FEEDSTOCK LOGISTICS (PART 2 OF 6)

TASK 1: DEVELOP BIOMASS RECOVERY COEFFICIENTS FOR OR, WA, ID, MT

Authors	ORGANIZATION
John Sessions	Oregon State University OSU
Kevin Boston	Oregon State University OSU
Rene Zamora-Cristales	Oregon State University OSU
Francisca Belart	Oregon State University OSU
Gevan Marrs	Consultant
Glen Murphy	Consultant

(This report is part of a larger collection: Sessions, J., Boston, K., Zamora-Cristales, R., Belart, F., Marrs, G. & Murphy, G. (2017). Feedstock Logistics. NARA Final Reports. Pullman, WA. Northwest Advanced Renewables Alliance (NARA). "Feedstock Logistics" can be retrieved at https://research.libraries.wsu.edu/xmlui/handle/2376/5310)

COMPLETED 2017

TABLE OF CONTENTS

nararenewables.org CC BY-NC-ND

NARA is led by Washington State University and supported by the Agriculture and Food Research Initiative Competitive Grant no. 2011-68005-30416 from the USDA National Institute of Food and Agriculture.

Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the U.S. Department of Agriculture.

LIST OF FIGURES

LIST OF TABLES

TASK 1: DEVELOP BIOMASS RECOVERY COEFFICIENTS FOR OR, WA, ID, MT

1. INTRODUCTION

This portion of the project will evaluate the availability of woody biomass the results as a by-product of forest harvesting for energy consumption and provide the inputs to the quantities of materials that remain on-site that is the basis for the discussions concerning the sustainability of these practices. This includes the protection of wildlife habitat and maintenance of nutrient cycling process while determining the supply of raw material available for processing.

The goals of the assessment portion of the project were to develop:

(1) Techniques to estimate the biomass piles;

(2) Apply these techniques to residue produced from harvesting operations to estimate amount of biomass that is available at various collection costs from forest harvesting units to support the more detailed logistical analysis of biomass hauling; and

(3) Determine the volume of residue that remains in the forest.

This information is used support further discussion of sustainability of the processes by providing volumes of material that may impact wildlife habitat, nutrient cycling and air quality due to the common practice of burning these piles as part of activities that make the area for ready for replanting.

There are a number of potential sources of woody biomass from forest operations, this can be solid material such as bark, fletches, trimming and sawdust that are produced during the lumber manufacturing project, or they can be liquid by-products such a black liquors from the kraft pulp-making processes. However, these manufacturing residues are already used as inputs to a variety of other products such as engineered wood products such as medium density fiberboard, bark is either burned in boilers often in combined heat and power generation activities that can support kiln drying of lumber or conditioning of logs prior peeling veneers. Therefore, this project considered that these products were unavailable for the production of jet fuel and that a new source of raw material was necessary for the production of jet fuel and that raw material was logging residue. This material is currently not used by other manufacturing process and is commonly burned on site as part of the operations to prepare the site for reforestation.

Contributions to the section reports for this task draw from:

Section 2.
Long, J.J., and K. Boston. 2014. An evaluation of alternative measurement techniques for estimating the volume of logging residues. **Forest Science**. 60(1):200-204.

Section 3,4.
Zamora-Cristales, R., K. Boston, J. Long, and J. Sessions. 2016. Economic Estimation of Available Biomass following Logging Operations in Western Oregon and Washington. Submitted to **Canadian J. of Forest Research,** December 2016.

Section 5.
Belart, Francisca, 2016. Forest Harvest Residue Moisture Management in the Pacific Northwest, USA, PhD dissertation, **Oregon State University**, Corvallis, OR. 126 pp.

Section 7.
Berry, M., R. Zamora-Cristales, and J. Sessions. 2015. Assessing Spatial Distribution and Availability of Forest Biomass by Harvesting System in the Pacific Northwest, USA. In Proceedings: 2015 *Council on Forest Engineering* (COFE*) annual meeting,* Univ. of Kentucky, July 19-22, Lexington, KY, USA.

2. ASSESSMENT METHODS

A variety of methods can be used to develop estimates of biomass. Some are broad regional models that use a recoverable percentage of the total available biomass as the basis for estimating available and remaining harvesting residues. These methods begin by estimating the total available biomass using allometric equations, equations that use the species, diameter and sometimes the height to estimate the biomass of the various components of a tree such as needles, bark, branches, tops and bole. This becomes the theoretical maximum volume available. It is assumed that harvesting operations remove the merchantable part of the tree bole, the remainder of the logging residue is available for collection. Factors are developed that then estimate the percentage of this material that is recovered during biomass harvesting operations.

There are many post-harvest forest residue assessments used to estimate the supply for biomass energy facilities. Thiffault et al. (2015) reviewed 68 studies in temperate and boreal forests of eastern North America and western Europe. They found an average slash recovery rate of 52% (sd = 18%, range 5-90%) with highest slash recovery rates in northern Europe. Early studies in Sweden summarized by

Hakkila (1989) suggested slash recovery levels of 50-75% following mechanized logging, but suggested that cost of collection goes up quickly with the recovery ratio and there is an increasing risk of contaminating residues. He concluded that a very high recovery ration is seldom feasible. Nilsson et al. (2015) found that about 70% of forest harvest residues are piled, but only about 55% reach the truck. Gan and Smith (2006) assumed that 70% of the residues after harvests was available as feed stock for biomass energy. Their estimate was calculated using the allometric equations developed by the United States Department of Agriculture Forest Service Forest Inventory and Analysis (FIA) data system. Kumar et al. (2003) estimated the available logging residue are between 15% and 25% of total residues available that produced an average 0.247 dry metric tonnes (DMt/ ha) (0.11 tons/ acre) of net residue per harvested hectare in Alberta, Canada. Likewise, in British Columbia, Canada, Akhtari et al. (2013) assumed that 80% of the residuals not recovered during the normal operation exists as roadside slash as part of standard logging practices in Canada. Kizha and Han (2015) reported on recovery from whole tree logging using cable and shovel logging in northern California on sites being converted from mixed stands of conifers and hardwoods to redwood. They reported that about 60% of the residues were recovered from cable harvest units and 70% were recovered on shovel units. Recovery rates were based on use of species-specific regional allometric equations using diameter at breast height as the input variable for estimating total potential harvest residue and weight scales at the power plant for calculating residues removed. Recovered biomass on the cable harvest units was about 110 BDT/ha and about 157 BDT/ha on the shovel harvest units.

Nurmi (2007) studied the impact of three different logging methods on the recovery of logging residues. These included felling and limbing on one side of the strip road, felling and limbing on both sides of the strip road and felling and limbing in the conventional manner in an 11 ha stand. They found that the recovered residues varied between 33.4 and 30.4 metric tonnes per hectare (ha). The recovery rate was between 58.4% and 78.6% of the estimated total biomass. The highest amount of recoverable residues was available when the material was piled along both sides of the road following ground-based logging operations.

The results of these studies showed that there is a significant variability in the amount of harvesting residues produced from the different forest types, and that is impacted by logging systems. The variation in the NARA region, Idaho, Montana, Oregon and Washington (Figure FL-1.1), ownership, terrain, vegetation types is large. For example, rotation ages vary between 35 in 50 in the western portion of the region and may approach 100 years in the eastern portion of the region. There are a variety of logging systems that include a full range of ground and cable logging systems that make "single number approach" difficult to justify.

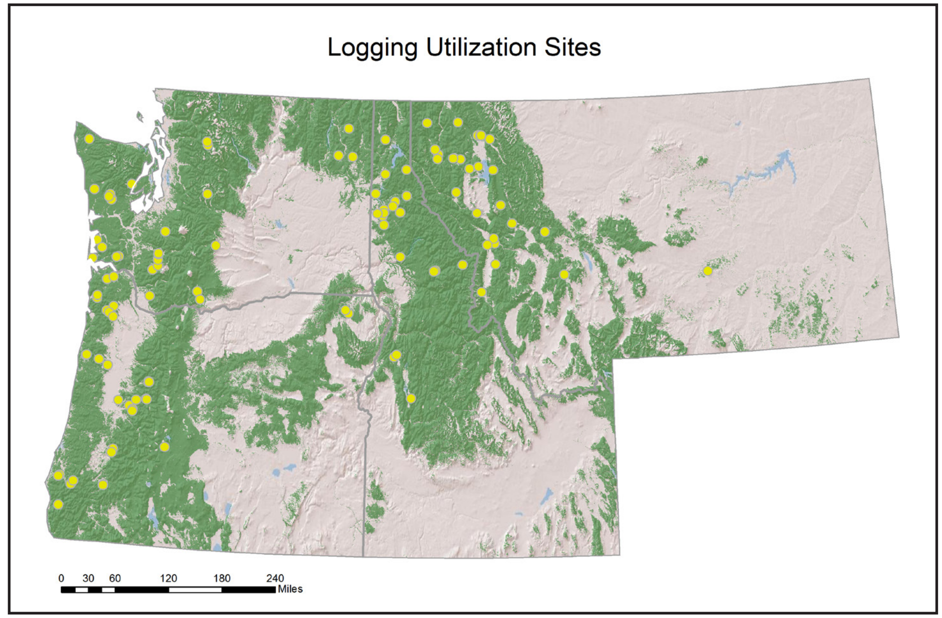

Figure FL-1.1. NARA Logging Utilization Sites. Map. [ca. 1:6,000,000]. Missoula, MT: Bureau of Business and Economic Research, University of Montana, 2016 prepared by Chelsea P. McIver.

