,235</td>
<td>3,940,146</td>
<td>4,352,488</td>
<td>4,089,235</td>
<td>3,247,966</td>
</tr>
<tr>
<td>WA Total</td>
<td>4,253,242</td>
<td>4,148,874</td>
<td>3,662,177</td>
<td>3,545,401</td>
<td>3,435,860</td>
<td>2,992,603</td>
</tr>
<tr>
<td>OR &amp; WA TOTAL</td>
<td>9,287,165</td>
<td>8,914,109</td>
<td>7,602,323</td>
<td>7,897,888</td>
<td>7,525,095</td>
<td>6,240,569</td>
</tr>
</tbody>
</table>
4.6 Allometric Equation and Imputation Error and Uncertainty

The average of 1170 predictions from the allometric equation uncertainty simulation for recoverable residues from merchantable trees excluding foliage on private industrial forests in the ten years (1998-2007) centered on the inventory period was 6,412,049 BDT (95% PI: 6,411,936, 6,412,156). The values ranged from a low of 6,411,846 BDT to a high of 6,412,238 BDT. We calculated a point estimate of 6,437,632 BDT for these residues. For the rough range estimate for these residues we used a low BDT/MBF ratio of 0.51 and a high BDT/MBF ratio of 1.1 (from the OR PSME and WA Hemlock species-BA groups, respectively). The lower limit for our 12 county range was 5,370,230 BDT and the upper limit for the 18 county range was 21,246,153 BDT. The point estimates, range estimates, and uncertainty simulation averages, medians and prediction intervals are displayed in Table 4.10.

Table 4.10. Point estimates, range estimates, and allometric equation uncertainty simulation averages, medians and prediction intervals of recoverable biomass (BDT) from PI forests in the project area during the ten years centered on the inventory period (1998-2007). Data are for the three residue criteria without foliage.

<table>
<thead>
<tr>
<th></th>
<th>MS-NF</th>
<th>MLNMS-NF</th>
<th>AS-NF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Estimate</td>
<td>6,437,632</td>
<td>7,548,172</td>
<td>8,073,256</td>
</tr>
<tr>
<td>Range Est.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 cnty</td>
<td>5,370,230 - 11,582,849</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18 cnty</td>
<td>9,850,489 - 21,246,153</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AU Model</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>6,412,049</td>
<td>7,521,738</td>
<td>8,044,723</td>
</tr>
<tr>
<td>Median</td>
<td>6,412,051</td>
<td>7,521,739</td>
<td>8,044,723</td>
</tr>
<tr>
<td>95% PI</td>
<td>6,411,936</td>
<td>7,521,623</td>
<td>8,044,608</td>
</tr>
<tr>
<td></td>
<td>6,412,156</td>
<td>7,521,855</td>
<td>8,044,836</td>
</tr>
</tbody>
</table>
5 Discussion

A few of the reviewed biomass assessments and studies had residue rates for timber harvests, and these can be used as a check to see how reasonable our calculated rates are. The average recoverable residue rates for our species-basal area groups are displayed in Tables 4.3 and 4.4. In Oneil and Lippke’s (2009) Eastern Washington Biomass Accessibility report, the combined quantity of dispersed residues greater than 5 inches in diameter and piled residues was 16 BDT/Ac in Douglas-fir stands and 42 BDT/Ac in mixed conifer. At a 70% recovery rate, these would yield 11.2 and 29.4 BDT/Ac, respectively. It is unclear if foliage was included. These residue criteria correspond most closely with the our combined merchantable and large non-merchantable residue class (MLNMS), which ranged from 15.8 to 20.9 BDT/Ac for the Douglas-fir group, from 14.4 to 29.2 for the low and high basal area Commercial Mix groups. Howard’s (1990) study of five western states found average wood and bark residue generation rates for clearcuts on private land were 0.53 BDT/MBF in western OR and 0.47 BDT/MBF in western WA. Caution should be used when comparing his BDT/MBF rates with those from present day research because the data for his paper was collected from 1979-1981 when average harvested tree diameter was larger. Over the last three decades, the ratio of MBF per ft$^3$ of stem wood in Oregon and Washington has decreased approximately 20-25% (Keegan and others 2010). Larger trees have a lower proportion of foliage and branches to bole wood. These two factors result in lower BDT/MBF ratios for older studies. Increasing Howard’s numbers 25% to account for the difference in MBF per ft$^3$ of stem wood and multiplying by a 70% residue recovery rate, they would be 0.464 BDT/MBF in western OR and 0.411 BDT/MBF in western WA. These rates are close to our Douglas-fir group’s rate. The Hood River County biomass
report (PES and MB&G 2007) estimated that residue production from timber harvests averaged 1.2 BDT/MBF, based on calculations made using FIA data for their study area. It is unclear from the report which log scale MBF was measured in. If they used short log scale, their MBF measurements used to calculate BDT/MBF would be approximately 20% greater than if they were measured in long log scale, which is the standard in the project area. Since this rate appears not to factor in the proportion of biomass lost during the recovery process their residue production rate, after adjustment for 70% residue recovery, would equal 0.84 BDT/MBF if MBF was measured in long log scale and 1.01 BDT/MBF if it was measured in short log scale. Although their report doesn’t specify exactly what materials they counted in their residue measurements, these two residue to merchantable material ratios are comparable to our calculations for private industrial forests of harvestable age. Because the average harvest residue rates for our forest groups were comparable to the published rates from other studies, we concluded that they were reasonable estimates for the project area. Table 5.1 lists a number of published harvest residue to harvested timber ratios, adjusted for recovery rate and current conditions as necessary, as well as the ranges of averages for our PSME and Hemlocks species-BA groups.

Table 5.1. Comparison of recoverable residue to harvested timber ratios. Adjusted for similar conditions and 70% residue recovery.

<table>
<thead>
<tr>
<th>Source</th>
<th>BDT/MBF</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Howard 1990</td>
<td>0.41</td>
<td>W. WA clearcuts on private land</td>
</tr>
<tr>
<td>Howard 1990</td>
<td>0.46</td>
<td>W. OR clearcuts on private land</td>
</tr>
<tr>
<td>Lord 2009</td>
<td>0.5 - 0.9</td>
<td>Willamette Valley, OR</td>
</tr>
<tr>
<td>Lord 2009</td>
<td>0.8 - 1.5</td>
<td>Coast Range, OR</td>
</tr>
<tr>
<td>McNeil Tech 2003</td>
<td>0.59 - 0.74</td>
<td>NE OR, from 2.1 GT/MBF at 40% and 50% MC</td>
</tr>
<tr>
<td>PES and MB&amp;G 2007</td>
<td>0.84 – 1.01</td>
<td>Hood River County, OR and surrounding area</td>
</tr>
<tr>
<td>Our project area</td>
<td>0.51 - 0.75</td>
<td>PSME, MS &amp; MS_NF for NW OR, SE WA</td>
</tr>
<tr>
<td>Our project area</td>
<td>1.08 - 1.32</td>
<td>Hemlocks, MS &amp; MS_NF for NW OR, SE WA</td>
</tr>
</tbody>
</table>
Because of the various methods, assumptions and sources of data used, a number of factors could have contributed to the uncertainty and potential error of our recoverable biomass estimate. We have attempted to estimate the uncertainty caused by the use of allometric regression equations with the uncertainty model discussed earlier. The difference between the point estimate and the average of the simulation outputs was 25,583 BDT, or 0.4% of the point estimate, for recoverable merchantable tree residues excluding foliage from private industrial forests for the 10 years centered on the inventory period. The point estimate was higher than the upper limit of the 95% prediction interval from the simulation as well as the maximum value from the 1170 iterations of the simulation. The range of the 1170 simulation outputs was only 392 BDT and the lower limit of the prediction interval was only 220 BDT less than the upper limit. The simulation results show that the use of allometric regression equations for predicting biomass in the forest plots contributes an insignificant amount of uncertainty to the final estimate of recoverable harvesting residues. Although the point estimate of recoverable residues differed significantly from simulation outputs relative to their range, this difference is minor relative to the actual values of the point estimate and simulation average (0.4%). The simulation outputs were expected to be centered around the point estimate. This minor discrepancy could be the result of a bug in the simulation code or differences in how the programs used for the point estimate and the simulation perform some of the intermediate calculations (of which there where thousands) necessary to produce an estimate.

This point estimate falls in the low end of the “ballpark” range estimate generated by applying the lowest and highest average BDT/MBF ratios from the species-BA groups to
the county timber harvest levels for 12 counties. It is 35% below the lower limit of the range estimate for 18 counties. Although the range estimate is a rough estimate, one of its strengths is that it required only two inputs, harvest levels and residue to harvest ratios. The harvest levels used for 9 of the 10 years were records, while only 1 of the 10 was a projection, so it is unlikely that the total for the ten years was substantially off. Both of the BDT/MBF ratios used in the range estimate were consistent with the range of published values. Because of this, the range estimates are quite credible for the two regions they each describe (12 and 18 counties) even though they are wide ranges. Because over 60% of the forests in the project area were Douglas-fir dominated (the source of our low BDT/MBF number for the range estimate) and only 22% were Hemlock dominated (the source of the high number), the true value of recoverable harvesting residues in the project area is more likely in the lower half of the range estimate than the upper half. Based on the simulation outputs and the range estimates, we conclude that the point estimate for recoverable residues from private industrial forests in the 10 years centered on the inventory period is reasonably close to the actual value.

Another source of uncertainty in the biomass estimate is the use of imputed vegetation data. Originally, we had intended to combine imputation uncertainty with the simulation for allometric equations uncertainty but due to time constraints we were unable to finish programming the imputation section. The planned imputation part of the simulation would make use of a prediction accuracy matrix like the one published in Ohmann and Gregory (2002). For the 823 inventory plots they used in their imputation equation classified each plot into one of ten vegetation classes. They then compared the vegetation class of the second nearest neighbor from the GNN algorithm for each of the
sample plots with the actual vegetation class and recorded the number of times plots in
each observed vegetation class were imputed to each predicted vegetation class. The
simulation would also make use the 1000 predictions of plot biomass for each FCID
found on private industrial forest land from the allometric equation uncertainty simulation,
a list of the dominant age and vegetation class for each of those FCID’s and the raster of
imputed FCID’s for all private industrial forest lands. For each cell in the raster the FCID
would be read and matched to its vegetation class. The number of cells in each
vegetation class would be recorded for the raster. Then for each iteration of the
simulation, for each vegetation class a new biomass value would be drawn for every cell
in that vegetation class and added to the grand total of recoverable biomass. The new
biomass value would be drawn by randomly selecting a new vegetation class from the
probability distribution described by the prediction accuracy matrix, then randomly
selecting an FCID from all the FCID’s that belong to that vegetation class and are found
on private industrial forests. If this new FCID has a dominant stand age value in the
harvestable age range, randomly select one of the 1000 biomass predictions for that
FCID and adjust it by the residue recovery rate to get the new cell biomass value. If the
FCID has a dominant stand age outside of the harvestable age range, the new cell
biomass value is zero. Once new biomass values have been chosen for all cells in all
vegetation classes in the raster and added to the grand total of recoverable biomass,
this total will be written to an output file and the next iteration will begin or the program
will end if there are no more iterations to run. After a sufficiently large number of
iterations, the distribution of predictions in the output file can be used to quantify the
uncertainty in the recoverable biomass total from use of allometric equations and
imputated vegetation data. Because the prediction accuracy matrix in Ohmann and
Gregory (2002) wasn’t designed for biomass estimation purposes this could limit the quality of results from this proposed simulation. The utility of this proposed simulation could be limited by how well the different vegetation classes predict quantity of harvesting residue. The concept may still be worth exploring.

Although we addressed the riparian and wetland management zones’ impact on availability of forest residues more thoroughly than most of the biomass assessments we reviewed, it is unclear how accurate our attempts were. It’s possible that the improvement in estimate accuracy resulting from construction and implementation of the R/WMZ GIS model was too small to justify the time and effort involved. The comparison of recoverable residues from Washington private industrial forests when using the GIS model of R/WMZ’s to recoverable residues when excluding the same area amount of restricted area in randomly selected cells indicates GIS modeling of R/WMZ’s in that area may have a significant effect on recoverable residues beyond that of chance, but the results are inconclusive due to various assumptions that had to be made. Further research into the effects of riparian and wetland harvesting restrictions on biomass availability could provide more information on the most efficient ways to account for their effects in future assessments.

The error caused by the methods used to represent growth is unknown. Because of time constraints we had to come up with a quick and simple way to account for growth, and the method that was used took shape along the way. The process of separating plots into different groups by species composition and basal area and projecting biomass calculations from older stands onto younger stands for the private industrial forests
turned out to be awkward and cumbersome to work with when conducting some of the analysis and error estimation work later. In the future, a reliable growth model should be used on private industrial forests to reduce the uncertainty and potential error in the estimate and make further analyses easier. On ODF forests another method was used to try and account for growth because the method used for forecasting on private industrial forests couldn’t be applied because of uncertainty regarding what selection process would be used for partial cut harvests. After the primary analyses for this thesis were completed, we discovered that the ODF plans already accounted for growth. This likely resulted in some overestimation of recoverable residues from ODF forests. Because ODF land was a small contributor to the recoverable biomass total, and the forecast period was only 12 years after the inventory period, it is unlikely that this significantly diminished the accuracy of the assessment.

Stand age was used to estimate when a stand would be harvested by the forest industry in northwest Oregon and southwest Washington. Using a target harvest age of 40-50 years for the forecast period (2010-2019), stands between 28 and 37 years in the inventory period would be the target stands for harvest. Although the GNN imputation method used by LEMMA was not specifically developed to predict age, review by three industrial landowners suggested the age class distribution for ages 30-50 years was reasonable. The procedure we used would not be appropriate on forests under uneven-aged management.