The Forest Industry Research Group (FIRP), Bureau of Business and Economic Research (BBER), University of Montana has developed a technique to calibrate these allometric models with site specific data to develop improved estimate the available biomass (Berg et al., 2016). The information included in their calibration model are: the logging system, utilization standard, such as the minimum top diameter accepted by saw mills and the categorical variables such as the existence of a pulp market. In low pulpwood markets, logs with top diameter ranging from 4 to 8 inches may not be utilized (Perez-Garcia et al. 2012) and become harvesting residue that is feedstock for bioenergy products (Table FL-1.1). Recently, Berg et al. (2016) presented predicted logging residue ratios for the PNW based on whether pulpwood was being recovered and logging method. In addition to the pulpwood and non-pulpwood residue, large diameter butt log chunks can be available. These latter pieces are usually the result of the resizing process of the logs at the landing, particularly to meet export log requirements.

Table FL-1.1. Physical characterization of forest biomass in Washington state (Perez-Garcia et al., 2012)

PHYSICAL CHARACTERIZATION OF FOREST BIOMASS IN WASHINGTON									
		WESTSIDE FOREST ECOSYSTEMS							
		DOUGLAS-FIR		WESTERN HEMLOCK		TRUE FIR/ MIXED CONIFER		RED ALDER	
		LOW RANGE	HIGH RANGE	LOW RANGE	HIGH RANGE	LOW RANGE	HIGH RANGE	LOW RANGE	HIGH RANGE
PROCESSED BIOMASS MATERIAL	PIECE SIZE	3/16"	4"	3/16"	4"	3/16"	4"	3/16"	4"
	SPECIFIC GRAVITY (Green Volume Basis)	0.45	0.48	0.42	0.45	0.31	0.42	0.37	0.41
	AS RECEIVED MOISTURE CONTENT (%)	35%	65%	35%	68%	35%	70%	35%	65%
	ASH CONTENT (%)	0.50%	1.50%	0.83%	1.85%	0.40%	2.60%	0.87%	5.90%
	HIGH HEATING VALUE (BTU/DRY LB)	8179	9134	8414	8900	8370	8974	7990	8760
UNPROCESSED MATERIAL	TOP DIB (INCHES) WITH PULP LOGS MERCHANDIZED	1.0	3.0	1.0	3.0	1.0	4.0	1.0	3.0
	TOP DIB (INCHES) WITHOUT PULP LOGS MERCHANDIZED	4.0	6.0	4.0	6.0	4.0	7.0	4.0	8.0

Data collection from active harvesting operations allow for improved estimates of the available biomass. Morgan and Spoelma (2008) have developed this method to estimate the biomass in California. Table FL-1.2 demonstrates the variability in the volume estimate for the various species found in California and that are also found in NARA region.

Table FL-1.2. Percentage of deliverable wood by species from site-specific region (Morgan and Spoelma, 2008).

Tree species	Percentage of felled trees	Percentage of mill-delivered volume (cubic basis)	Percentage of growing-stock removals (cubic basis)	Percentage of logging residue (cubic basis)
True firs	35.8	34.2	34.0	31.9
Douglas-fir	23.8	26.7	26.9	27.8
Redwood	15.0	14.5	14.7	17.9
Ponderosa pine	12.5	14.0	13.8	11.2
Incense-cedar	5.7	2.5	2.6	4.5
Sugar pine	4.4	5.0	4.9	4.0
Other softwoods	2.8	3.0	3.0	2.6
Hardwoods	0.1	0.0	0.0	0.0
All species	100%	100%	100%	100%

The samples were taken from the four ecoregions in the NARA areas (Figure FL-1.1) including the western Oregon, (orange), western Washington (green), the Blue Mountains (yellow) and Inland Empire (blue). The results from the sampling and analysis are shown in Figure FL-1.2 for Oregon and Washington. It describes the percentage of volume by diameter class that is available for biomass collection. In Oregon, where the primary species is Douglas-fir (*Pseudotsuga menziesii*), the percentage varies from 2 to 8 percent with an average around 3 percent of total standing biomass that includes the tree bole for saw timber. In Washington, where western hemlock (*Tsuga heterophylla)* composes more of the stands, the range is similar to Douglas-fir, between 2 and 8 percent with an average near 4%. Hemlock is considered to have a higher limb density than Douglas-fir accounting for this decrease (Simmons et al., 2015). In Washington, the residue factor for trees in the 6-inch diameter class was over six times higher than in Oregon primarily associated with difference between Douglas-fir and western hemlock (Simmons et al., 2015).

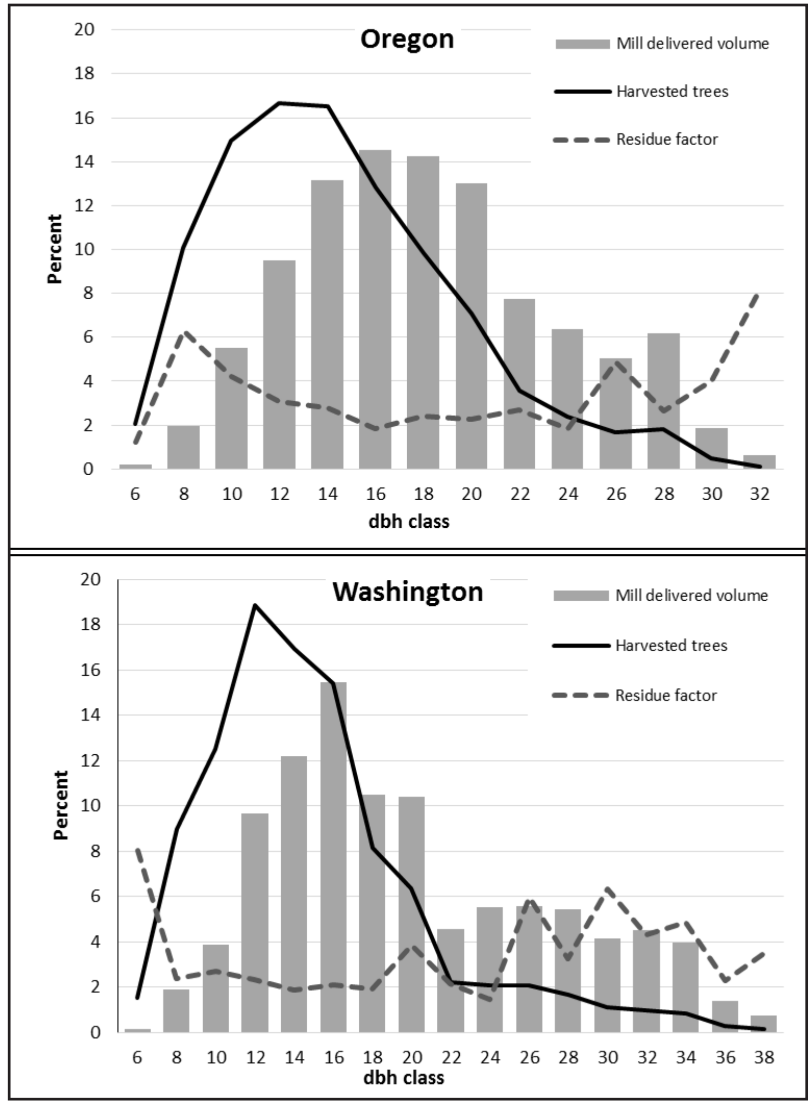

Figure FL-1.2. Volume and residue yields from various diameter groups in Oregon and Washington from logging operations sampled between 2011 and 2015.

The work of the Forest Industry Research Group (FIRP), Bureau of Business and Economic Research (BBER), University of Montana was to estimate the total available biomass that was available; however, their work did not consider the economics of collection of the harvesting residue, which we believed to a key factor in the success of the NARA project was to have an estimate the cost to collect this biomass. Thus, new methods were developed to determine the economically available harvest residue in the region. The goal was to both provide factors to these regionally calibrated models as well as support logistic operations as the unit level with reliable estimates that is commonly used in break-even analysis to evaluate various collection systems.