Recovery and breakage/defect rates have a profound effect on recoverable biomass levels, affecting the estimate of residue for every tree in each of the six residue criteria,
but little research has been done on these. The breakage and defect rate we used was based on estimates provided by three of the major private industrial landowners in the area. It's unclear whether these estimates were calculated from records and measurements of breakage rate or are simply best guesses based on professional experience. The recovery rate came from a few published estimates and one study, but the amount of supporting research is limited. We assumed that almost all private industrial harvesting operations in the project area will use whole-tree yarding which delivers most of the residues to the landing where they are easier to recover. In western Oregon and Washington, where whole-tree yarding is very common, this is a reasonable assumption. The recovery rate used in this thesis may not be appropriate for assessments focusing on regions or owner groups where other harvesting methods are more common. As more biomass assessments are commissioned and forest biomass energy facilities are built, accurate information about these factors will be necessary to perform high quality assessments.

Many of the numbers used in calculations of the BDT/MBF rates were approximations of common values for the area, such as the green tons per log truck, MBF per log truck, moisture content (the same one was used for all species), etc. These weren’t used in calculating the numbers in the recoverable biomass raster or totals. They were only used for calculating the estimates of average BDT/MBF for the different forest groups, so their accuracy is less important than residue recovery or breakage and defect rates.

In hindsight, it may have been advantageous to implement a minimum biomass areal density for inclusion to reflect the fact that if a logging unit generates a low volume of fuel
biomass, recovery equipment move-in costs may drive marginal biomass cost too high to justify recovery. A minimum site productivity limit, like those used by the USDA FS (2005), Lord and others (2006), and PES and MB&G (2007), could be useful in future assessments. For example, some areas in the Non-Commercial species-basal area group had very low merchantable timber per acre. If these areas had the potential to be productive timberland and they were owned by commercial timber companies, they would likely be cut eventually to be replanted with commercial species but it’s possible that the cost of bringing in yarding and other biomass recovery equipment would be too high and the owners may elect to pile and burn these units instead. Because the Non-Commercial forest group accounted for only 2.5% of Private Industrial forests in the project area (Table 4.6), this issue didn’t significantly affect the estimate of recoverable residues for this project.

Spatially-explicit biomass assessments can aid in determining detailed transportation costs to different locations and for different scenarios. However, like Ohmann and Gregory (2002) stated about their imputation map, care must be taken to ensure that others who use the assessment aren’t led to believe that it has greater precision than it actually does due to the high resolution. Because the GNN imputation method can be applied anywhere with samples of georeferenced inventory plots representative of the diversity of forest cover and GIS maps of environmental variables and remotely sensed data, this general method of biomass assessment is also applicable outside of LEMMA project areas. Ohmann and Gregory (2002) also note that the GNN process can be modified to improve prediction of particular environmental variables of interest, as Wimberly and others (2003) demonstrated with wildfire fuel modeling. Customizing the
GNN algorithm for fuel biomass and possibly stand age prediction could improve the potential utility of imputed vegetation maps in biomass assessment. Future research should also focus on biomass recovery rates. Measuring average recovery rates for different biomass components and how these vary between harvesting systems and site characteristics could improve biomass assessment methods. Developing methods for quantifying error and uncertainty in biomass assessments could also improve future assessments.
6 Conclusion

Accurate and detailed biomass assessments are important for the development of bioenergy. Better biomass assessments will improve the chances for new biomass energy facilities to be successful and profitable and as more of these projects are completed successfully, investors will be more willing to invest in similar projects elsewhere. Considering factors that affect accessibility and recovery of woody biomass, not just the quantity of material physically present in an assessment area, is critical to conducting an accurate and useful biomass assessment. Such factors include legal restrictions on access and cutting in riparian and wetland management zones, Wilderness and designated Roadless Areas, management intentions of landowners with regard to if and when their lands will be harvested, and harvesting systems used in the area and how that affects recovery rate and costs. Even in areas with sufficient potential supply, the costs of recovery, transport, processing and conversion of biomass are near the price biomass facilities receive for the energy produced and the profit margins for biomass suppliers and consumers are tight. In order for biomass energy to be economically viable efficiency of the supply chain needs to be maximized. Incorporating greater spatial detail in biomass assessments allows planners to determine optimal facility locations and fuel sourcing patterns before facilities are built. This can help developers to invest in projects and areas that are most likely to be successful and profitable.

We estimated the spatial distribution and availability of forest harvesting residues on ODF and industrial forest lands in northwest Oregon and southwest Washington. We included models of riparian and wetland management zones in our recoverable biomass
estimates and examined their effects on total recoverable residue biomass. Depending on the proportion of the area in these zones, they may have a significant effect on available biomass, roughly equivalent to the percentage of land in such zones. Our calculations of recoverable biomass to merchantable timber ratios were comparable with a number of other ratios from studies done in the Pacific Northwest. Our estimate of total recoverable biomass from private industrial forests during the inventory period was in the low end of the approximate range calculated from harvest records and our BDT/MBF ratios for the area. This was expected, as most of the forests in the area had BDT/MBF ratios similar to the one used for the lower bound of the range estimate. We developed a computer simulation to attempt to quantify the error and uncertainty in our biomass estimate resulting from use of allometric equations. The simulation outputs had a small variance and an average that was only 0.4% below our estimate of total recoverable biomass. These results indicate that our estimate was reasonable and that use of allometric equations was probably an insignificant source of error in our estimate. The comparison of our biomass estimate for the inventory period with the calculations from harvest records lend support to our estimates for the forecast period, which used similar methods, although it’s uncertain how accurately we accounted for the effects of growth from the inventory period to the forecast period. Due to time constraints we calculated average biomass densities for different forest types in stands that were of harvestable age during the inventory period and projected those values onto those forest types in stands that would be harvestable age during the forecast period (2010-2019). We suggest future assessments use growth and yield models to reduce this source of variability.
Howard (1990) noted that current published biomass assessments lacked the “depth and precision” necessary to effectively manage the regional biomass resource. The spatial detail of our recoverable biomass estimate adds some of that depth. The GNN imputation method used by LEMMA to create the predicted vegetation map we used can be applied to other areas with appropriate georeferenced inventory plots and GIS maps of the appropriate environmental characteristics. The GNN method has the potential to be tailored to predict specific variables, like dominant forest age and residue biomass density, with greater precision (Ohmann and Gregory 2002). Developing an effective means of assessing the error in recoverable biomass estimates, combined with enhancement of the precision of the GNN imputed maps for forest biomass estimating purposes would allow more accurate analysis of available supply, transportation and siting options, and operating cost for potential woody biomass projects. With more accurate and precise information and better decision tools, more people will be willing to invest and cooperate in biomass energy projects, capital may be available at lower interest rates, and biomass projects that are constructed are more likely to be successful.
References


APPENDICES
Appendix A - Allometric equations and and biomass database calculations

Allometric equations

Format:
Species or Species Group (sorted alphabetically) –
Tree component /  Equation   /  Terms   / Source

Commercial Species

**Abies amabilis** -
Foliage:  \[ Y = \exp(-4.5487 + 2.1926 \ln X) \]  
X:  Diam. at Breast Height (DBH) in cm.  [4,2]
Y:  Biomass (bone dry kg)

Live Branches:  \[ Y = \exp(-5.2370 + 2.6261 \ln X) \]  
“  

Stem Wood:  \[ Y = \exp(-3.5057 + 2.5744 \ln X) \]  
“  

Stem Bark:  \[ Y = \exp(-6.1166 + 2.8421 \ln X) \]  
“  

**Abies procera** –
Foliage:  \[ Y = \exp(-4.8728 + 2.1683 \ln X) \]  
X:  DBH (cm)  [4,2]
Y:  Biomass (bone dry kg)

Live Branches:  \[ Y = \exp(-4.1817 + 2.3324 \ln X) \]  
“  

Stem wood:  \[ Y = \exp(-3.7158 + 2.7592 \ln X) \]  
“  

Stem bark:  \[ Y = \exp(-6.1000 + 2.8943 \ln X) \]  
“  

**Abies spp. (pooled)** –
Foliage:  \[ Y = \exp(-3.4662 + 1.9278 \ln X) \]  
X:  DBH (cm)  [4,2]
Y:  Biomass (bone dry kg)

Live Branches:  \[ Y = \exp(-4.8287 + 2.5585 \ln X) \]  
“  

Stem Wood:  \[ Y = \exp(-3.7389 + 2.6825 \ln X) \]  
“  

Stem Bark:  \[ Y = \exp(-6.1918 + 2.8796 \ln X) \]  
“  

**“Aspen/Alder/Cottonwood/Willow” group**
AGB:  \[ Y = \exp(-2.2094 + 2.3867 \ln X) \]  
X:  DBH (cm)  [5]
Y:  Biomass (bone dry kg)

**Alnus rubra** -
Foliage:  \[ M = 0.0100 \times D^{1.9398} \]  
D:  DBH (cm)  [14,15]
M:  Biomass (bone dry kg)

Branches:  \[ M = 0.0069 \times D^{2.6516} \]  
“  

[108]
**Chamaecyparis nootkatensis, Thuja plicata and Cedar (pooled)** –

Foliage: \[ Y = \exp(-2.617 + 1.7824 \ln X) \]  
X: DBH (cm) \[ [4,2] \]  
Y: Biomass (bone dry kg)  

Live Branches: \[ Y = \exp(-3.2661 + 2.0877 \ln X) \]  
"  
Stem Wood: \[ Y = \exp(-2.0927 + 2.1863 \ln X) \]  
"  
Stem Bark: \[ Y = \exp(-4.1934 + 2.1101 \ln X) \]  
"  

**Larix larcina** –

Foliage: \[ M = 0.0466 \times D^{1.7250} \]  
D: DBH (cm) \[ [16,15] \]  
M: Biomass (bone dry kg)  

Branches: \[ M = 0.0436 \times D^{1.9810} \]  
"  
Stem Wood and Bark: \[ M = 0.0762 \times D^{2.3051} \]  
"  

**Larix occidentallis** –

Foliage: \[ M = 0.1307 \times D^{1.0557} \]  
D: DBH (cm) \[ [3,15] \]  
M: Biomass (bone dry kg)  

Branches: \[ M = 0.1821 \times D^{1.2885} \]  
"  
Stem Wood and Bark: \[ M = 0.2942 \times D^{1.5593} \]  
"  

**Picea engelmannii** –

Foliage: \[ M = 0.3346 \times D^{1.2765} \]  
D: DBH (cm) \[ [3,15] \]  
M: Biomass (bone dry kg)  

Branches: \[ M = 0.1687 \times D^{1.5799} \]  
"  
Stem Wood and Bark: \[ M = 0.2844 \times D^{1.3782} \]  
"  

**Picea sitchensis** -

Foliage: \[ M = 0.0030 \times D^{2.7800} \]  
D: DBH (cm) \[ [1,15] \]  
M: Biomass (bone dry kg)  

Branches: \[ M = 0.0056 \times D^{2.5180} \]  
"  
Stem Wood and Bark: \[ M = 0.0402 \times D^{2.5520} \]  
"  

**Pinus contorta** -

Foliage: \[ Y = \exp(-3.6187 + 1.8362 \ln X) \]  
X: DBH (cm) \[ [4,2] \]  
Y: Biomass (bone dry kg)  

Live Branches: \[ Y = \exp(-4.6004 + 2.3533 \ln X) \]  
"  
Stem Wood plus Bark: \[ Y = \exp(-2.9849 + 2.4287 \ln X) \]  
"
**Pinus lambertiana** –
Foliage: \[ Y = \exp(-4.0230 + 2.0327 \ln X) \]  \( X: \) DBH (cm)  \[4,2\]
Live Branches: \[ Y = \exp(-7.637 + 3.3648 \ln X) \]  \( Y: \) Biomass (bone dry kg)
Stem Wood: \[ Y = \exp(-3.984 + 2.6667 \ln X) \]  \( " \)[4,2]
Stem Bark: \[ Y = \exp(-5.295 + 2.6184 \ln X) \]  \( " \)[4,2]

**Pinus ponderosa** –
Foliage: \[ Y = \exp(-4.2612 + 2.0967 \ln X) \]  \( X: \) DBH (cm)  \[4,2\]
Live Branches: \[ Y = \exp(-5.3855 + 2.7185 \ln X) \]  \( Y: \) Biomass (bone dry kg)
Dead Branches: \[ Y = \exp(-2.5766 + 1.444 \ln X) \]  \( " \)[4,2]
Stem Wood: \[ Y = \exp(-4.4907 + 2.7587 \ln X) \]  \( " \)[4,2]
Stem Bark: \[ Y = \exp(-4.2063 + 2.2312 \ln X) \]  \( " \)[4,2]

**Pines (pooled)** –
Foliage: \[ Y = \exp(-3.9739 + 2.0039 \ln X) \]  \( X: \) DBH (cm)  \[4,2\]
Live Branches: \[ Y = \exp(-5.2900 + 2.6524 \ln X) \]  \( Y: \) Biomass (bone dry kg)
Dead Branches: \[ Y = \exp(-3.7969 + 1.7426 \ln X) \]  \( " \)[4,2]
Stem Wood: \[ Y = \exp(-4.2847 + 2.7180 \ln X) \]  \( " \)[4,2]
Stem Bark: \[ Y = \exp(-3.6187 + 1.8362 \ln X) \]  \( " \)[4,2]

**Pseudotsuga menziesii** –
Foliage: \[ Y = \exp(-2.8462 + 1.7009 \ln X) \]  \( X: \) DBH (cm)  \[4,2\]
Live Branches: \[ Y = \exp(-3.6941 + 2.1382 \ln X) \]  \( Y: \) Biomass (bone dry kg)
Dead Branches: \[ Y = \exp(-3.529 + 1.7503 \ln X) \]  \( " \)[4,2]
Stem Wood: \[ Y = \exp(-3.0396 + 2.5951 \ln X) \]  \( " \)[4,2]
Stem Bark: \[ Y = \exp(-4.3103 + 2.4300 \ln X) \]  \( " \)[4,2]

**Tsuga heterophylla** –
Foliage: \[ Y = \exp(-4.130 + 2.128 \ln X) \]  \( X: \) DBH (cm)  \[4,2\]
Live Branches: \[ Y = \exp(-5.149 + 2.778 \ln X) \]  \( Y: \) Biomass (bone dry kg)
Dead Branches: \[ Y = \exp(-2.409 + 1.312 \ln X) \]  \( " \)[4,2]
Stem Wood: \[ Y = \exp(-2.172 + 2.257 \ln X) \]  \( " \)[4,2]
Stem Bark: \[ Y = \exp(-4.373 + 2.258 \ln X) \]  \( " \)[4,2]
**Tsuga mertensiana**

<table>
<thead>
<tr>
<th>Component</th>
<th>Equation</th>
<th>X: DBH (cm)</th>
<th>Y: Biomass (bone dry kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foliage</td>
<td>$Y = \exp(-3.8169 + 1.9756 \ln X)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live Branches</td>
<td>$Y = \exp(-5.2581 + 2.6045 \ln X)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dead Branches</td>
<td>$Y = \exp(-9.9449 + 3.2845 \ln X)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem Wood</td>
<td>$Y = \exp(-4.8164 + 2.9308 \ln X)$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stem Bark</td>
<td>$Y = \exp(-5.5868 + 2.7654 \ln X)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Non-Commercial Species

*Acer macrophyllum* –
Foliage: \[ Y = \exp(-3.765 + 1.617 \ln X) \]  
X: DBH (cm) \[ [4,2]\]  
Y: Biomass (bone dry kg)  
Live Branches: \[ Y = \exp(-4.236 + 2.430 \ln X) \]  
" \[ [4,2]\]  
Dead Branches: \[ Y = \exp(-2.116 + 1.092 \ln X) \]  
" \[ [4,2]\]  
Stem Wood: \[ Y = \exp(-3.493 + 2.723 \ln X) \]  
" \[ [4,2]\]  
Stem Bark: \[ Y = \exp(-4.574 + 2.574 \ln X) \]  
" \[ [4,2]\]

*Arbutus menziesii* –
*This equation excludes foliage.*  
AGB: \[ TVOL = 0.0000821921 * D^1.96628 * H^{0.83458} \]  
D: DBH (cm) \[ [10]\]  
H: Height (m)  
TVOL: Total wood and bark volume (m$^3$)  
SG12: 0.61  
Converted to SGg: 0.56  
Wood Density: 560 Bone dry kg/Green m$^3$

“Aspen/Alder/Cottonwood/Willow” group
AGB: \[ Y = \exp(-2.2094 + 2.3867 \ln X) \]  
X: DBH (cm) \[ [6]\]  
Y: Biomass (bone dry kg)

*Betula papyrifera* –
AGB: \[ M = 0.0882 * D^{2.5620} \]  
D: DBH (cm) \[ [12,13]\]  
M: Biomass (bone dry kg)

*Chrysolepis chrysophylla* –
Foliage: \[ Y = \exp(-3.123 + 1.693 \ln X) \]  
X: DBH (cm) \[ [4,2]\]  
Y: Biomass (bone dry kg)  
Live Branches: \[ Y = \exp(-4.579 + 2.576 \ln X) \]  
" \[ [4,2]\]  
Dead Branches: \[ Y = \exp(-7.124 + 2.883 \ln X) \]  
" \[ [4,2]\]  
Stem Wood: \[ Y = \exp(-3.708 + 2.658 \ln X) \]  
" \[ [4,2]\]  
Stem Bark: \[ Y = \exp(-5.923 + 2.989 \ln X) \]  
" \[ [4,2]\]

*Juniperus occidentalis* –
Foliage: \[ M = 0.0144 * D^{1.5606} \]  
D: DBH (cm) \[ [4,2]\]  
M: Biomass (bone dry kg)  
Branches: \[ M = 0.0007 * D^{2.3337} \]  
" \[ [4,2]\]  
Stem Wood: \[ M = 0.0002 * D^{2.6389} \]  
" \[ [4,2]\]  
Stem Bark: \[ M = 0.00004 * D^{2.6333} \]  
" \[ [4,2]\]
**Lithocarpus densiflorus** –
*This equation excludes foliage.*
AGB:
\[ TVOL = 0.0000763045 \times D^{1.94165} \times H^{0.86562} \]

D: DBH (cm)  
H: Height (m)  
TVOL: Total wood and bark volume (m³)

SGg: 0.58  
Wood Density: 580 Bone dry kg/Green m³

**“Mixed hardwood” group** –

AGB:
\[ Y = \exp(-2.4800 + 2.4835 \ln X) \]

X: DBH (cm)  
Y: Biomass (bone dry kg)

**Populus baslamifera (>10 cm DBH)** –

AGB:
\[ W2 = -64.76640 + 23.04832D - 5.61381H + 0.01724H^2D - 1.15929D^2 + 0.01751D^3 \]

D: DBH (cm)  
H: Height (m)  
W2: Biomass (bone dry kg)

**Populus tremuloides** –

AGB:
\[ M = 0.0527 \times D^{2.5084} \]

D: DBH (cm)  
M: Biomass (bone dry kg)

**Quercus chrysolepis** –
*This equation excludes foliage.*

AGB:
\[ TVOL = 0.0000730718 \times D^{2.20527} \times H^{0.61190} \]

D: DBH (cm)  
H: Height (m)  
TVOL: Total wood and bark volume (m³)

SGg: 0.70  
Wood Density: 700 Bone dry kg/Green m³

**Quercus garryana** –
*This equation excludes foliage.*

AGB:
\[ TVOL = 0.0000674342 \times D^{2.14321} \times H^{0.74220} \]

D: DBH (cm)  
H: Height (m)  
TVOL: Total wood and bark volume (m³)

SG12: 0.68  
Converted to SGg: 0.61  
Wood Density: 610 Bone dry kg/Green m³
**Quercus kelloggii** –
*This equation excludes foliage. AGB:

\[ TVOL = 0.0000870843 \times D^{1.97437} \times H^{0.85034} \]

D: DBH (cm)  \[10\]
H: Height (m)  \[9\]
TVOL: Total wood and bark volume (m^3)  \[17\]

SG12: 0.57
Converted to SGg: 0.53
Wood Density: 530 Bone dry kg/Green m^3

**“Soft maple/Birch” group** -
AGB:

\[ Y = \exp(-1.9123 + 2.3651 \ln X) \]

X: DBH (cm)  \[6\]
Y: Biomass (bone dry kg)

**Umbellularia californica** –
*This equation excludes foliage. AGB:

\[ TVOL = 0.0000763133 \times D^{1.94553} \times H^{0.88389} \]

D: DBH (cm)  \[10\]
H: Height (m)  \[10\]
TVOL: Total wood and bark volume (m^3)  \[7\]

SGg: 0.51
Wood Density: 510 Bone dry kg/Green m^3
Biomass Density Calculation Methods (with foliage)

Biomass densities for different Forest Class ID’s (FCID’s) from the 2006 LEMMA raster map were created by performing the following series of calculations on a database of the live sample trees representing each unique FCID. These calculated biomass densities were then joined to the 2006 LEMMA raster map by their corresponding FCID to create a map of biomass densities over the project area.

Definition of variables and field names:

- **D**: Diameter at Breast Height (DBH) in cm
- **H**: Height (m)
- **Fuel_Foliage**: Bone dry kg (BDkg) of foliage per tree
- **Fuel_Branches**: BDkg of live and dead branches per tree
- **Fuel_StemWood**: BDkg of stem wood per tree
- **Fuel_StemBark**: BDkg of stem bark per tree
- **Fuel_AbvGrnd**: BDkg of above-ground biomass per tree
- **Fuel_Stump**: BDkg of stump per tree
- **Fuel_TopStem**: BDkg of stem wood and bark per tree above the minimum top diameter.
- **Fuel_BrkDfct**: BDkg of biomass from breakage and defect per tree
- **GrossMerchWgt**: BDkg of stem wood and bark per tree from the top of the stump up to the minimum top diameter for commercial species of merchantable size
- **NetMerchWgt**: BDkg of stem wood and bark in the merchantable log recovered during harvesting
- **Fuel_MSlash**: BDkg of harvesting residues per tree from live merchantable trees
- **Fuel_SNMSlash**: BDkg of biomass per tree produced from cutting live “small” non-merchantable trees
- **Fuel_LNMSlash**: BDkg of biomass per tree produced from cutting live “large” non-merchantable trees
- **FuelPH_MSlash**: BDkg/Ha of residues from live merchantable trees
- **FuelPH_SNMSlash**: BDkg/Ha of biomass from cutting live “small” non-merchantable trees
- **FuelPH_LNMSlash**: BDkg/Ha of biomass from cutting live “large” non-merchantable trees
- **FuelPH_AbvGrnd**: BDkg/Ha of live tree above-ground biomass
- **GrossMerchWgt_PH**: BDkg/Ha of Gross Merchantable stem wood and bark
- **NetMerchWgt_PH**: BDkg/Ha of Net Merchantable stem wood and bark
- **Slash_T_Ac**: Bone dry Tons (BDT) per Acre of slash from all live trees in an FCID
- **MSlash_T_Ac**: BDT/Ac of slash from all live merchantable trees in an FCID
- **SNMSlash_T_Ac**: BDT/Ac of slash from all live “small” non-merchantable trees in an FCID
- **LNMSlash_T_Ac**: BDT/Ac of slash from all live “large” non-merchantable trees in an FCID
AGB_T_Ac: BDT/Ac of biomass from all live trees in an FCID
GrossMerch_T_Ac: BDT/Ac of gross merchantable stem wood and bark in an FCID
NetMerch_T_Ac: BDT/Ac of stem wood and bark recovered in merchantable logs in an FCID
MinMerchDBH: The minimum DBH (cm) at which a commercial species tree is merchantable
MinTopDiam: The minimum diameter (cm) of the top of a merchantable log (and the diameter of the bottom of the non-merchantable top section)
Pct_Stump: BDkg of tree stump divided by the BDkg of total above-ground biomass
TPH_FC: Number of trees per hectare that the sample tree represents
LNM_DBH: Minimum DBH for a non-merchantable tree to be classified as “large”
Step 1 – Calculate biomass weights for individual sample trees

Conifers, Commercial Species:

**Abies amabilis**
Fuel Foliage = \( \exp(-4.5487 + 2.1926 \ln D) \)
Fuel Branches = \( \exp(-5.2370 + 2.6261 \ln D) \)
Fuel StemWood = \( \exp(-3.5057 + 2.5744 \ln D) \)
Fuel StemBark = \( \exp(-6.1166 + 2.8421 \ln D) \)

**Abies concolor, A. grandis, A. lasiocarpa, A. magnifica, A. x shastensis**
Fuel Foliage = \( \exp(-3.4662 + 1.9278 \ln D) \)
Fuel Branches = \( \exp(-4.8287 + 2.5585 \ln D) \)
Fuel StemWood = \( \exp(-3.7389 + 2.6825 \ln D) \)
Fuel StemBark = \( \exp(-6.1918 + 2.8796 \ln D) \)

**Abies procera**
Fuel Foliage = \( \exp(-4.8728 + 2.1683 \ln D) \)
Fuel Branches = \( \exp(-4.1817 + 2.3324 \ln D) \)
Fuel StemWood = \( \exp(-3.7158 + 2.7592 \ln D) \)
Fuel StemBark = \( \exp(-6.1000 + 2.8943 \ln D) \)

**Abies x shastensis – see Abies concolor**

**Calocedrus decurrens, Chamaecyparis lawsoniana, Chamaecyparis nootkatensis, Thuja plicata**
Fuel Foliage = \( \exp(-2.617 + 1.7824 \ln D) \)
Fuel Branches = \( \exp(-3.2661 + 2.0877 \ln D) \)
Fuel StemWood = \( \exp(-2.0927 + 2.1863 \ln D) \)
Fuel StemBark = \( \exp(-4.1934 + 2.1101 \ln D) \)

**Larix lyalli**
*Larix larcina* equations were used because no *Larix lyalli* equations were available.
Fuel Foliage = \( 0.0466 \times D^{1.7250} \)
Fuel Branches = \( 0.0436 \times D^{1.9810} \)
Fuel StemWood = \( 0.0762 \times D^{2.3051} \)
Fuel StemBark = 0

**Larix occidentalis**
Fuel Foliage = \( 0.1307 \times D^{1.0557} \)
Fuel Branches = \( 0.1821 \times D^{1.2885} \)
Fuel StemWood = \( 0.2942 \times D^{1.5593} \)
Fuel StemBark = 0
\textbf{Picea engelmannii}

\begin{align*}
\text{Fuel\_Foliage} &= 0.3346 \times D^{1.2765} \\
\text{Fuel\_Branches} &= 0.1687 \times D^{1.5799} \\
\text{Fuel\_StemWood} &= 0.2844 \times D^{1.3782} \\
\text{Fuel\_StemBark} &= 0
\end{align*}

\textbf{Picea sitchensis}

\begin{align*}
\text{Fuel\_Foliage} &= 0.0030 \times D^{2.7800} \\
\text{Fuel\_Branches} &= 0.0056 \times D^{2.5180} \\
\text{Fuel\_StemWood} &= 0.0402 \times D^{2.5520} \\
\text{Fuel\_StemBark} &= 0
\end{align*}

\textbf{Pinus albicaulis, Pinus jeffreyi, Pinus monticola}

\begin{align*}
\text{Fuel\_Foliage} &= \exp(-3.9739 + 2.0039 \ln D) \\
\text{Fuel\_Branches} &= \exp(-5.2900 + 2.6524 \ln D) + \exp(-3.7969 + 1.7426 \ln D) \\
\text{Fuel\_StemWood} &= \exp(-4.2847 + 2.7180 \ln D) \\
\text{Fuel\_StemBark} &= \exp(-3.6187 + 1.8362 \ln D)
\end{align*}

\textbf{Pinus contorta}

\begin{align*}
\text{Fuel\_Foliage} &= \exp(-3.6187 + 1.8362 \ln D) \\
\text{Fuel\_Branches} &= \exp(-4.6004 + 2.3533 \ln D) \\
\text{Fuel\_StemWood} &= \exp(-2.9849 + 2.4287 \ln D) \\
\text{Fuel\_StemBark} &= 0
\end{align*}

\textbf{Pinus jeffreyi} – see \textit{Pinus albicaulis}

\textbf{Pinus lambertiana}

\begin{align*}
\text{Fuel\_Foliage} &= \exp(-4.0230 + 2.0327 \ln D) \\
\text{Fuel\_Branches} &= \exp(-7.637 + 3.3648 \ln D) \\
\text{Fuel\_StemWood} &= \exp(-3.984 + 2.6667 \ln D) \\
\text{Fuel\_StemBark} &= \exp(-5.295 + 2.6184 \ln D)
\end{align*}