There are several assumptions that were made. One assumption was that only the harvesting reside that was in piles following the logging and site preparation was available for collection to be considered for feedstock. No new collection of dispersed slash would be considered due to high cost of this process. The second was that a constant packing ratio, a ratio of solid wood to voids was used in the piles. 0.20 (Hardy 1996). Therefore, the goal was to estimate the volume shell for all of the piles in a logging unit and apply the 0.20 packing ratio compute the solid wood component.

The first step was to determine a suitable method to measure the harvesting residue piles. Measuring biomass piles is a difficult task due the variations in wood piece sizes that are found in the biomass piles. There can be large, defective pieces from bole of the tree to very small limbs with needles on. Thus, biomass piles do not have uniformity of sand, gravel or even wood chips that will stack themselves at an angle of repose. Large pieces will stick out of the pile, and the result is piles that form odd shapes. Howard (1981) developed a technique to estimate the pile size using a two-step process. The first step estimates the basic shape of the pile and the second step measures the parameters for that particular shape pile. For example, if a pile were a half-sphere, the step would be to recognize that pile shape, half-sphere, then measure the diameter of the sphere to compute the volume. Figure FL-1.3 describes the shapes used by Howard (1981) to estimate the volume in the biomass piles.

To test this suitability of this approach at measuring piles for the NARA project, four student workers were asked to independently measure the volume of these piles. All of the students had training in elementary surveying and forest measurements. The result was that the students could not agree to the shape of the piles, and as a result of not being able to agree on the basic shape of the pile, there was a very large variation in their volume estimates. The larger piles made by machine resulted in increased complexity of the shape that made determining the shape difficult to estimate and the ultimately resulted in significant disagreements to the pile volume.

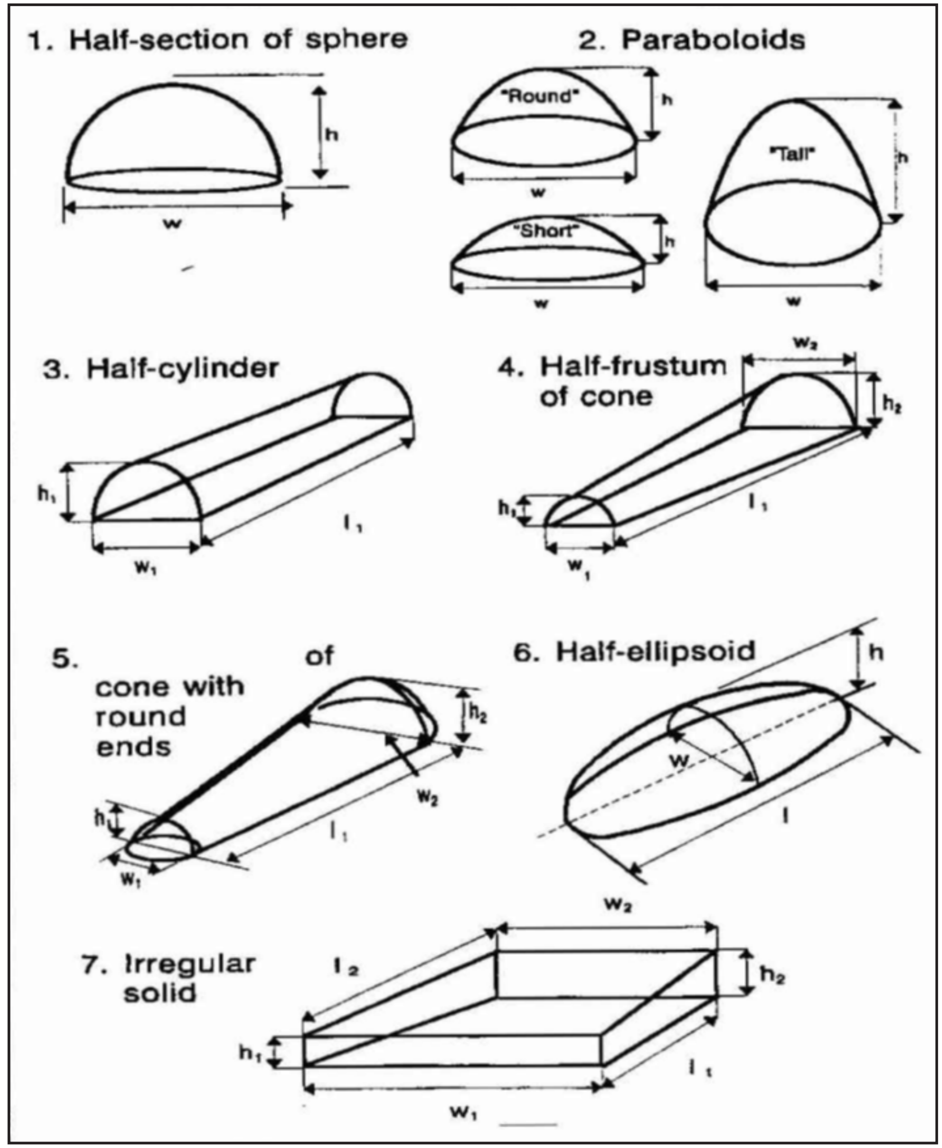

Figure FL-1.3. Example shapes used to estimate the volume in biomass piles (Howard, 1981; Hardy, 1996).

Thus, a new technique had to be found. It must be able to estimate complex pile shapes in a consistent manner and not rely on the judgment of the person measuring the biomass pile. Due to the height and unstable nature of the biomass piles, one constraint was to measure these piles, but no one was allowed to climb on the piles to take measurements. This eliminated many traditional surveying techniques.

The system selected combined the MapSmart software with a laser range-finder. Data is shared using Blue-Tooth communications between the laser range-finder and the handheld data recorder. The laser range-finder eliminated the need to climb on the piles as the measurements could be collected remotely. Thus, this system had the desirable characteristics: it could be performed by one person, and it was consistent among a variety of users. We began with a validation of the study of the systems.

To compare with the best estimated, the MapSmart system was compared to terrestrial LIDAR data. LIDAR data allows for the capture of the greatest amount of detail; however, the cost of the equipment and time to process the data result in the approach being uneconomical for measuring a large number biomass piles. Additionally, our terrestrial LIDAR unit can be damaged by water making it unsuitable for working in much of the NARA region for much of the year.

Thirty piles were selected from a variety of harvesting treatments in the NARA region. The piles ranged from 29.2 to 1,775 m^3 with an average pile size of 157 m^3. The pile volumes were estimated using the geometric method, the laser scanner method with MAPSmart software and the Terrestial LIDAR (Long and Boston, 2014). A minimum of 150 points were collected from each pile with the laser scanner. The data was used to compute a triangular irregular network (TIN) that was used to compute the volume of the shell that best enclosed the pile. To estimate the volume of solid wood, a 0.2 packing ratio (Hardy, 1996) was applied to these estimates. Examples of the different techniques are showed in Figures FL-1.4 through FL-1.7. Figure FL-1.4 is the natural picture of the pile; Figure FL-1.5 is the LIDAR and shows the complexity of the pile with large log segments coming out of the pile. Figure FL-1.6 shows the MAP smart representation of the pile a TIN. Finally, Figure FL-1.6 is the geometric shape of the pile.

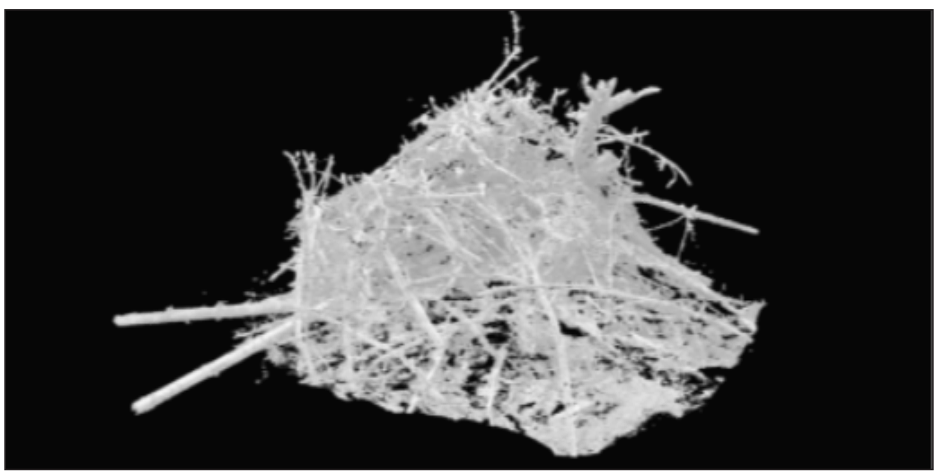

Figure FL-1.4. This shows the mixture of material in a pile.

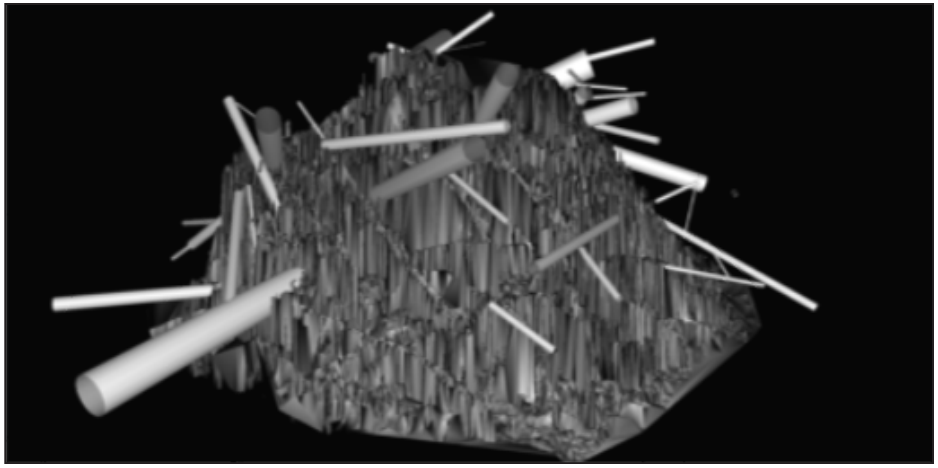

Figure FL-1.5. The LIDAR representation of the pile with a computed volume of 39.6 cubic meters

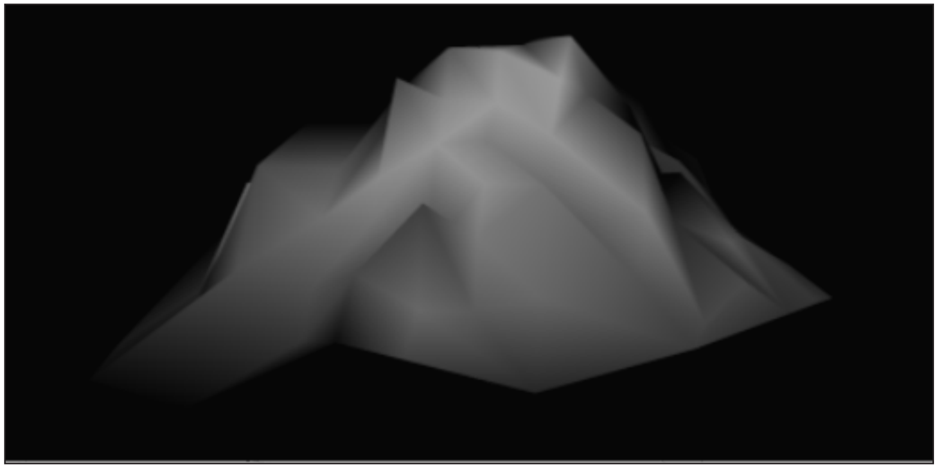

Figure FL-1.6. The MAPSmart system with laser and computed volume of 35.7 cubic meters.

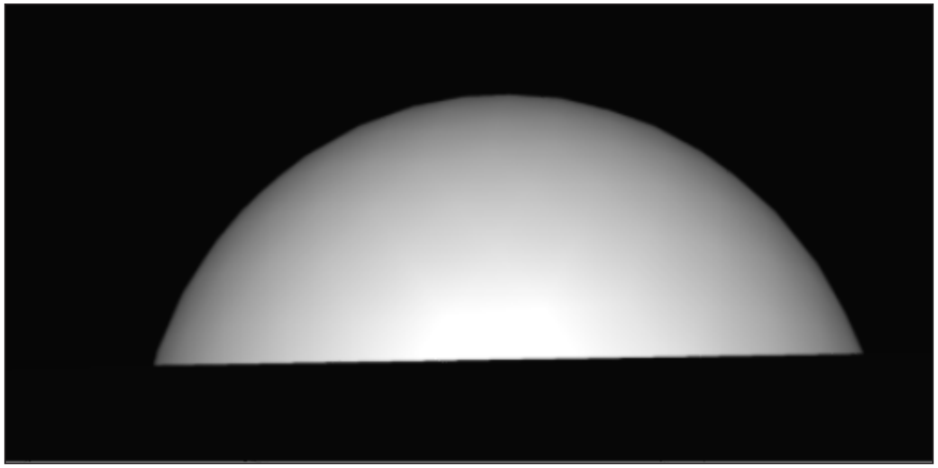

Figure FL-1.7. The geometric shape for this, which was a short paraboloid with a volume 22.8 cubic meters.

Two statistical methods were applied to determine whether lower costs testing methods produced results that are significantly different from higher costs methods. One between the terrestrial LIDAR and the MapSmart System and the second was between the LIDAR and the geometric methods. The goal was compare these easier to implement methods with the costly terrestrial LIDAR estimates.

After the data was collected and pile volumes were computer derived for the three methods, two paired t-tests were performed to determine whether the geometric and laser rangefinder measurements were significantly different from the LiDAR-generated estimates. The first was between the MAPSmart system and the terrestrial LiDAR estimates, and the other was between the geometric method and the terrestrial LiDAR estimate. The results showed that there were no statistically significant differences between the geometric and the laser rangefinder techniques and the more accurate LiDAR-method ($P = 0.82$ and $P = 0.13$, respectively). (Long and Boston, 2014). However, the geometric method was applied by a single person that found the variation in the measurements of the piles was not incorporated in this comparison.

A more detailed statistical test was performed, the concordance correlation analysis was used to determine whether the geometric and MAPSmart system would be a reliable substitute for control system, the terrestrial LIDAR. Measurement techniques with perfect repeatability would result in a concordance correlation coefficient of 1. The results of the concordance correlation analysis indicated that the geometric and control volume estimates were moderately correlated (0.73) (Figure FL-1.8). As a result, geometric volume estimates were not a reasonable substitute for the more complicated control estimates. However, a concordance correlation coefficient of 0.91 suggested that the laser rangefinder and LiDAR volume estimates were strongly correlated (Figure FL-1.9), indicating that the laser rangefinder was a reasonable substitute for control measurements (Long and Boston 2014). The conclusion was that the MAPSmart system was a reliable and low cost alternative to the LIDAR to determine pile volume.

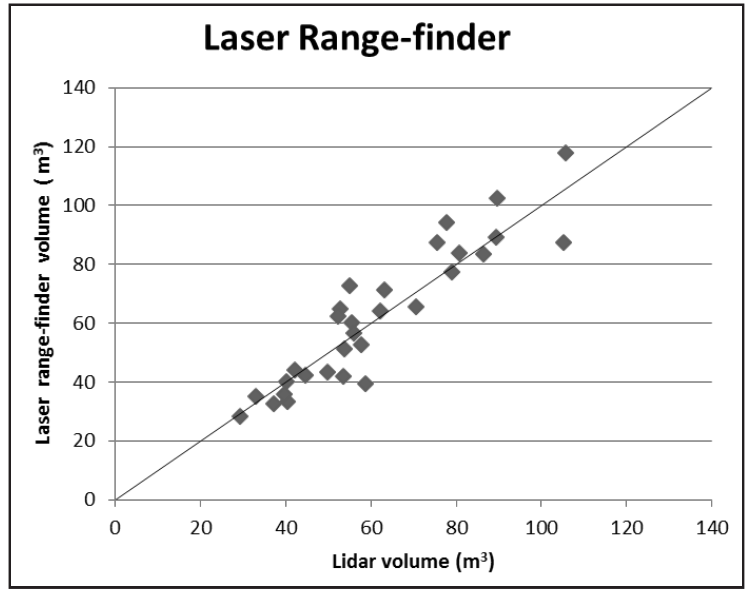

Figure FL-1.8. Concordance comparison between LIDAR and MAPSMART systems for 30 piles (Long and Boston, 2014).

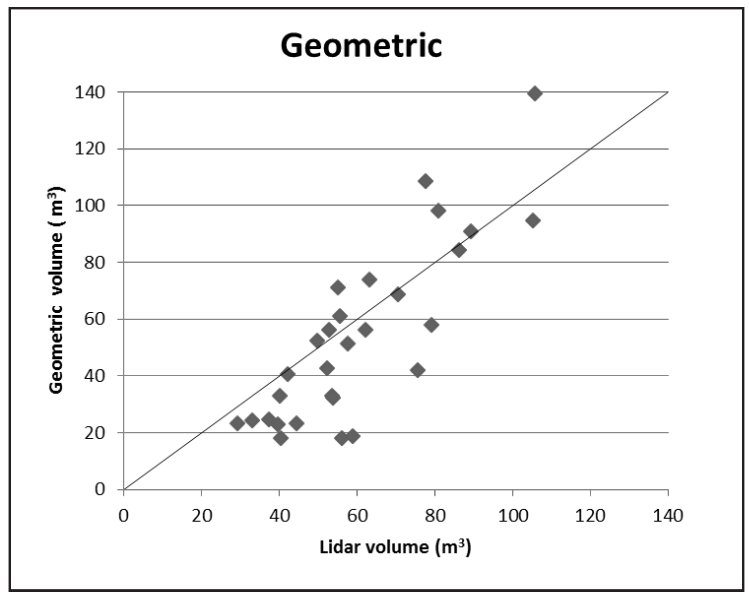

Figure FL-1.9. Concordance comparison between LIDAR and geometric systems for 30 piles (Long and Boston, 2014).