\textbf{Pinus monticola} – see \textit{Pinus albicaulis}

\textbf{Pinus ponderosa}

\begin{align*}
\text{Fuel\_Foliage} &= \exp(-4.2612 + 2.0967 \ln D) \\
\text{Fuel\_Branches} &= \exp(-5.3855 + 2.7185 \ln D) + \exp(-2.5766 + 1.444 \ln D) \\
\text{Fuel\_StemWood} &= \exp(-4.4907 + 2.7587 \ln D) \\
\text{Fuel\_StemBark} &= \exp(-4.2063 + 2.2312 \ln D)
\end{align*}

\textbf{Pseudotsuga menziesii}

\begin{align*}
\text{Fuel\_Foliage} &= \exp(-2.8462 + 1.7009 \ln D) \\
\text{Fuel\_Branches} &= \exp(-3.6941 + 2.1382 \ln D) + \exp(-3.529 + 1.7503 \ln D) \\
\text{Fuel\_StemWood} &= \exp(-3.0396 + 2.5951 \ln D) \\
\text{Fuel\_StemBark} &= \exp(-4.3103 + 2.4300 \ln D)
\end{align*}

\textit{Thuja plicata} – see \textit{Calocedrus decurrens}
**Tsuga heterophylla**

Fuel Foliage = \( \exp(-4.130 + 2.128 \ln D) \)

Fuel Branches = \( \exp(-5.149 + 2.778 \ln D) + \exp(-2.409 + 1.312 \ln D) \)

Fuel StemWood = \( \exp(-2.172 + 2.257 \ln D) \)

Fuel StemBark = \( \exp(-4.373 + 2.258 \ln D) \)

**Tsuga mertensiana**

Fuel Foliage = \( \exp(-3.8169 + 1.9756 \ln D) \)

Fuel Branches = \( \exp(-5.2581 + 2.6045 \ln D) + \exp(-9.9449 + 3.2845 \ln D) \)

Fuel StemWood = \( \exp(-4.8164 + 2.9308 \ln D) \)

Fuel StemBark = \( \exp(-5.5868 + 2.7654 \ln D) \)

**Conifers, Non-Commercial Species:**

**Juniperus occidentalis**

Fuel Foliage = \( 0.0144 \times D^{1.5606} \)

Fuel Branches = \( 0.0007 \times D^{2.3337} \)

Fuel StemWood = \( 0.0002 \times D^{2.6389} \)

Fuel StemBark = \( 0.00004 \times D^{2.6333} \)

**Taxus brevifolia**

*Grier and Logan applied *Tsuga heterophylla* equations to *Taxus brevifolia*.

Fuel Foliage = \( \exp(-4.130 + 2.128 \ln D) \)

Fuel Branches = \( \exp(-5.149 + 2.778 \ln D) + \exp(-2.409 + 1.312 \ln D) \)

Fuel StemWood = \( \exp(-2.172 + 2.257 \ln D) \)

Fuel StemBark = \( \exp(-4.373 + 2.258 \ln D) \)

**Hardwoods, Commercial Species:**

**Alnus rubra**

*Species specific stem wood and bark equations were inaccurate for larger trees, so above-ground biomass was calculated with the “Aspen/Alder/Cottonwood/Willow” group equation and stem wood and bark was found by subtracting foliage and branches from above-ground biomass.

Fuel Foliage = \( 0.0100 \times D^{1.9398} \)

Fuel Branches = \( 0.0069 \times D^{2.6516} \)

Fuel StemWood = \( \exp(-2.2094 + 2.3867 \ln D) - (0.0100 \times D^{1.9398}) - (0.0069 \times D^{2.6516}) \)

Fuel StemBark = 0

Fuel AbvGrnd = \( \exp(-2.2094 + 2.3867 \ln D) \)
Hardwoods, Non-Commercial Species:

*Acer circinatum, Acer glabrum*

**“Soft maple/Birch” group equation**

\[
\text{Fuel}_{\text{AbvGrnd}} = \exp(-1.9123 + 2.3651 \ln D)
\]

*Acer macrophyllum*

\[
\begin{align*}
\text{Fuel}_{\text{Foliage}} &= \exp(-3.765 + 1.617 \ln D) \\
\text{Fuel}_{\text{Branches}} &= \exp(-4.236 + 2.430 \ln D) + \exp(-2.116 + 1.092 \ln D) \\
\text{Fuel}_{\text{StemWood}} &= \exp(-3.493 + 2.723 \ln D) \\
\text{Fuel}_{\text{StemBark}} &= \exp(-4.574 + 2.574 \ln D)
\end{align*}
\]

*Alnus rhombifolia*

**“Aspen/Alder/Cottonwood/Willow” group equation**

\[
\text{Fuel}_{\text{AbvGrnd}} = \exp(-2.2094 + 2.3867 \ln D)
\]

*Arbutus menziesii*

\[
\text{Fuel}_{\text{AbvGrnd}} = 560 \times (0.0000821921 \times D^{1.96628} \times H^{0.83458})
\]

*This equation excludes foliage.*

*Betula papyrifera*

\[
\text{Fuel}_{\text{AbvGrnd}} = 0.0882 \times D^{2.5620}
\]

*Chrysolepis chrysophylla*

\[
\begin{align*}
\text{Fuel}_{\text{Foliage}} &= \exp(-3.123 + 1.693 \ln D) \\
\text{Fuel}_{\text{Branches}} &= \exp(-4.579 + 2.576 \ln D) + \exp(-7.124 + 2.883 \ln D) \\
\text{Fuel}_{\text{StemWood}} &= \exp(-3.708 + 2.658 \ln D) \\
\text{Fuel}_{\text{StemBark}} &= \exp(-5.923 + 2.989 \ln D)
\end{align*}
\]

*Cornus nuttallii*

*Grier and Logan applied Acer macrophyllum equations to Cornus nuttallii.*

\[
\begin{align*}
\text{Fuel}_{\text{Foliage}} &= \exp(-3.765 + 1.617 \ln D) \\
\text{Fuel}_{\text{Branches}} &= \exp(-4.236 + 2.430 \ln D) + \exp(-2.116 + 1.092 \ln D) \\
\text{Fuel}_{\text{StemWood}} &= \exp(-3.493 + 2.723 \ln D) \\
\text{Fuel}_{\text{StemBark}} &= \exp(-4.574 + 2.574 \ln D)
\end{align*}
\]

*Fraxinus latifolia*

**“Mixed Hardwood” group equation**

\[
\text{Fuel}_{\text{AbvGrnd}} = \exp(-2.4800 + 2.4835 \ln D)
\]

*Lithocarpus densiflorus*

\[
\text{Fuel}_{\text{AbvGrnd}} = 580 \times (0.0000763045 \times D^{1.94165} \times H^{0.86562})
\]

*This equation excludes foliage.*

*Prunus emarginata, Prunus virginiana, Prunus spp.*

**“Mixed Hardwood” group equation**

\[
\text{Fuel}_{\text{AbvGrnd}} = \exp(-2.4800 + 2.4835 \ln D)
\]
**Populus balsamifera** ([D] <= 10cm)

```
*“Aspen/Alder/Cottonwood/Willow” group equation
Fuel_AbvGrnd = \exp(-2.2094 + 2.3867 \ln D)
```

**Populus balsamifera** ([D] > 10cm)

```
Fuel_AbvGrnd = -64.76640 + 23.04832*D – 5.61381*H + 0.01724*H*D^2 - 1.15929*D^2 + 0.01751*D^3
```

**Populus tremuloides**

```
Fuel_AbvGrnd = 0.0527 * D^2.5084
```

**Quercus chrysolepis**

```
Fuel_AbvGrnd = 700 * (0.0000730718 * D^2.20527 * H^0.61190)
*This equation excludes foliage.*
```

**Quercus garryana**

```
Fuel_AbvGrnd = 610 * (0.0000674342 * D^2.14321 * H^0.74220)
*This equation excludes foliage.*
```

**Quercus kelloggii**

```
Fuel_AbvGrnd = 530 * (0.0000870843 * D^1.97437 * H^0.85034)
*This equation excludes foliage.*
```

**Salix scouleriana and Salix spp.**

```
*“Aspen/Alder/Cottonwood/Willow” group equation
Fuel_AbvGrnd = \exp(-2.2094 + 2.3867 \ln D)
```

**Umbellularia californica**

```
Fuel_AbvGrnd = 510 * (0.0000763133 * D^1.94553 * H^0.88389)
*This equation excludes foliage.*
```

---

**Step 2 – Calculate above-ground biomass from tree components**

For sample trees with [Fuel_AbvGrnd] = 0:

```
Fuel_AbvGrnd = [Fuel_Foliage] + [Fuel_Branches] + [Fuel_StemWood] + [Fuel_StemBark]
```

**Step 3 – Calculate stem top biomass for merchantable trees and stump biomass**

For merchantable conifer species with dbh > 5” and red alder with dbh > 6” stem tops were calculated using the stem wood and stem bark equations. Because diameter at breast height (4.5 ft) is the input for these equations, using the diameter at the base of the non-merchantable top may overestimate biomass by effectively calculating an
extra 4.5 ft of length at the base. To prevent this, an estimate of diameter 4.5 ft up from the bottom of the non-merchantable tops ([MinTopDiam]) was used as the input. These diameters were calculated using estimates of top taper based on 10-20 sample trees for both conifers and hardwoods. For conifers tops, diameter at the top of a 4.5 foot section was 86.5% of the diameter of the bottom of the section. For hardwood tops it was 88.75%. The minimum top diameter for all merchantable species was 4 inches. Stumps were estimated to be 2.5% of above-ground biomass (Jenkins 2003).

**Stem Tops**

**Conifers:**

*Abies amabilis*

\[ \text{Fuel\_TopStem} = (\exp(-3.5057 + 2.5744 \ln (0.865 \cdot [\text{MinTopDiam}])) + (\exp(-6.1166 + 2.8421 \ln (0.865 \cdot [\text{MinTopDiam}])) \]

*Abies concolor, A. grandis, A. lasiocarpa, A. magnifica, A. x shastensis*

\[ \text{Fuel\_TopStem} = (\exp(-3.7389 + 2.6825 \ln (0.865 \cdot [\text{MinTopDiam}])) + (\exp(-6.1918 + 2.8796 \ln (0.865 \cdot [\text{MinTopDiam}])) \]

*Abies procera*

\[ \text{Fuel\_TopStem} = (\exp(-3.7158 + 2.7592 \ln (0.865 \cdot [\text{MinTopDiam}])) + (\exp(-6.1000 + 2.8943 \ln (0.865 \cdot [\text{MinTopDiam}])) \]

*Abies x shastensis – see Abies concolor*

*Calocedrus decurrens, Chamaecyparis lawsoniana, Chamaecyparis nootkatensis, Thuja plicata –*

\[ \text{Fuel\_TopStem} = (\exp(-2.0927 + 2.1863 \ln (0.865 \cdot [\text{MinTopDiam}])) + (\exp(-4.1934 + 2.1101 \ln (0.865 \cdot [\text{MinTopDiam}])) \]

*Larix lyalli*

\[ \text{Fuel\_TopStem} = 0.0762 \cdot (0.865 \cdot [\text{MinTopDiam}])^{2.3051} \]

*Larix occidentalis*

\[ \text{Fuel\_TopStem} = 0.2942 \cdot (0.865 \cdot [\text{MinTopDiam}])^{1.5593} \]

*Picea engelmannii*

\[ \text{Fuel\_TopStem} = 0.2844 \cdot (0.865 \cdot [\text{MinTopDiam}])^{1.3782} \]

*Picea sitchensis*

\[ \text{Fuel\_TopStem} = 0.0402 \cdot (0.865 \cdot [\text{MinTopDiam}])^{2.5520} \]
**Pinus albicaulis, Pinus jeffreyi, Pinus monticola**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-4.2847 + 2.7180 \ln (0.865 \times [\text{MinTopDiam}]))) \\
+ (\exp(-3.6187 + 1.8362 \ln (0.865 \times [\text{MinTopDiam}])))
\]

**Pinus contorta**

\[
\text{Fuel} \_\text{TopStem} = \exp(-2.9849 + 2.4287 \ln (0.865 \times [\text{MinTopDiam}]))
\]

**Pinus jeffreyi** – see **Pinus albicaulis**

**Pinus lambertiana**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-3.984 + 2.6667 \ln (0.865 \times [\text{MinTopDiam}]))) \\
+ (\exp(-5.295 + 2.6184 \ln (0.865 \times [\text{MinTopDiam}])))
\]

**Pinus monticola** – see **Pinus albicaulis**

**Pinus ponderosa**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-4.4907 + 2.7587 \ln (0.865 \times [\text{MinTopDiam}]))) \\
+ (\exp(-4.2063 + 2.2312 \ln (0.865 \times [\text{MinTopDiam}])))
\]

**Pseudotsuga menziesii**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-3.0396 + 2.5951 \ln (0.865 \times [\text{MinTopDiam}]))) \\
+ (\exp(-4.3103 + 2.4300 \ln (0.865 \times [\text{MinTopDiam}])))
\]

**Thuja plicata** – see **Calocedrus decurrens**

**Tsuga heterophylla**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-2.172 + 2.257 \ln (0.865 \times [\text{MinTopDiam}]))) \\
+ (\exp(-4.373 + 2.258 \ln (0.865 \times [\text{MinTopDiam}])))
\]

**Tsuga mertensiana**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-4.8164 + 2.9308 \ln (0.865 \times [\text{MinTopDiam}]))) \\
+ (\exp(-5.5868 + 2.7654 \ln (0.865 \times [\text{MinTopDiam}])))
\]

**Hardwoods:**

**Alnus Rubra**

\[
\text{Fuel} \_\text{TopStem} = (\exp(-2.2094 + 2.3867 \ln (0.8875 \times [\text{MinTopDiam}]))) \\
- (0.0100 \times (0.8875 \times [\text{MinTopDiam}])^{1.9398}) \\
- (0.0069 \times (0.8875 \times [\text{MinTopDiam}])^{2.6516})
\]

**Stumps**

**All Trees**

\[
\text{Fuel} \_\text{Stump} = [\text{Pct}_\text{Stump}] \times [\text{Fuel}_\text{AbvGrnd}]
\]
Step 4 - Calculate gross merchantable, breakage and defect, net merchantable, merchantable-tree slash and non-merchantable large and small tree slash biomass

15.24cm (6") was the value of [LNM_DBH] used for all species. “Large” and “small” non-merchantable slash are tallied separately because small diameter non-merchantable logs have low value and are time-consuming to haul to the landing. It's unlikely that a commercial timber harvesting operation would extract non-merchantable trees less than 6” DBH, so small non-merchantable tree slash is not available for fuel. Larger non-merchantable trees may be hauled to the landing if the operators had incentive to do so, so it’s possible that large non-merchantable tree slash could be available under certain conditions. Most industrial timber harvesting operations in northwest Oregon and southwest Washington use whole-tree yarding. This system accumulates slash from merchantable trees at the roadside as a result of timber extraction, and therefore has little additional fuel extraction cost. Merchantable tree slash is the most reliable and readily available forest biomass fuel.