3. ECONOMICALLY AVAILABLE BIOMASS

3.1 Methodology

The goal for this portion of the assessment project is to be able to categorize the amount and location of the biomass piles found in the forest following site preparations. The goal is to support the logistics analysis and the regional supply analysis to determine the available volume that can be produced using increasing collection costs such as going further into the harvest unit to retrieve piles. The theoretical model is shown in Figure FL-1.10 that displays the potential collection of biomass from harvesting units based on the distance from the mill. Closer to mill, collection could reach further from the landing to produce raw material for the bioenergy production. Further from the mill, less effort can be expended in collecting biomass due to the higher hauling costs from the collection point to the final destination. Thus, in the outer circle in Figure FL-1.10, one may only collect the biomass that is pile on the road at points that are easily accessible by large trucks, as the comminution and hauling can consume all of the value from the raw material that results in no value remaining for moving the piles to the comminution site.

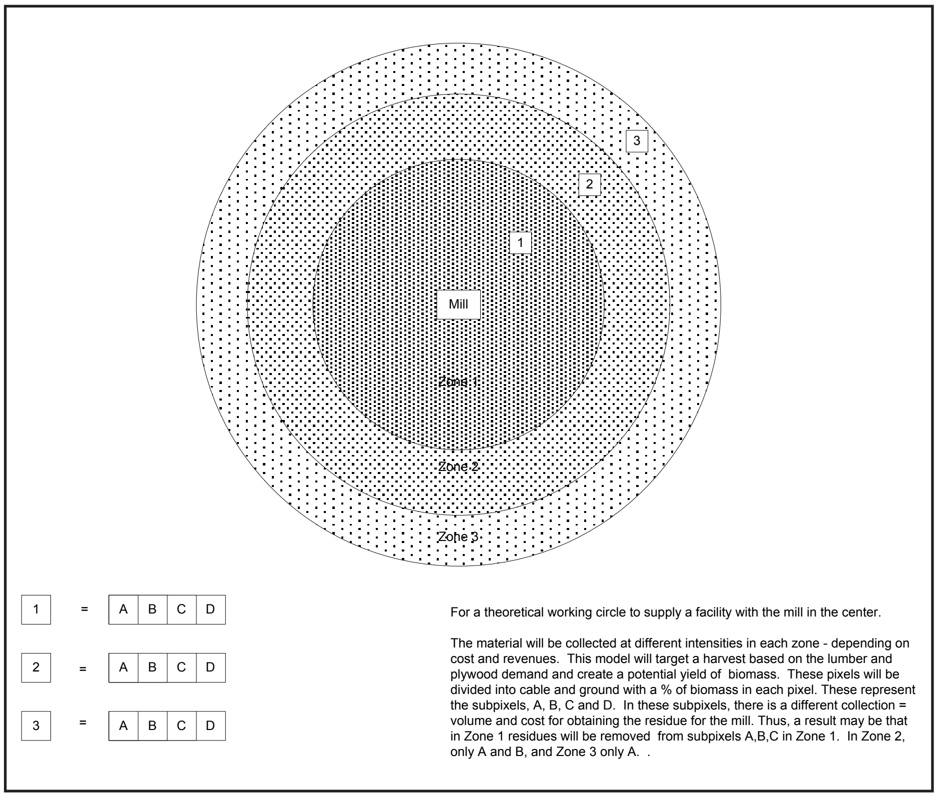

Figure FL-1.10. Theoretical biomass distribution model around an existing facility.

To support the development of the regional supply biomass model that would include variable collection within the harvest unit, a spatially located biomass estimate was needed. Fifty harvest units from the NARA region were selected as they became available to avoid any bias based on their location, size or silvicultural treatments. The dynamic nature of harvest prevents the creation of a population from which samples are drawn from to allow for a formal statistical inference to be drawn from. We believe that the data represent a range of conditions to be encountered in the NARA areas. The rules limited samples from those harvesting units that utilized one logging systems, either cable or ground-based, and that harvest residue had to be piled following logging operations. Cable logging include all forms of cable yarding from live skyline systems, running skylines and yoders (yarder-loader). Ground-based systems primarily included skidders, forwarder and shovel. The forest types can be grouped into two broad categories. The first, primarily in Oregon were the Douglas-fir forests and the second was the hemlock forest, primarily in western Washington. These represent the private practices found in the Northwest Advanced Renewable Alliance area for private timber timberlands to supply the raw material for wood-based raw material supply. At this time, the focus of the NARA project was shifting to private practices that allowed for the renewable energy credits to occur; therefore, our sample focuses on Oregon and Washington private practices.

The data collected at each unit included measuring the unit's perimeter using the Global Positioning Systems data. The coordinates were collected and area was calculated using ArcMap software. All biomass piles larger than 2 cubic yards were measured. Initial estimates were made using geometric methods. For those piles that exceeded the threshold, we employed a pile measurement tool, MAPSmart, described by Long and Boston (2014). Additionally, the pre-harvest, estimated Scribner sawlog volume per acre was obtained from either the purchaser or landowner. Geographic information system analysis was completed that placed each pile into 50-foot buffer strips surrounding each the road. This analysis allowed us to determine the volume of material and the distance from the roads.

Examples of the data are shown in Figures FL-1.11a,b for the Yellow Jacket cable and shovel units. The cable logging is too steep for mechanical site preparation; thus, only material the reaches the landing as part of the whole tree yarding process is considered. The result is fewer, but larger piles located on the edge of landings. The shovel logging unit is able to mechanically pile the logging residue. The result is a significant number of smaller piles that are unfortunately built primarily to facilitate burning as part of the site preparation activities.

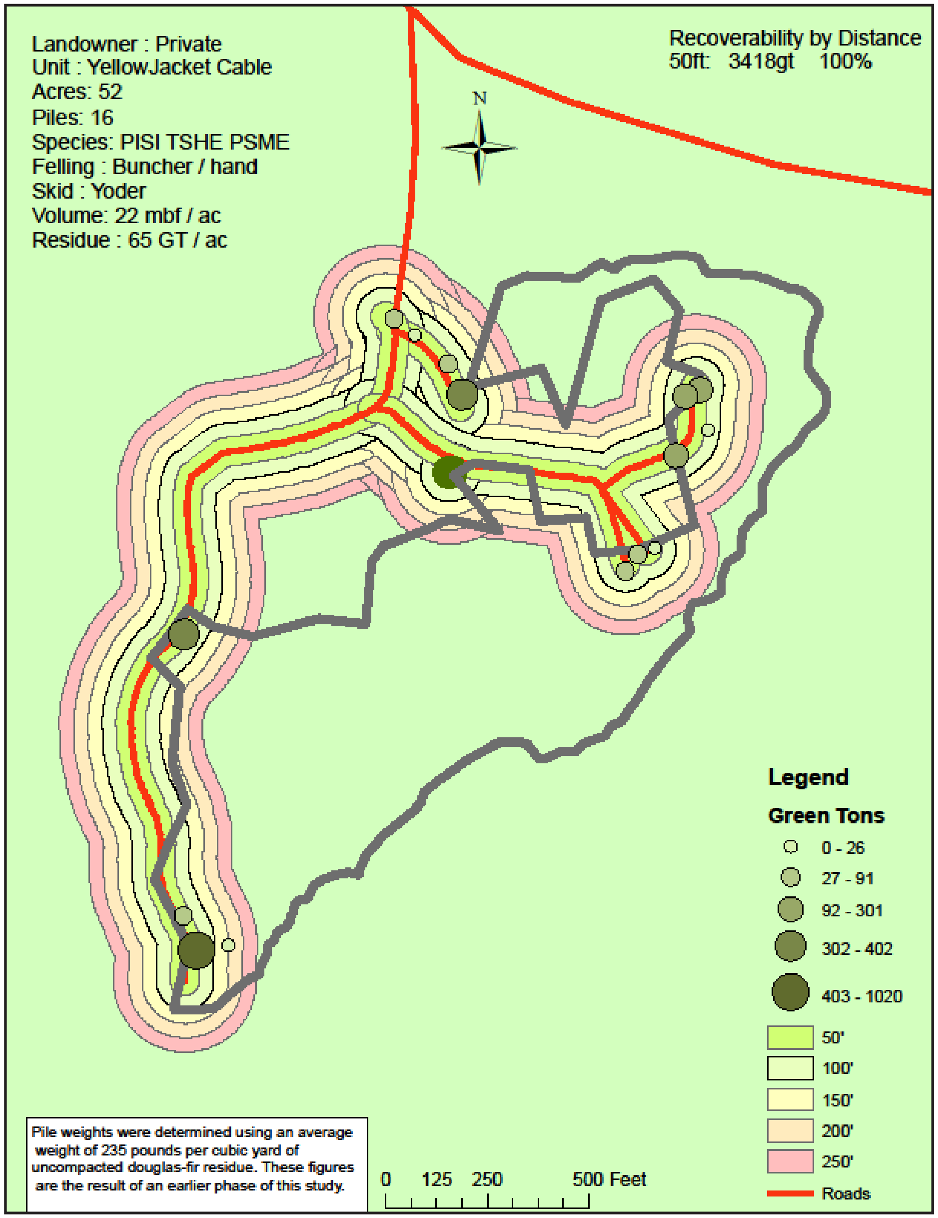

Figure FL-1.11a. Yellow Jacket cable logging unit with pile locations.

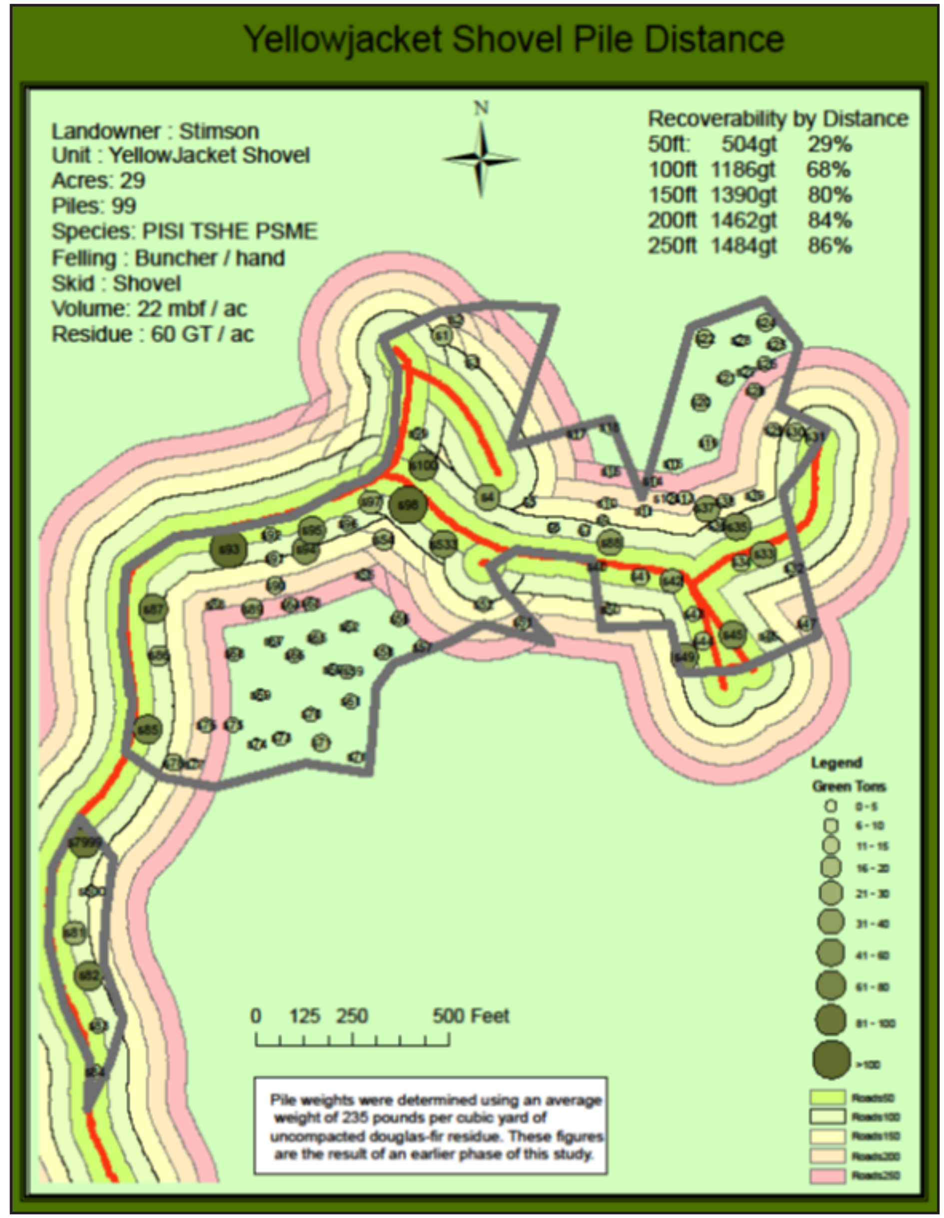

Figure FL-1.11b. Yellow Jacket ground-based harvest unit with pile locations.

We can use these results to estimate the average volume in green tons per acre based on logging system and subregion within the NARA region. Table FL-1.3 shows the green tons per acre of biomass based on the logging system and state. The Washington data was collected during a time when the pulp market was significant; while the Oregon data was during a time with minimal demand for pulp logs (see later discussion and Figure FL-1.14); thus the composition of the two piles was different. This is the dynamic nature of measuring the volume in these biomass piles.

Table FL-1.3. Comparison of the green biomass by distance from road or landing in green tons per acre by State and harvest system.

Source	50 ft. band	100 ft. band	150 ft. band
Oregon Cable	32.2	32.2	32.2
Oregon Ground	13.4	32.8	45.7
Washington Cable	19.0	19.4	19.4
Washington Ground	6.4	18.5	23.4

3.2 Further analysis

The economic supply was estimated using a subset of this data. Twenty sites were selected at random from the population of 50 units. This goal for this analysis was to estimate the cost to transport the piles from the various locations in the harvest unit to landing or collection point. The result was detailed economic analysis processed in the GIS system.

For units harvested with cable aerial system, only roadside piles were available for recovery since typically the whole tree is yarded to the landing. For units harvested with ground-based equipment, we modeled the collection and transport of each residue pile (roadside and not roadside) to the most cost-effective landing.

For each pile we overlay a slope raster that was derived from a 10 m pixel digital elevation model (GEO Enterprise, 2013). The slope raster allowed us to calculate feasible operational routes to take the residue to the nearest landing using ground-based equipment. We assign a cost to each pixel starting with 10 for pixels with slope value of 30 percent and decreasing linearly up to 0 percent of slope, if any. Then, we identified all the potential landings that have good access to chips vans and have enough space to place the machine and allow the trucks to be loaded. Then, we created the potential routes from each pile to each candidate landing. Using a shortest path algorithm, we estimated the least cost path from each centralized collection point in the grid to the nearest landing. Once potential distances from each pile to the landing were calculated, we proceeded to input the information in a simulation model developed to optimize forest biomass operations taking into account equipment availability and balancing (Zamora-Cristales et al., 2017).

For each pile, we established different options depending of their location (Zamora and Sessions, 2016). For residue piles located at 150 feet or less from the landing we assumed that they could be taken to the landing using one excavator loader. From 150 to 300 ft., we assumed that one forwarder would collect the residues. For distances higher that 300 ft., we assumed that two forwarders needed to be used to collect the material. For the forwarder options, it was assumed that a loader would be loading the forwarder. Based on the residue available at different distances from the landing, the costs was estimated.

Costs were estimated based on previous work (Zamora-Cristales et al., 2017; Zamora-Cristales et al., 2015) for collection and grinding. Collection cost considers the three options previously mentioned. Additionally, these costs were calculated for fresh material since it is expected that the collection take place after harvesting. Grinding cost assumes that all trucks needed for the grinder are available, thus the processing machine is only waiting for trucks to turn-around and positioning. Collection costs were estimated when residue is fresh since this is the most likely scenario given that the area needs to be clean after harvesting to favor replanting and ensure the successful growth of the trees. Transportation cost from the landing to the bioenergy facility were not considered in this study since our main focus is on understanding the effect of pile location and distance from the landing on the economics. It is assumed for the study that the landings selected to place the grinder are large enough to pile the material, place the grinder, and load the trucks.

3.2.1 Ground-based units available residue

The ground-based units were divided according to the geographic distribution. The West Oregon units have an average pile size of 7.7 GT, and analyzed units were 7.2 acres in average (Table FL-1.4a). The number of piles per unit was an average of 42 piles per unit. The piles were located at different distances from the landings. The volume in each of the units varied from 249 to 872 GT of residue. A feller buncher was used in all but one of the units. The use of the excavator shovel was the preferred method for yarding the trees to the landings. The available piled residue per acre was 38.8 GT. Pile size varied from 2.7 to 17.2 GT.