All Commercial Species

If \([D] < [MinMerchDBH]\):

\[
\begin{align*}
\text{GrossMerchWgt} & = 0 \\
\text{Fuel\_BrkDfct} & = 0 \\
\text{NetMerchWgt} & = 0 \\
\text{Fuel\_MSlash} & = 0 \\
\text{Fuel\_SNMSlash} & = [\text{Fuel\_AbvGrnd}] - [\text{Fuel\_Stump}] \\
\text{Fuel\_LNMSlash} & = 0
\end{align*}
\]

If \([D] \geq [MinMerchDBH]\):

\[
\begin{align*}
\text{GrossMerchWgt} & = [\text{Fuel\_AbvGrnd}] - [\text{Fuel\_Stump}] - [\text{Fuel\_Foliage}] - [\text{Fuel\_Branches}] - [\text{Fuel\_TopStem}] \\
\text{Fuel\_BrkDfct} & = 0.03 \times [\text{GrossMerchWgt}] \\
\text{NetMerchWgt} & = [\text{GrossMerchWgt}] - [\text{Fuel\_BrkDfct}] \\
\text{Fuel\_MSlash} & = [\text{Fuel\_Foliage}] + [\text{Fuel\_Branches}] + [\text{Fuel\_BrkDfct}] + [\text{Fuel\_TopStem}] \\
\text{Fuel\_SNMSlash} & = 0 \\
\text{Fuel\_LNMSlash} & = 0
\end{align*}
\]

All Non-Commercial Species

If \([D] < [LNM\_DBH]\):

\[
\begin{align*}
\text{GrossMerchWgt} & = 0 \\
\text{Fuel\_BrkDfct} & = 0 \\
\text{NetMerchWgt} & = 0 \\
\text{Fuel\_MSlash} & = 0 \\
\text{Fuel\_SNMSlash} & = [\text{Fuel\_AbvGrnd}] - [\text{Fuel\_Stump}] \\
\text{Fuel\_LNMSlash} & = 0
\end{align*}
\]
If \([D] \geq [LNM\_DBH]\):
\[
\begin{align*}
\text{GrossMerchWgt} &= 0 \\
\text{Fuel\_BrkDfct} &= 0 \\
\text{NetMerchWgt} &= 0 \\
\text{Fuel\_MSlash} &= 0 \\
\text{Fuel\_SNMSlash} &= 0 \\
\text{Fuel\_LNMSlash} &= [\text{Fuel\_AbvGrnd}] - [\text{Fuel\_Stump}]
\end{align*}
\]

Step 5 – Convert BDkg/tree biomass values to BDkg/Ha

**All Trees**
\[
\begin{align*}
\text{GrossMerchWght\_PH} &= [\text{TPH\_FC}] \times [\text{GrossMerchWgt}] \\
\text{NetMerchWgt\_PH} &= [\text{TPH\_FC}] \times [\text{NetMerchWgt}] \\
\text{FuelPH\_MSlash} &= [\text{TPH\_FC}] \times [\text{Fuel\_MSlash}] \\
\text{FuelPH\_SNMSlash} &= [\text{TPH\_FC}] \times [\text{Fuel\_SNMSlash}] \\
\text{FuelPH\_LNMSlash} &= [\text{TPH\_FC}] \times [\text{Fuel\_LNMSlash}] \\
\text{FuelPH\_AbvGrnd} &= [\text{TPH\_FC}] \times [\text{Fuel\_AbvGrnd}]
\end{align*}
\]

Step 6 - Convert from BDkg/Ha to BDT/Ac and sum total slash
\[
\begin{align*}
\text{MSlash\_T\_Ac} &= [\text{FuelPH\_MSlash}] / 2241.7 \\
\text{SNMSlash\_T\_Ac} &= [\text{FuelPH\_SNMSlash}] / 2241.7 \\
\text{LNMSlash\_T\_Ac} &= [\text{FuelPH\_LNMSlash}] / 2241.7 \\
\text{AGB\_T\_Ac} &= [\text{FuelPH\_AbvGrnd}] / 2241.7 \\
\text{GrossMerch\_T\_Ac} &= [\text{GrossMerchWght\_PH}] / 2241.7 \\
\text{NetMerch\_T\_Ac} &= [\text{NetMerchWgt\_PH}] / 2241.7 \\
\text{Slash\_T\_Ac} &= [\text{MSlash\_T\_Ac}] + [\text{SNMSlash\_T\_Ac}] + [\text{LNMSlash\_T\_Ac}]
\end{align*}
\]

Step 7 – Sum up biomass densities by Forest Class ID (FCID)
For each FCID, the values for [Slash\_T\_Ac], [MSlash\_T\_Ac], [SNMSlash\_T\_Ac], [LNMSlash\_T\_Ac], [AGB\_T\_Ac], [GrossMerch\_T\_Ac] and [NetMerch\_T\_Ac] of every the sample tree in the FCID were summed up. The results were saved in a new datatable. This datatable was then exported and joined to the LEMMA raster GIS file by FCID value.
Biomass Density Calculation Methods (without foliage)

Another copy of the LEMMA 2006 live sample tree database was made to calculate biomass densities for each FCID without foliage. Most of the methods used to calculate these densities were similar to those for the biomass densities with foliage.

Definitions of variables and field names:
*All of the variables and fields from the Biomass Density Calculation Methods with Foliage were used with a few additional fields.

- **Fuel_{AGNoFol}**: BDkg of above-ground biomass minus foliage per tree
- **FuelPH_{AGNoFol}**: BDkg/Ha of live tree above-ground biomass
- **AGB_{NoFol_T_Ac}**: BDT/Ac of biomass minus foliage from all live trees in an FCID
- **Pct_Foliage**: Estimated percent of above-ground biomass dry weight from foliage

Step 1 – Calculate biomass weights for individual sample trees
*Equations used were the same as Step 1 of Biomass Density Calculation Methods with Foliage, except for six non-commercial hardwoods. These six species use Pillsbury and Kirkley’s 1984 above-ground biomass equations, which exclude foliage. Because following steps subtract foliage from all trees, approximate foliage biomass is added to these six species in this step to prevent subtracting foliage biomass twice.

**Arbutus menziesii**

Fuel_{AbvGrnd} = (560 * (0.0000821921 * D^1.96628 * H^0.83458)) * (1 - [Pct_Foliage])

**Lithocarpus densiflorus**

Fuel_{AbvGrnd} = (580 * (0.0000763045 * D^1.94165 * H^0.86562)) * (1 - [Pct_Foliage])

**Quercus chrysolepis**

Fuel_{AbvGrnd} = (700 * (0.0000730718 * D^2.20527 * H^0.61190)) * (1 - [Pct_Foliage])

**Quercus garryana**

Fuel_{AbvGrnd} = (610 * (0.0000674342 * D^2.14321 * H^0.74220)) * (1 - [Pct_Foliage])

**Quercus kelloggii**

Fuel_{AbvGrnd} = (530 * (0.0000870843 * D^1.97437 * H^0.85034)) * (1 - [Pct_Foliage])
**Umbellularia californica**

\[
\text{Fuel\_AbvGrnd} = (510 \times (0.0000763133 \times D^{1.94553} \times H^{0.88389}) \times (1 - \text{[Pct\_Foliage]})
\]

Step 2 - Calculate above-ground biomass from tree components and above-ground biomass without foliage

*For species that used above-ground biomass equations instead of component biomass equations, foliage dry biomass weight was estimated to be 4% of above-ground biomass.

For sample trees with [Fuel\_AbvGrnd] \(\neq 0\):
\[
\text{Fuel\_AGNoFol} = (1 - \text{[Pct\_Foliage]}) \times \text{[Fuel\_AbvGrnd]}
\]

For sample trees with [Fuel\_AbvGrnd] = 0:
\[
\begin{align*}
\text{Fuel\_AbvGrnd} &= \text{[Fuel\_Foliage]} + \text{[Fuel\_Branches]} + \text{[Fuel\_StemWood]} + \text{[Fuel\_StemBark]} \\
\text{Fuel\_AGNoFol} &= \text{[Fuel\_Branches]} + \text{[Fuel\_StemWood]} + \text{[Fuel\_StemBark]}
\end{align*}
\]

Step 3 - Calculate stem top biomass for merchantable trees and stump biomass

*Same as Biomass Density Calculation Methods with Foliage.

Step 4 - Calculate gross merchantable, breakage and defect, net merchantable, merchantable-tree slash and non-merchantable large and small tree slash biomass

**All Commercial Species**

If \([D] < [\text{MinMerchDBH}]\):
\[
\begin{align*}
\text{GrossMerchWgt} &= 0 \\
\text{Fuel\_BrkDfct} &= 0 \\
\text{NetMerchWgt} &= 0 \\
\text{Fuel\_MSlash} &= 0 \\
\text{Fuel\_SNMSlash} &= \text{[Fuel\_AGNoFol]} - \text{[Fuel\_Stump]} \\
\text{Fuel\_LNMSlash} &= 0
\end{align*}
\]
If \([D] \geq [\text{MinMerchDBH}]\):
\[
\text{GrossMerchWgt} = \text{[Fuel\_AbvGrnd]} - \text{[Fuel\_Stump]} - \text{[Fuel\_Foliage]}
- \text{[Fuel\_Branches]} - \text{[Fuel\_TopStem]}
\]
\[
\text{Fuel\_BrkDfct} = 0.03 \times \text{[GrossMerchWgt]}
\]
\[
\text{NetMerchWgt} = \text{[GrossMerchWgt]} - \text{[Fuel\_BrkDfct]}
\]
\[
\text{Fuel\_MSlash} = \text{[Fuel\_Branches]} + \text{[Fuel\_BrkDfct]} + \text{[Fuel\_TopStem]}
\]
\[
\text{Fuel\_SNMSlash} = 0
\]
\[
\text{Fuel\_LNMSlash} = 0
\]

All Non-Commercial Species

If \([D] < [\text{LNM\_DBH}]\):
\[
\text{GrossMerchWgt} = 0
\]
\[
\text{Fuel\_BrkDfct} = 0
\]
\[
\text{NetMerchWgt} = 0
\]
\[
\text{Fuel\_MSlash} = 0
\]
\[
\text{Fuel\_SNMSlash} = \text{[Fuel\_AGNoFol]} - \text{[Fuel\_Stump]}
\]
\[
\text{Fuel\_LNMSlash} = 0
\]

If \([D] \geq [\text{LNM\_DBH}]\):
\[
\text{GrossMerchWgt} = 0
\]
\[
\text{Fuel\_BrkDfct} = 0
\]
\[
\text{NetMerchWgt} = 0
\]
\[
\text{Fuel\_MSlash} = 0
\]
\[
\text{Fuel\_SNMSlash} = 0
\]
\[
\text{Fuel\_LNMSlash} = \text{[Fuel\_AGNoFol]} - \text{[Fuel\_Stump]}
\]

Step 5 - Convert BDkg/tree biomass values to BDkg/Ha

All Trees
\[
\text{FuelPH\_MSlash} = \text{[TPH\_FC]} \times \text{[Fuel\_MSlash]}
\]
\[
\text{FuelPH\_SNMSlash} = \text{[TPH\_FC]} \times \text{[Fuel\_SNMSlash]}
\]
\[
\text{FuelPH\_LNMSlash} = \text{[TPH\_FC]} \times \text{[Fuel\_LNMSlash]}
\]
\[
\text{FuelPH\_AbvGrnd} = \text{[TPH\_FC]} \times \text{[Fuel\_AbvGrnd]}
\]
\[
\text{FuelPH\_AGNoFol} = \text{[TPH\_FC]} \times \text{[Fuel\_AGNoFol]}
\]
\[
\text{GrossMerchWght\_PH} = \text{[TPH\_FC]} \times \text{[GrossMerchWgt]}
\]
\[
\text{NetMerchWgt\_PH} = \text{[TPH\_FC]} \times \text{[NetMerchWgt]}
\]
Step 6 - Convert from BDkg/Ha to BDT/Ac and sum total slash

\[
\begin{align*}
\text{MSlash\_T\_Ac:} & \quad [\text{FuelPH\_MSlash}] / 2241.7 \\
\text{SNMSlash\_T\_Ac:} & \quad [\text{FuelPH\_SNMSlash}] / 2241.7 \\
\text{LNMSlash\_T\_Ac:} & \quad [\text{FuelPH\_LNMSlash}] / 2241.7 \\
\text{AGB\_T\_Ac:} & \quad [\text{FuelPH\_AbvGrnd}] / 2241.7 \\
\text{AGBNoFol\_T\_Ac:} & \quad [\text{FuelPH\_AGNoFol}] / 2241.7 \\
\text{GrossMerch\_T\_Ac:} & \quad [\text{GrossMerchWght\_PH}] / 2241.7 \\
\text{NetMerch\_T\_Ac:} & \quad [\text{NetMerchWgt\_PH}] / 2241.7 \\
\text{Slash\_T\_Ac:} & \quad \text{[MSlash\_T\_Ac]} + \text{[SNMSlash\_T\_Ac]} + \\
\text{[LNMSlash\_T\_Ac]} & \quad
\end{align*}
\]

Step 7 – Sum up biomass densities by Forest Class ID (FCID)