Table FL-1.4a. Descriptive statistics of available biomass in Oregon ground-based harvest units.

Felling	Buncher	Hand	Buncher	Buncher	Buncher	Buncher	
Yarding	Shovel	Shovel	Shovel	Shovel	Shovel	Shovel	
Harvest Unit	BaldBarney	Dunn_400 Shovel	East Honey	Old Peak Rose	OldPeak North	South Gellatly	Averages
Mean (GT/pile)	3.5	9.0	6.9	11.0	7.1	9.0	7.7
Median (GT/Pile)	3.0	8.7	7.0	9.6	6.8	9.6	7.5
Standard Deviation (GT/Pile)	1.4	5.5	3.3	5.6	2.5	3.9	3.7
Minimum (GT/Pile)	1.0	2.1	1.0	5.2	3.8	3.1	2.7
Maximum (GT/Pile)	8.0	20.8	23.0	24.2	11.6	15.4	17.2
Sum (GT)	249.0	108.5	872.0	175.8	112.9	134.3	275.4
Count (# piles)	71.0	12.0	127.0	16.0	16.0	15.0	42.8
Area (Acres)	7.4	3.1	22.0	3.7	3.9	2.8	7.2
Tons/acre	33.6	35.2	39.6	47.5	29.0	48.0	38.8
MBF/Acre	23.0	13.0	47.0	26.1	26.1	31.1	27.7
GT/MBF	1.5	2.7	0.8	1.8	1.1	1.5	1.6

Table FL-1.4b. Descriptive statistics of available material available in Washington Olympic Peninsula ground-based harvest units

Felling	Buncher	Buncher	Buncher	Buncher	Buncher	Buncher	
Yarding	Shovel	Shovel	Shovel	Shovel	Shovel	Shovel	
Harvest Unit	Blowdown _1	Blowdown _2_N	Blowdown_ 2_S	Dawn Lookout_2_N	Dawn Lookout_2_S	DawnLookout_ Shovel	Averages
Mean (GT/pile)	8.9	15.5	10.8	51.5	21.9	11.2	20.0
Median (GT/Pile)	4.7	10.6	10.0	60.5	16.2	7.2	18.2
Standard Deviation (GT/Pile)	15.4	15.7	6.1	27.2	19.2	11.5	15.8
Minimum (GT/Pile)	1.1	2.2	3.8	14.8	1.1	1.0	4.0
Maximum (GT/Pile)	82.5	69.5	24.7	82.3	72.9	42.6	62.4
Sum (GT)	391.4	448.9	194.3	514.9	241.0	291.3	347.0
Count (# piles)	44.0	29.0	18.0	10.0	11.0	26.0	23.0
Area (Acres)	11.8	7.2	3.6	19.0	7.6	20.9	11.7
Tons/acre	33.2	62.3	54.0	27.1	31.7	13.9	37.0
MBF/Acre	33.5	33.5	38.9	29.0	29.0	35.7	33.3
GT/MBF	1.0	1.9	1.4	0.9	1.1	0.4	1.1

Units located in the Olympic Peninsula and Washington have an average pile size of 20 GT, with an available piled residue of 37.0 GT/acre (Table FL-1.4b). Average harvest unit size was 11.7 acres. Compared to the Oregon units, current practices created bigger piles of residue. The number of piles per unit was 23. Interestingly, the amount of residue per acre in the Washington units is similar to the one found in Oregon. However, the green tons of residue per MBF harvested was lower in the Washington units (1.1 GT/MBF) compared to the Oregon units where the value was on average 1.6 GT/MBF. This is somewhat surprising since western hemlock generally has more branches and foliage per cubic meter of bole than Douglas-fir, and the percentage of hemlock is higher on the Washington Olympic Peninsula than in Oregon. Differences in pulp markets are probably the contributing factor (Figure FL-1.12). During 2012-2013 mill delivered pulpwood prices in western Oregon averaged less than 50% of the price of mill delivered pulpwood in western Washington. Higher pulp prices encourage greater recovery of pulpwood during logging. Delivered chip prices to pulp mills in Oregon were also about 40% lower than Washington during the study period.

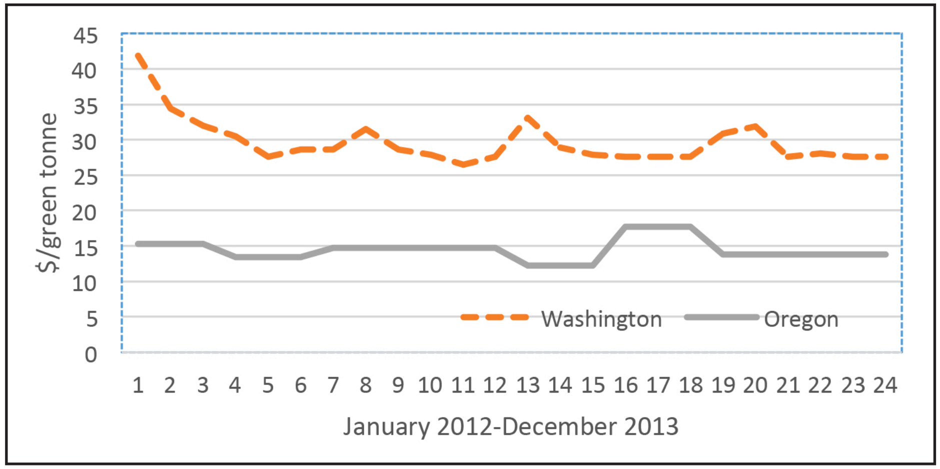

Figure FL-1.12. Weighted utility log prices for Douglas-fir/Hemlock in coastal Washington (WA DNR, 2016) and northwest Oregon and Willamette Valley (ODF 2016) for the 24-month period from January 2012 to December 2013.

In terms of the economics, the collection and grinding cost of the material will range from $16.3 per green ton of residue (GT) at 50 ft. or less to $33.7/GT at 750-800 feet from the landing (Figure FL-1.13). This cost represented the weighted average cost for each of the distance classes (e.g. $16.3/GT is the weighted average cost for the material available in the studied harvest units at distances of less than 150 ft.). Transportation costs are added from the landing to the bioenergy conversion facility. Although research has demonstrated that few differences in cost can be expected from grinding fresh versus aged residue (Zamora et al., 2017), the transportation cost is very sensitive to changes in moisture content. Ideally, the material needs to be below 35% of moisture content (wet basis) to favor the economics by increasing the amount of delivered dry material per truck per trip. With 35% moisture content, the costs range from $25.1 per bone dry ton (BDT) to $51.8/BDT (for distances of 750 to 800 ft.).

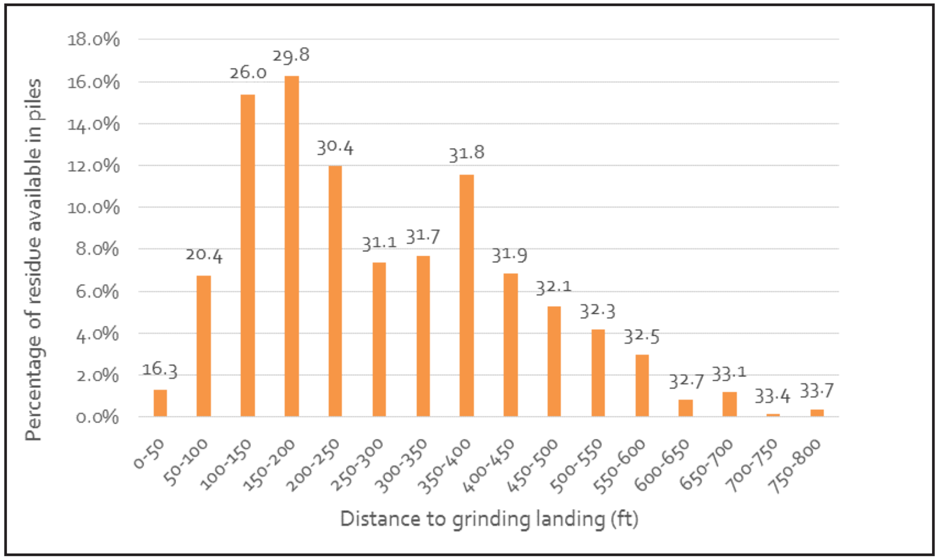

Figure FL-1.13. Available residue by distance from the landing in Douglas-fir units in western Oregon. The numbers located over the bars represent the collection cost from each pile location to the landing plus the grinding cost.