For each FCID, the values for [Slash\_T\_Ac], [MSlash\_T\_Ac], [SNMSlash\_T\_Ac], [LNMSlash\_T\_Ac], [AGB\_T\_Ac], [AGBNoFol\_T\_Ac], [GrossMerch\_T\_Ac] and [NetMerch\_T\_Ac] of every the sample tree in the FCID were summed up. The results were saved in a new datatable. This datatable was then exported and joined to the LEMMA raster GIS file by FCID value.
## Source Reference Numbers

<table>
<thead>
<tr>
<th>Reference #</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bormann 1990</td>
</tr>
<tr>
<td>2</td>
<td>Briggs 1994</td>
</tr>
<tr>
<td>3</td>
<td>Brown 1978</td>
</tr>
<tr>
<td>4</td>
<td>Gholz et al 1979</td>
</tr>
<tr>
<td>5</td>
<td>Grier and Logan 1977</td>
</tr>
<tr>
<td>6</td>
<td>Jenkins et al 2003</td>
</tr>
<tr>
<td>7</td>
<td>Markwardt and Wilson 1935</td>
</tr>
<tr>
<td>8</td>
<td>Milota and Fuller 1995</td>
</tr>
<tr>
<td>9</td>
<td>Overholser 1977</td>
</tr>
<tr>
<td>10</td>
<td>Pillsbury and Kirkley 1984</td>
</tr>
<tr>
<td>11</td>
<td>Peralta and Alban 1994</td>
</tr>
<tr>
<td>12</td>
<td>Schmitt and Grigal 1981</td>
</tr>
<tr>
<td>13</td>
<td>Singh 1984</td>
</tr>
<tr>
<td>14</td>
<td>Snell and Little 1993</td>
</tr>
<tr>
<td>15</td>
<td>Ter-Mikaelian and Korzukhin 1997</td>
</tr>
<tr>
<td>16</td>
<td>Young et al 1980</td>
</tr>
<tr>
<td>17</td>
<td>Wood Handbook 1987</td>
</tr>
</tbody>
</table>
References


Appendix B - Oregon RMZ Modeling Script
Appendix C - Washington R/WMZ Modeling Script

#==============================================================
#  --WA PI Land Riparian and Wetland Management Zone buffering tool--
#==============================================================

#This script takes buffer distances, the input geodatabase path and the output FC suffix
as parameters. It then
#buffers the different stream and wetland types on WA PI lands; merges these features
together; adds a common
#field to use for dissolving and raster processing; clips this merged buffer FC to the WA
PI land FC (to
# eliminate parts of buffers that extend over the land boundary; saves this resulting
output FC to be used to
#generate a fuel reduction raster; then dissolves all these features together to create an
output FC that will
# give an accurate Total Area number. The Total Area of this Dissolved Buffers FC will be
compared to the total
#WA PI land area to generate a ratio of RMZ/WMZ and water body area to total area for
WA PI lands. The ratio of
# RMZ/WMZ's (excluding the waters themselves) to total land should be .18-.20 (or
maybe up to .22). I will estimate
# waters to take up 1-2.5% of the total land, so the ratio of the Dissolved Buffers FC area
to total WA PI land
# area should be .19-.225 (or maybe up to .245).
#that will be used for and it dissolves the
#
#------------------------------------------

#INPUTS:  - Buffer widths for all stream classes and wetland classes
#
#         - Name and Path for both output FC's
#
#         - File name Suffix (to help tell the difference and prevent overwriting
#         model runs for different parameters)
#
#------------------------------------------

#OUPUTS:  - Merged and Clipped Stream/Wetland Buffers FC with extra field added
#         and populated
#
#         - Merged, Clipped and Dissolved Stream/Wetland Buffers (for area calculations)
#------------------------------------------

import sys, os, string, arcgisscripting

gp = arcgisscripting.create(9.3)
gp.setproduct("ArcInfo")

gp.Addtoolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Analysis Tools.tbx")
gp.Addtoolbox("C:/Program Files/ArcGIS/ArcToolbox/Toolboxes/Data Management Tools.tbx")

print "Reading variables..."
try:
#=====VARIABLES=====  

```
GeoDB = "C:\GISwork\WADNR\WA_Waters_onPI.gdb"
suffix = "01"  #!!!!!!!!!Be sure to change this or you'll overwrite data!!!!!!!!!!!!

#Buffer Distance Variables
S_SC1dist = 150 + 20
S_SC2dist = 128 + 20
S_SC3dist = 105 + 20
S_SC4dist = 83 + 20
S_SC5dist = 68 + 20
S_SCNCMdist = 68 + 20
S_SCNDdist = 75 + 20
S_SCRAdist = 105 + 20
F_SC1dist = 150+5
F_SC2dist = 128+5
F_SC3dist = 105+5
F_SC4dist = 83+5
F_SC5dist = 68+5
F_SCNCMdist = 68+5
F_SCNDdist = 68+5
F_SCRAdist = 105+5
Np_dist = 50+2
Ns_dist = 0
Nu_dist = 25+2
```
U_SC1dist = 62
U_SC2dist = 62
U_SC3dist = 52
U_SC4dist = 27
U_SC5dist = 27
U_SCNCMDist = 27
U_SCNDist = 27
U_SCRADist = 27

AL_dist = 100
AM_dist = 50

AS_dist = 1 #Not sure about this one
BL_dist = 50
BM_dist = 25
BS_dist = 1

#Don't buffer Forested Wetlands, but maybe exclude their area from the harvest.
CutFW = True

except:
    print gp.getmessages(0)
    print "Error while setting variables"
    sys.exit()

print "Building buffer distance and Feature Class lists..."
try:

    #Build buffer distance and FC name lists
    liStrBuffDist =
    [S_SC1dist,S_SC2dist,S_SC3dist,S_SC4dist,S_SC5dist,S_SCNCMdist,S_SCNDdist,S_SCRAdist,F_SC1dist,\
     F_SC2dist,F_SC3dist,F_SC4dist,F_SC5dist,F_SCNCMdist,F_SCNDdist,F_SCRAdist,Np_dist,Ns_dist,Nu_dist,\
     U_SC1dist,U_SC2dist,U_SC3dist,U_SC4dist,U_SC5dist,U_SCNCMdist,U_SCNDdist,U_SCRAdist]

    liStrFCs =
    ["Streams_S_SC1","Streams_S_SC2","Streams_S_SC3","Streams_S_SC4","Streams_S_SC5","Streams_S_SCNCM","Streams_S_SCND",\
     "Streams_S_SCRA","Streams_F_SC1","Streams_F_SC2","Streams_F_SC3","Streams_F_SC4","Streams_F_SC5","Streams_F_SCNCM",\
     "Streams_F_SCRA","Streams_Np","Streams_Ns","Streams_Nu","Streams_U_SC1","Streams_U_SC2","Streams_U_SC3",\
     "Streams_U_SC4","Streams_U_SC5","Streams_U_SCNCM","Streams_U_SCND","Streams_U_SCRA"]
NumberStr = len(liStrBuffDist)

liWLBuffDist = [AL_dist, AM_dist, AS_dist, BL_dist, BM_dist, BS_dist]

liWLFCs = ["WL_A_L", "WL_A_M", "WL_A_S", "WL_B_L", "WL_B_M", "WL_B_S"]

NumberWL = len(liWLBuffDist)

except:
    print gp.getmessages(0)
    print "Error while building lists."
    sys.exit()

#=====START MAIN SCRIPT=====

#---Buffer Streams---
print "Beginning Stream buffering..."

gp.workspace = GeoDB + os.sep + "Streams"

n = 0

#Buffer syntax: Buffer_analysis (in_features, out_feature_class, buffer_distance_or_field,
line_side, line_end_type, dissolve_option, dissolve_field)

try:
    while n < NumberStr:
try:
    if liStrBuffDist[n] > 0:
        print "Buffering " + liStrFCs[n]
        gp.buffer_analysis(liStrFCs[n], liStrFCs[n] + "Buff" + suffix, liStrBuffDist[n])
except:
    print gp.Getmessages(0)
    print "An error occurred while buffering " + liStrFCs[n]
    sys.exit()
    n = n + 1

except:
    print gp.getmessages(0)
    print "Error occurred while attempting While loop to buffer streams"
    sys.exit()

#---Buffer Wetlands---
print "Beginning Wetland buffering..."
gp.workspace = GeoDB + os.sep + "Wetlands"
    n = 0

try:
    while n < NumberWL:
        try:
            
try:
if liWLBuffDist[n] > 0:

    print "Buffering " + liWLFCs[n]
    gp.buffer_analysis(liWLFCs[n], liWLFCs[n] + "Buff" + suffix, liWLBuffDist[n])

except:

    print gp.Getmessages(0)
    print "An error occurred while buffering " + liWLFCs[n]
    sys.exit()

    n = n + 1

except:

    print gp.getmessages(0)
    print "Error occurred while attempting While loop to buffer Wetlands"
    sys.exit()

#---Merge Stream Buffers---

#Merge syntax: Merge_management (inputs, output, field_mappings)

    gp.workspace = GeoDB + os.sep + "Streams"

#Build input string for Streams

    print "Building stream buffer Merge input string..."

    n = 1

    MergeInput = liStrFCs[0] + "Buff" + suffix
try:

    while n < NumberStr:
        if liStrBuffDist[n] > 0:
            MergeInput = MergeInput + "; " + liStrFCs[n] + "Buff" + suffix
            n = n + 1

except:

    print gp.getmessages(0)
    print "Error occurred while building streams Merge Input string."
    sys.exit()

#Merge stream buffers

try:

    print "Merging Stream buffers..."
    gp.Merge_management(MergeInput, "Stream_Buffs" + suffix)

except:

    print gp.getmessages(0)
    print "Error occurred while Merging streams."
    sys.exit()


#---Merge Wetland Buffers---

print "Building wetland buffer Merge input string..."

gp.workspace = GeoDB + os.sep + "Wetlands"
# Build input string for Wetlands

n = 1

if CutFW:
    MergeInput = liWLFCs[0]
else:
    MergeInput = "WL_FW; " + liWLFCs[0]

try:
    while n < NumberWL:
        MergeInput = MergeInput + "; " + liWLFCs[n]
        n = n + 1
except:
    print gp.getmessages(0)
    print "Error occurred while building wetlands Merge Input string."
    sys.exit()

# Merge Wetland buffers

try:
    print "Merging Wetland buffers..."
    gp.Merge_management(MergeInput, "WL_Buffs" + suffix)
except:
    print gp.getmessages(0)
    print "Error occurred while Merging wetlands."
    sys.exit()
#Merge Stream buffers and Wetland buffers

gp.workspace = GeoDB + os.sep + "Streams"

try:
    print "Merging Stream and Wetland buffers..."
    gp.Merge_management(GeoDB + os.sep + "Streams" + os.sep + "Stream_Buffs" + suffix + "; " + GeoDB + os.sep + "Wetlands" + os.sep + "WL_Buffs" + suffix, "Str_WL_Buffs" + suffix)
except:
    print gp.getmessages(0)
    print "Error occurred while Merging stream and wetland buffers."
    sys.exit()

#---Clip Buffers to WA PI land---

#Clip syntax: Clip_analysis (in_features, clip_features, out_feature_class, cluster_tolerance)

try:
    print "Clipping merged buffers to WA PI land boundaries..."
    gp.Clip_analysis("Str_WL_Buffs" + suffix, GeoDB + os.sep + "WA_PI_Dslv", "Str_WL_Buffs" + suffix + "_Clip")
except:
    print gp.getmessages(0)
    print "Error occurred while clipping the merged buffers FC."
sys.exit()

---Add and calculate dissolve field, then Dissolve---

#Add Field syntax: AddField_management (in_table, field_name, field_type, field_precision, field_scale,
  # field_length, field_alias, field_is_nullable, field_is_required, field_domain)

#Calculate field syntax: CalculateField_management (in_table, field, expression, expression_type, code_block)

#Dissolve syntax: Dissolve_management (in_features, out_feature_class, dissolve_field, statistics_fields,
  # multi_part, unsplit_lines)

try:
    print "Adding dissolve field..."
    gp.AddField_management("Str_WL_Buffs" + suffix + "_Clip", "Dslv_200", "short")
except:
    print gp.getmessages(0)
    print "Error occurred while Adding a Field to the clipped, merged buffers FC."
    sys.exit()

try:
    print "Calculating field..."
gp.CalculateField_management("Str_WL_Buffs" + suffix + ", Clip", "Dslv_200", "200")

except:

    print gp.getmessages(0)

    print "Error occurred while Calculating Field in the clipped, merged buffers FC."

    sys.exit()

try:

    print "Dissolving merged and clipped Stream and Wetland buffers..."

    gp.Dissolve_management ("Str_WL_Buffs" + suffix + "Clip", "Str_WL_Buffs" + suffix + "ClipDslv", "Dslv_200","", "True")

except:

    print gp.getmessages(0)

    print "Error occurred while Dissolving the clipped, merged buffers FC."

    sys.exit()


print ""

print "Script Completed."
Appendix D – Allometric equation uncertainty simulation

Part 1

# Summary: This program generates predictions for the biomass quantities of interest (BQI's) for each FCID in the input inventory file.
# This version EXCLUDES foliage from the slash predictions.

import os, shutil, random, csv
from math import *

#fname = 'Test_Sorted_LEMMA_DB_CSV2.txt'
fname = 'ProjArea_Biomass-TREE_LIVE_Sorted.txt'
bkp = 'TEMP_COPY_Proj_Biomass.txt'
outname = 'FCID_NF_PredInts15.txt'
#maxitr = 3
maxitr = 1000
folpct = .04 #Percent of AGB from foliage for AGB only eqns
pct_stump = .025 # Stump biomass in proportion to AGB
mmdc = 2.54 * 5 #Min merch DBH, conifers
mmdh = 2.54 * 6 #Min merch DBH, hardwoods
mtd = 2.54 * 4 #Min top diam
lnmd = 2.54 * 6 #Large non-merch fuel class minimum dbh
def MkBkp():
    cwd = os.getcwd()
    print cwd
    try:
        shutil.copy(cwd+'/'+fname, cwd+'/'+b kp)
        print 'Backup made.'
    except:
        print 'Copy failed'
        return False
    #now work on the backup and delete it manually when the script finishes
    return True

def Main():
    srcf = open(bkp, 'rb')
    try:
        csvr = csv.reader(srcf)
        old_fcid = 0
        li_fBQI = []
        i = 0
        for liLn in csvr:
            liLn = stripquotes(liLn)
            #Check if it’s the first line, if so, jump to next line.
            if len(liLn) < 2: continue
            if HdrLine(liLn[:2]): continue
fcid = int(liLn[1])

# Check line fcid against last fcid
if fcid != old_fcid and old_fcid != 0:
    # Write the FCID BQI tallies to file
    Write_fBQIs(old_fcid, li_fBQI)

    # Reset FCID BQI tallies
    li_fBQI = []

    old_fcid = fcid

# Calc BQI's for the tree
li_tBQI = BQI_Calc(liLn)

# Add tree BQI's to the FCID tallies
li_fBQI = AddBQI(li_tBQI, li_fBQI)

if i % 10000 == 0: print 'Finished line #' + str(i)

    i += 1

## print 'Finished line #', i

Write_fBQIs(old_fcid, li_fBQI)

del csvr

finally:
	sr.cf.close()

    print 'Closed Source File.'

def stripquotes(li):

    newli = []

    for i in range(len(li)):
if li[i].startswith('"') and li[i].endswith('"'):
    newli.append(li[i][1:-1])
else:
    newli.append(li[i])
return newli

def HdrLine(liLn):
    if not liLn[1].isdigit():
        print 'Header line skipped:', liLn
        return True
    elif liLn[1].isdigit(): return False
    else:
        print 'ERROR HdrLine: Only one of the first two fields is alphanumeric'
        prompt = raw_input('Press enter to continue...
')

def BQI_Calc(liLn):
    try:
        dbh = float(liLn[6])
    except:
        print 'Bad dbh value...\n', liLn
        Badtree(liLn)
        return [0, 0, 0, 0, 0, 0, 0]
    try: li_pred = di_eqns.get(liLn[2])(liLn)
    except:
print '\n\n', 50*'\n', 'ERROR: Couldn\'t find equations for the spp',\n'code:', liLn[2], '\n\n', liLn
raw_input('Press enter to continue.')
return [0, 0, 0, 0, 0, 0, 0]

#if any of the prediction values are negative, set them to 0
for i in range(len(li_pred)):
    if li_pred[i] < 0: li_pred[i] = 0

# li_pred format: [foliage, branch, stemwood, stembark, agb, agb_nf, topstem]
# Calc derivative quantities
stump = pct_stump * li_pred[4]
    # calcs for comm con
    if dbh >= mmdc:
        if gmerch < 0: gmerch = 0
        brkdfct = 0.03 * gmerch
        netmerch = gmerch - brkdfct
        aslash = m_lnms = mslash
    else:
        gmerch = netmerch = mslash = m_lnms = 0
elif liLn[2] == 'ALRU2':

    if dbh >= mmdh:
        if gmerch < 0: gmerch = 0
        brkdfct = 0.03 * gmerch
        netmerch = gmerch - brkdfct
        aslash = m_lnms = mslash
    else:
        gmerch = netmerch = mslash = m_lnms = 0
    else:

        # Calcs for non-comm spp
        if dbh >= lnmd:
            # Large non-comm trees
            gmerch = netmerch = mslash = 0
            aslash = m_lnms = li_pred[4] - stump - li_pred[0]  # No foliage
        else:

            # Small non-comm trees
            gmerch = netmerch = mslash = m_lnms = 0

        # Biomass quantities of interest in kg per tree
        bkpt = [aslash, m_lnms, mslash, gmerch, netmerch, li_pred[4], li_pred[5]]
#Make sure no numbers are negative
for i in range(len(bkpt)):
    if bkpt[i] < 0: bkpt[i] = 0

#If any numbers are unreasonably large, cap them
li_cap = [16000, 16000, 2700, 15500, 15000, 17000, 17000]
for i in range(len(bkpt)):
    if bkpt[i] > li_cap[i]: bkpt[i] = li_cap[i]

#Multiply biomass kg per tree by trees per Ha, then convert to t/Ac
btpa = [x * float(liLn[14]) / 2241.7 for x in bkpt]

#Return list of BQI's that the tree represents on a tons/Ac basis
return btpa

def AddBQI(li_tr, li_fc):
    #Add the values in the tree's list to the FCID's list
    #*Handle the first BQI set differently (li_fc will be [])
    if li_fc == []:
        return li_tr
    else:
        for i in range(len(li_tr)):
            li_fc[i] = li_fc[i] + li_tr[i]
        return li_fc

def Write_fBQIs(fcid, li_fc):
    #Write the FCID BQI tallies to file
outrow = [str(fcid)]
outrow.extend(li_fc)
csvw.writerow(outrow)

def pqty(se, n):
    """Prediction variation quantity""
    return (tvariate(n-2) * se * (1 + 1/n)**(1/2))

def tvariate(nu):
    """nu = degrees of freedom. This function is from
    x = random.gauss(0.0, 1.0)
    y = 2.0*random.gammavariate(0.5*nu, 2.0)
    return x / (sqrt(y/nu))

def Badtree(li):
    print 'The following tree caused an error.'
    print 'FCID:', li[1], ' Spp:', li[2], ' DBH:', li[6]
    print 'kg Foliage:', li[19], ' kg Branches:', li[18]
    print 'kg Stemwood:', li[20], ' kg Stembark:', li[21]

def OddTree(li):
    #For uncommon trees that didn't have any allometric equations
    return [0, 0, 0, 0, 0, 0]
def Pred_ABAM(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0925, 9))
    br = exp(log(float(liLn[18])) + pqty(.1346, 9))
    sw = exp(log(float(liLn[20])) + pqty(.0359, 14))
    sb = exp(log(float(liLn[21])) + pqty(.0592, 14))
    ts = exp(-3.5057 + 2.5744 * log(.865 * mtd) + pqty(.0359, 14)) +
        exp(-6.1166 + 2.8421 * log(.865 * mtd) + pqty(.0592, 14))
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_Abies(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0797, 25))
    br = exp(log(float(liLn[18])) + pqty(.089, 26))
    sw = exp(log(float(liLn[20])) + pqty(.0652, 20))
    sb = exp(log(float(liLn[21])) + pqty(.0534, 20))
    ts = exp((-3.7389 + 2.6825 * log(0.865 * mtd)) + pqty(.0652, 20))\
        + exp((-6.1918 + 2.8796 * log(0.865 * mtd)) + pqty(.0534, 20))
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]
def Pred_ABPR(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0753, 6))
    br = exp(log(float(liLn[18])) + pqty(.1821, 6))
    sw = exp(log(float(liLn[20])) + pqty(.1025, 6))
    sb = exp(log(float(liLn[21])) + pqty(.0992, 6))
    ts = exp(-3.7158 + 2.7592 * log(.865 * mtd) + pqty(.1025, 6)) +
        exp(-6.1000 + 2.8943 * log(.865 * mtd) + pqty(.0992, 6))
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_Cedar(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.119, 6))
    br = exp(log(float(liLn[18])) + pqty(.1088, 6))
    sw = exp(log(float(liLn[20])) + pqty(.0983, 6))
    sb = exp(log(float(liLn[21])) + pqty(.0957, 6))
    ts = exp(-2.0927 + 2.1863 * log(.865 * mtd) + pqty(.0983, 6)) +
        exp(-4.1934 + 2.1101 * log(.865 * mtd) + pqty(.0957, 6))
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]
def Pred_LALY(liLn):
    dbh = float(liLn[6])
    fol = float(liLn[19]) + pqty(.457, 23)
    br = float(liLn[18]) + pqty(.341, 23)
    sw = float(liLn[20]) + pqty(.141, 23)
    sb = 0
    ts = 0.0762 * (.865 * mtd)**2.3051 + pqty(.141, 23)
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_LAOC(liLn):
    dbh = float(liLn[6])
    fol = float(liLn[19]) + pqty(.324, 14)
    br = float(liLn[18]) + pqty(.459, 14)
    sw = float(liLn[20]) + pqty(.502, 13)
    sb = 0
    ts = 0.2942 * (.865 * mtd)**1.5593 + pqty(.502, 13)
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_PIEN(liLn):
dbh = float(liLn[6])
fol = float(liLn[19]) + pqty(.43, 13)

br = float(liLn[18]) + pqty(.479, 13)
sw = float(liLn[20]) + pqty(.213, 10)
sb = 0
ts = 0.2844 * (.865 * mtd)**1.3782 + pqty(.213, 10)

agb_nf = br + sw + sb
agb = agb_nf + fol

return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_PISI(liLn):
    dbh = float(liLn[6])
    fol = float(liLn[19]) + pqty(.13, 28)
    br = float(liLn[18]) + pqty(.13, 28)
    sw = float(liLn[20]) + pqty(.05, 21)
    sb = 0
    ts = 0.0402 * (.865 * mtd)**2.5520 + pqty(.05, 21)
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_Pinus(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0882, 33))
lbr = \exp(-5.2900 + 2.6524 \times \log(dbh) + pqty(.0809, 33))

dbr = \exp(-3.7969 + 1.7426 \times \log(dbh) + pqty(.096, 14))

sw = \exp(\log(float(liLn[20])) + pqty(.0507, 14))

sb = \exp(\log(float(liLn[21])) + pqty(.0692, 14))

ts = \exp(-4.2847 + 2.7180 \times \log(.865 \times mtd) + pqty(.0507, 14)) + \exp(-3.6187 + 1.8362 \times \log(.865 \times mtd) + pqty(.0692, 14))

br = lbr + dbr

agb_nf = br + sw + sb

agb = agb_nf + fol

return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_PICO(liLn):
    dbh = float(liLn[6])
    fol = \exp(\log(float(liLn[19])) + pqty(.11, 19))
    br = \exp(\log(float(liLn[18])) + pqty(.1131, 19))
    sw = \exp(\log(float(liLn[20])) + pqty(.0523, 19))
    sb = 0
    ts = \exp(-2.9849 + 2.4287 \times \log(.865 \times mtd) + pqty(.0523, 19))
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_PILA(liLn):
    dbh = float(liLn[6])
### Pred_PIPO(liLn):

```python
dbh = float(liLn[6])
fol = exp(log(float(liLn[19])) + pqty(.1938, 9))

lbr = exp(-5.3855 + 2.7185 * log(dbh) + pqty(.0683, 9))
# No SEE given for dbr eqn, used SEE from lbr instead

dbr = exp(-2.5766 + 1.444 * log(dbh) + pqty(.0683, 9))
sw = exp(log(float(liLn[20])) + pqty(.0587, 9))

sb = exp(log(float(liLn[21])) + pqty(.0837, 9))

ts = exp(-4.4907 + 2.7587 * log(.865 * mtd) + pqty(.0587, 9)) +\n   exp(-4.2063 + 2.2312 * log(.865 * mtd) + pqty(.0837, 9))

br = lbr + dbr

agb_nf = br + sw + sb

agb = agb_nf + fol

return [fol, br, sw, sb, agb, agb_nf, ts]
```

```
fol = exp(log(float(liLn[19])) + pqty(.296, 5))
br = exp(log(float(liLn[18])) + pqty(.2449, 5))
sw = exp(log(float(liLn[20])) + pqty(.0872, 5))
sb = exp(log(float(liLn[21])) + pqty(.1273, 5))
ts = exp(-3.984 + 2.6667 * log(.865 * mtd) + pqty(.0872, 5)) +\n   exp(-5.295 + 2.6184 * log(.865 * mtd) + pqty(.1273, 5))
agb_nf = br + sw + sb

agb = agb_nf + fol

return [fol, br, sw, sb, agb, agb_nf, ts]
```
def Pred_PSME(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0627, 123))
    lbr = exp((-3.6941 + 2.1382*log(dbh)) + pqty(.057, 123))
    dbr = exp((-3.529 + 1.7503*log(dbh)) + pqty(.079, 85))
    sw = exp(log(float(liLn[20])) + pqty(.0311, 99))
    sb = exp(log(float(liLn[21])) + pqty(.0324, 99))
    ts = exp(-3.0396 + 2.5951*log(0.865 * mtd) + pqty(.0311, 99)) +
        exp(-4.3103 + 2.4300*log(0.865 * mtd) + pqty(.0324, 99))
    br = lbr + dbr
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_TSHE(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.1025, 18))
    lbr = exp((-5.149 + 2.778 * log(dbh)) + pqty(.0992, 18))
    dbr = exp((-2.409 + 1.312 * log(dbh)) + pqty(.1887, 18))
    sw = exp(log(float(liLn[20])) + pqty(.0279, 18))
    sb = exp(log(float(liLn[21])) + pqty(.0325, 18))
    ts = exp((-2.172 + 2.257 * log(0.865 * mtd)) + pqty(.0279, 18)) +
        exp((-4.373 + 2.258 * log(0.865 * mtd)) + pqty(.0325, 18))
br = lbr + dbr
agb_nf = br + sw + sb
agb = agb_nf + fol
return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_TSME(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0477, 11))
    lbr = exp(-5.2581 + 2.6045 * log(dbh) + pqty(.0369, 11))
    dbr = exp(-9.9449 + 3.2845 * log(dbh) + pqty(.0447, 6))
    sw = exp(log(float(liLn[20])) + pqty(.0609, 14))
    sb = exp(log(float(liLn[21])) + pqty(.0604, 14))
    ts = exp(-4.8164 + 2.9308 * log(.865 * mtd) + pqty(.0609, 14)) +
        exp(-5.5868 + 2.7654 * log(.865 * mtd) + pqty(.0604, 14))
    br = lbr + dbr
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_JUOC(liLn):
    dbh = float(liLn[6])
    fol = float(liLn[19]) + pqty(.049, 10)
    br = float(liLn[18]) + pqty(.0825, 10)
    sw = float(liLn[20]) + pqty(.0539, 10)
sb = float(liLn[21]) + pqty(.1233, 10)

    ts = 0.0002 * (.865 * mtd)**2.6389 + pqty(.0539, 10) +
        0.00004 * (.865 * mtd)**2.6333 + pqty(.1233, 10)

agb_nf = br + sw + sb

    agb = agb_nf + fol

    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_TABR(liLn):

    dbh = float(liLn[6])

    fol = exp(log(float(liLn[19])) + pqty(.1025, 18))

    lbr = exp(-5.149 + 2.778 * log(dbh) + pqty(.0992, 18))

    dbr = exp(-2.409 + 1.312 * log(dbh) + pqty(.1887, 18))

    sw = exp(log(float(liLn[20])) + pqty(.0279, 18))

    sb = exp(log(float(liLn[21])) + pqty(.0325, 18))

    ts = exp(-2.172 + 2.257 * log(.865 * mtd) + pqty(.0279, 18)) +
        exp(-4.373 + 2.258 * log(.865 * mtd) + pqty(.0325, 18))

    br = lbr + dbr

    agb_nf = br + sw + sb

    agb = agb_nf + fol

    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_ALRU2(liLn):

    dbh = float(liLn[6])

    fol = float(liLn[19]) + pqty(.444, 53)
br = float(liLn[18]) + qty(.574, 53)
agb = exp(log(float(liLn[27])) + qty(.0644, 230))
sw = agb - fol - br
sb = 0

ts = exp(-2.2094 + 2.3867 * log(.865 * mtd) + qty(.0644, 230)) -
    (0.0100 * (.865 * mtd)**1.9398 + qty(.444, 53)) -
    (0.0069 * (.865 * mtd)**2.6516 + qty(.574, 53))

agb_nf = agb - fol

return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_SMBGr(liLn):
    dbh = float(liLn[6])
    agb = float(liLn[27]) + qty(.0551, 316)
    fol = folpct * agb
    agb_nf = agb - fol
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_ACMA3(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + qty(.0749, 18))
    lbr = exp(-4.236 + 2.430 * log(dbh) + qty(.1118, 18))
    dbr = exp(-2.116 + 1.092 * log(dbh) + qty(.3216, 18))
    sw = exp(log(float(liLn[20])) + qty(.0279, 18))
sb = \exp(\log(\text{float(liLn}[21]) + \text{pqty}(0.0568, 18))

\begin{align*}
ts &= \exp(-3.493 + 2.723 \times \log(0.865 \times \text{mtd}) + \text{pqty}(0.0279, 18)) + \\
& \quad \exp(-4.574 + 2.574 \times \log(0.865 \times \text{mtd}) + \text{pqty}(0.0568, 18))
\end{align*}

br = lbr + dbr

agb\_nf = br + sw + sb

agb = agb\_nf + fol

return [fol, br, sw, sb, agb, agb\_nf, ts]

def Pred_AACWGr(liLn):
    dbh = float(liLn[6])
    agb = float(liLn[27]) + \text{pqty}(0.0644, 230)
    fol = folpct \times agb
    agb\_nf = agb - fol
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb\_nf, ts]

def Pred_ARME(liLn):
    dbh = float(liLn[6])
    agb\_nf = float(liLn[28]) + \text{tvariate}(57) \times 1.23 \times (1 + 1/60)**(1/2)
    agb = agb\_nf / (1 - folpct)
    fol = agb - agb\_nf
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb\_nf, ts]
def Pred_BEPA(liLn):
    dbh = float(liLn[6])
    agb = float(liLn[27]) + pqty(10.5, 204)
    fol = folpct * agb
    agb_nf = agb - fol
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_CHCH7(liLn):
    dbh = float(liLn[6])
    fol = exp(log(float(liLn[19])) + pqty(.0987, 19))
    lbr = exp(-4.579 + 2.576 * log(dbh) + pqty(.1086, 19))
    dbr = exp(-7.124 + 2.883 * log(dbh) + pqty(.1683, 19))
    sw = exp(log(float(liLn[20])) + pqty(.0481, 19))
    sb = exp(log(float(liLn[21])) + pqty(.0598, 19))
    ts = exp(-3.708 + 2.658 * log(.865 * mtd) + pqty(.0481, 19)) +
        exp(-5.923 + 2.989 * log(.865 * mtd) + pqty(.0598, 19))
    br = lbr + dbr
    agb_nf = br + sw + sb
    agb = agb_nf + fol
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_MHGr(liLn):
    dbh = float(liLn[6])
agb = float(liLn[27]) + pqty(.0582, 289)
fol = folpct * agb
agb_nf = agb - fol
br = sw = sb = ts = 0
return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_LIDE3(liLn):
    dbh = float(liLn[6])
    agb_nf = float(liLn[28]) + tvariate(57) * 1.22 * (1 + 1/60)**(1/2)
    agb = agb_nf / (1 - folpct)
    fol = agb - agb_nf
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_POBAT(liLn):
    dbh = float(liLn[6])
    if dbh <= 10:
        agb = exp(log(float(liLn[27])) + pqty(.0644, 230))
    else:
        agb = float(liLn[27]) + tvariate(49) * 42.44 * (1 + 1/55)**(1/2)
    fol = folpct * agb
    agb_nf = agb - fol
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]
def Pred_POTR5(liLn):
    dbh = float(liLn[6])
    agb = float(liLn[27]) + pqty(.141, 118)
    fol = folpct * agb
    agb_nf = agb - fol
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_QUCH2(liLn):
    dbh = float(liLn[6])
    agb_nf = float(liLn[28]) + tvariate(55) * 1.18 * (1 + 1/58)**(1/2)
    agb = agb_nf / (1 - folpct)
    fol = agb - agb_nf
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_QUGA4(liLn):
    dbh = float(liLn[6])
    agb_nf = float(liLn[28]) + tvariate(57) * 1.26 * (1 + 1/60)**(1/2)
    agb = agb_nf / (1 - folpct)
    fol = agb - agb_nf
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]
def Pred_QUKE(liLn):
    dbh = float(liLn[6])
    agb_nf = float(liLn[28]) + tvariate(56) * 1.22 * (1 + 1/59)**(1/2)
    agb = agb_nf / (1 - folpct)
    fol = agb - agb_nf
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

def Pred_UMCA(liLn):
    dbh = float(liLn[6])
    agb_nf = float(liLn[28]) + tvariate(57) * 1.24 * (1 + 1/60)**(1/2)
    agb = agb_nf / (1 - folpct)
    fol = agb - agb_nf
    br = sw = sb = ts = 0
    return [fol, br, sw, sb, agb, agb_nf, ts]

#-----------------------------------------------#

di_eqns = {"PSME": Pred_PSME, "ABAM":Pred_ABAM, \
           "ABCO":Pred_Abies, "ABGR":Pred_Abies, \
           "ABLA":Pred_Abies, "ABMA":Pred_Abies, \
           "ABSH":Pred_Abies, "ABPR":Pred_ABPR, \}
"CADE27":Pred_Cedar, "CHLA":Pred_Cedar, \
"CHNO":Pred_Cedar, "THPL":Pred_Cedar, \
"LALY":Pred_LALY, "LAOC":Pred_LAOC, \
"PIEN":Pred_PIEN, "PISI":Pred_PISI, \
"PIAL":Pred_Pinus, "PIJE":Pred_Pinus, \
"PIMO3":Pred_Pinus, "PICO":Pred_PICO, \
"PILA":Pred_PILA, "PIPO":Pred_PIPO, \
"TSHE":Pred_TSHE, "TSME":Pred_TSME, \
"JUOC":Pred_JUOC, "TABR2":Pred_TSHE, \
"ALRU2":Pred_ALRU2, "ACCI":Pred_SMBGr, \
"ACGL":Pred_SMBGr, "ACMA3":Pred_ACMA3, \
"CONU4":Pred_ACMA3, "ALRH2":Pred_AACWGr, \
"SASC":Pred_AACWGr, "SALIX":Pred_AACWGr, \
"ARME":Pred_ARME, "BEPA":Pred_BEPA, \
"BEPAC":Pred_BEPA, "CHCH7":Pred_CHCH7, \
"FRLA":Pred_MHGr, "PREM":Pred_MHGr, \
"PRVI":Pred_MHGr, "PRUNU":Pred_MHGr, \
"LIDE3":Pred_LIDE3, "POBAT":Pred_POBAT, \
"POTR5":Pred_POTR5, "QUCH2":Pred_QUCH2, \
"QUGA4":Pred_QUGA4, "QUKE":Pred_QUKE, \
"UMCA":Pred_UMCA, "2TN":OddTree, "FRPU7":OddTree, \
"CRATA":OddTree, "SEGI2":OddTree, "MAFU":OddTree, \
"CELE3":OddTree, "2TB":OddTree}
if MkBkp():

    outfile = open(outname, 'ab')

    try:

        csvw = csv.writer(outfile)

        for itr in range(maxitr):

            print 30*'\-', '\n', 'Beginning iteration #', itr

            Main()

        del csvw

    finally:

        outfile.close()

        print 'Close output file.'
Part 2

This program takes a raster of FCID's in harvestable forests and a set of multiple biomass predictions for each FCID and predicts the recoverable biomass from those forests by randomly drawing a new plot biomass value for each cell from one of the multiple biomass predictions for that FCID.

import csv, random

maxiter = 100

#Inventory period raster of FCID's in cells that will yield biomass, nodata values in in the other cells.
rastn = 'rast_PI1004_40to59_FCIDs.txt'
FCIDpredfn = 'FCID_NF_Preds15.txt' #List of biomass predictions for the FCID's
resultsfn = 'ProjTotalBDT_AlloUnc_Distn_NF_TEST-quicker.txt' #output file
ACPERCELL = 0.222394843
RECOVRT = 0.7

def main():
    print 'Initializing raster and prediction data...'
    ndval = get_ndval() #Get NODATA value for the raster
    #Build dict of fcids and their cell counts in raster
di_fcid_cells = read_raster(ndval)
    #Build dict of fcids and their predxn lists
di_fcid_preds = make_pred_di(di_fcid_cells)

li_fcid = di_fcid_cells.keys() #Create list of FCIDs in rast
li_fcid.sort()  #Sort the list

for i in range(maxiter):
    print 'Starting iteration #', i
    #Now pick a bqi set for each biomass bearing cell from its FCID preds
    li_bt = 7 * [0]
    for fcid in li_fcid:
        li_fbt = pick_preds4fcid(di_fcid_cells[fcid], di_fcid_preds[fcid],
                                  len(li_bt), fcid)
        for i in range(len(li_bt)):
            li_bt[i] += li_fbt[i]
    print '\n\nRcvd biomass totals for raster =', li_bt, '\n\n'

    #Write results for iteration to output file.
    outf = open(resultsfn, 'ab')
    try:
        print 'Opened output file.'
        wtr = csv.writer(outf)
        wtr.writerow(li_bt)
    finally:
        outf.close()
        print 'Closed output file'
def read_raster(ndval):
    di_fcid_cells = {} # dict of fcids and their cell counts in raster
    tot_cells = 0
    rast = open(rastn, 'r')
    try:
        print 'Opened raster text file.'
        for line in rast:
            if line[0].isalpha(): continue
            li_row = line.split(' ')
            for cell in li_row:
                # process each cell
                #!!NOTE: cell == '' may be unnecessary
                if cell.strip() == "": continue
                if int(cell) == ndval: continue
                # Read the cell's FCID
                fcid = int(cell)
                # Is it in the dict? If so, add 1 to cell cnt for that FCID
                if fcid in di_fcid_cells: di_fcid_cells[fcid] += 1
                # If no, add FCID to dict with a cell count = 1
                else: di_fcid_cells[fcid] = 1
                tot_cells += 1 # Increment the total cell tally
finally:
    rast.close()
    print 'Closed raster text file.'

# Double check total cell tally

tot_cells_b = 0
for j in di_fcid_cells.values():
    tot_cells_b += j
print '
Total number of biomass cells in raster =', tot_cells

if tot_cells != tot_cells_b:
    print '

TOTAL CELLS AND SUM OF CELLS IN ALL VEG CLASSES',
    'DON\'T MATCH!'

print 'Sum of cells in all VC\'s =', tot_cells_b, '\n'
    stop()

return di_fcid_cells

def make_pred_di(di_fcid_cells):
    li_fcid = di_fcid_cells.keys()  # Create list of FCIDs in rast
    li_fcid.sort()  # Sort the list

    # Initialize the FCID predxns lists dictionary
    di_fcid_preds = {}
    for fcid in li_fcid:
        di_fcid_preds[fcid] = []
    # Then open grand predxn file and sort predxns into dict
f = open(FCIDpredfn, 'rb')

try:
    print 'Grand prediction file opened'
    rdr = csv.reader(f)
    for row in rdr:
        if int(row[0]) in li_fcid:
            di_fcid_preds[int(row[0])].append(row[1:])

finally:
    f.close()
    print 'Grand prediction file closed.'
    del rdr
    return di_fcid_preds

def pick_preds4fcid(cellcount, li_preds, bt_len, fcid):
    li_fbt = [0] * bt_len  # Fcid Biomass Totals
    # For each occurrence of that FCID in the raster draw a bqi predxn
    for cell in range(cellcount):
        # Pick one of the predictions at random
        ri = int(random.random() * len(li_preds))  # Rand list index
        # Add those biomass quantities to the raster totals
        for i in range(bt_len):
            if int(RECOVRT * float(li_preds[ri][i]) + 0.5) > 0:
                li_fbt[i] += (RECOVRT * float(li_preds[ri][i]) * APERCELL)
            if (RECOVRT * float(li_preds[ri][i]) * APERCELL) > 700:
print \n\nABNORMALLY LARGE BIOMASS VALUE!

print 'FCID ': fcid ',  BQI #: ', i ',  recovered biomass =', \n(RECOVRT * float(li_preds[ri][i]) * ACPERCELL)

print 'Raw BQI\'s (Tons/Ac) for this FCID:', \ni_preds[ri], \n
stop()

## print 'Recvd biomass totals for FCID #', fcid ', cell count =', cellcount
## print li_fbt
return li_fbt

def get_nodval():
    """Get the NODATA value from the raster file"""

    line = ""
    rast = open(rastn, 'r')
    try:
        for j in range(6):
            line = rast.readline()
    finally: rast.close()
    li_line = line.split(' ')
    return int(li_line[-1])

def stop():
    raw_input('Press Ctrl-c... or enter to continue')
main()