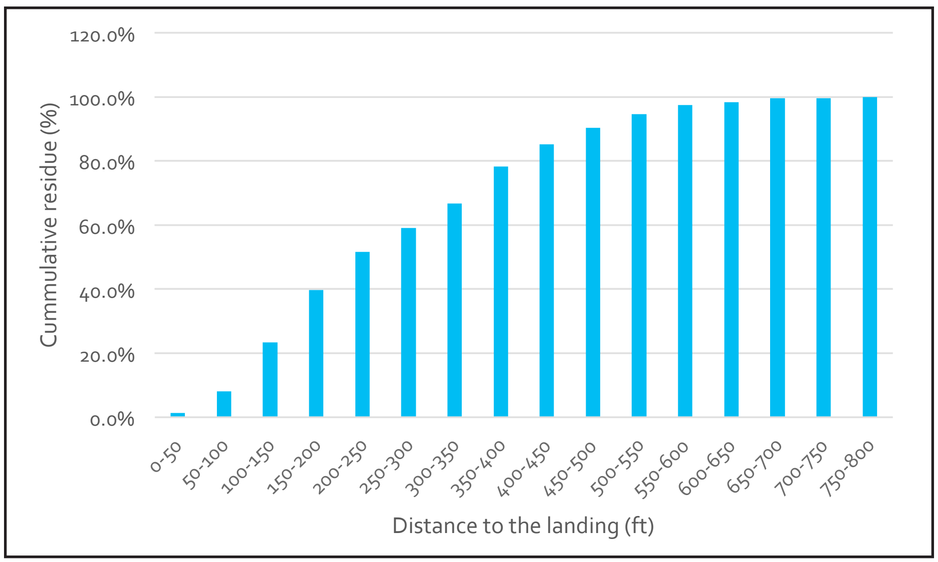

Figure FL-1.14. Cumulative residue by distance from the landing in Oregon ground-based units

Approximately 59% of the residue in the analyzed units was 300 feet or less from the landing in the Oregon units (FL-1.14) and about 61% in the Washington units (FL-1.15). So, there is a potential of recovering that material only using the excavator loader. However, the cost increases greatly at that distance since at least three swings (with a 50ft boom) will be needed to move the material to the landing as shown in FL-1.13 and FL-1.16.

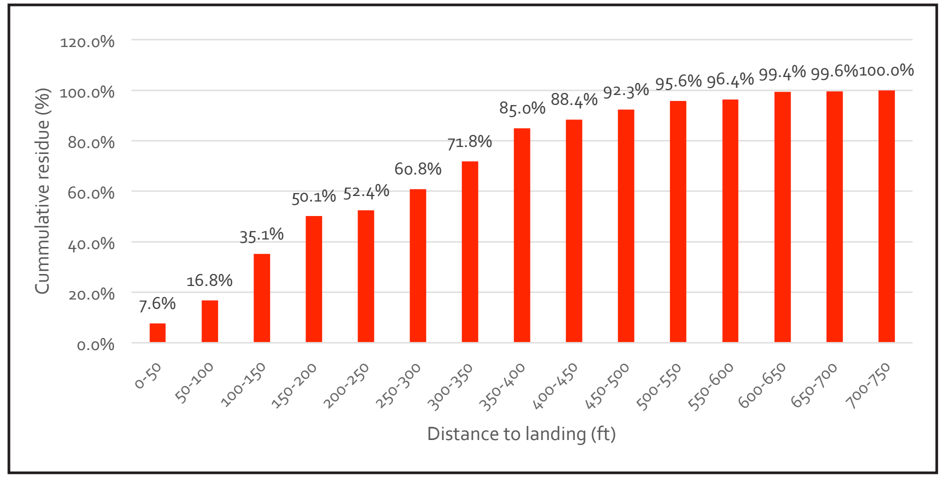

Figure FL-1.15. Cumulative residue by distance from the landing in Washington ground-based units

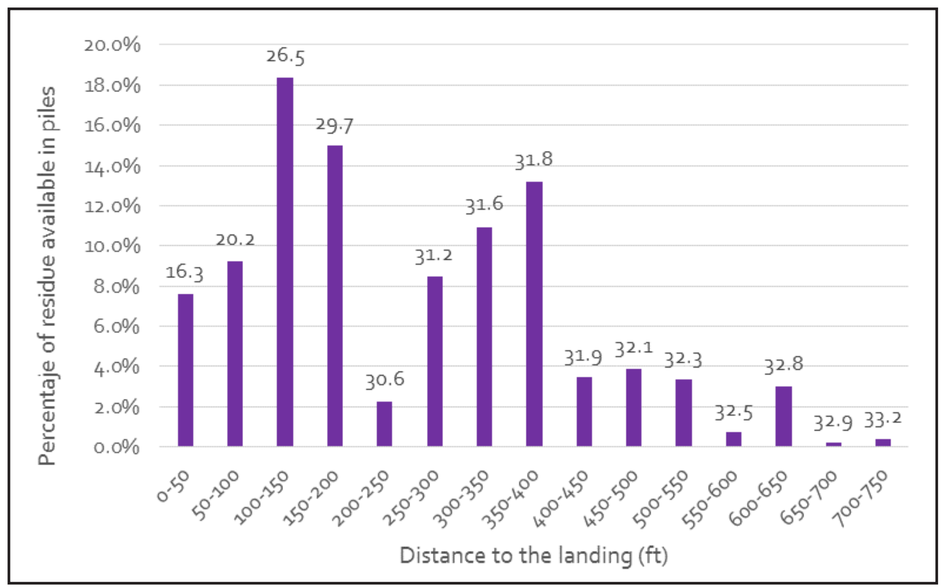

Figure FL-1.16. Available residue by distance from the landing in Douglas-fir units in western Washington. The numbers located over the bars represent the collection and grinding cost calculated as the weighted average cost for each distance to landing class.

3.2.2 Cable logging units available residue

For the cable logging units, the average pile size was 51.4 GT of residue (Table FL-1.5). An average of 11 green tons per acre was found in piles. Average unit size was 65 acres. All of the cable-logging units were hand-felled, and we found that an average of 0.32 GT per MBF can be recovered from those units. The larger piles compared to those found in ground-based systems is the result of the processing of the trees that is performed at, or around, the harvesting landings. The steep terrain associated with these units does not allow for recovering material left in the unit that is a product of the breakage during yarding.

Table FL-1.5. Descriptive statistics of available material at measured cable logging units in Oregon and Washington.

Region	Olympic	Alsea	Olympic	Olympic	Kings Valley	Kings Valley	Forest Grove	
Felling	Hand	Hand	Hand	Hand	Hand	Hand	Hand	
Yarding	Cable	Cable	Cable	Cable	Cable	Helicopter	Cable	
Unit	Boundary Creek Cable1	Bummer Cable	Dawn Lookout Cable	Dawn Lookout Cable2	Maxfield01	Maxfield02	NightLight	Average
Mean (GT/Pile)	59.5	2.8	156.5	62.1	4.2	29.7	45.0	51.4
Minimum (GT/Pile)	59.5	0.4	45.6	5.6	2.1	24.2	4.0	20.2
Maximum (GT/Pile)	59.5	9.8	267.4	118.7	8.7	35.3	280.4	111.4
Sum (GT/Pile)	59.5	34.1	313.0	124.3	29.4	59.5	584.5	172.0
Count (Piles)	1.0	12.0	2.0	2.0	7.0	2.0	13.0	5.6
Area (acres)	3.3	7.0	12.1	10.1	30.8	65.0	41.3	24.2
Tons/Acre	18.0	4.9	25.9	12.3	1.0	0.9	14.2	11.0
MBF/Acre	30.4	28.0	35.7	35.7	37.0	25.0	38.0	32.8
GT/MBF	0.59	0.17	0.72	0.34	0.03	0.04	0.37	0.32

The conclusions from the economic availability study were that steep units harvested with aerial methods produce fewer green tonnes per MBF harvested compared to the units harvested with ground-based equipment. However, cost significantly increase as the material is farther from the landing for the ground-based units. Collection cost range between about $16/GT at distances of 50 feet from the landing to $34/GT at distances of more than 700 feet from the landing. Depending on the transportation distance of the comminuted material from the landing to the bioenergy conversion facility, it can be possible to estimate how far from the landing is economically feasible to collect the material. For example, units that are very close to the conversion facility may have lower transportation cost compared to those that are farther, so the savings can be used to collect more material as shown in the theoretical model (Figure FL-1.10). The key is in considering this operational constraint and account for them along the supply chain. In any case, the market will determine how much material is economically available.

4. SUSTAINABILITY ISSUES

The creation of standards for material that remains on harvest sites has been primarily achieved through state forest practices rules. However, The Forest Stewards Guild (2013) has developed guidelines for residue retention following logging in the Pacific Northwest. Their voluntary guidelines include estimates of woody material retention levels to maintain wildlife habitat and the availability of soil nutrients. They recommend 30% of the fine woody material (FWM), material less than 15 cm (6 inches) in diameter, remain on gentle slopes and 50% of the FWM on remain on steep sites. Additionally, they recommend 5% ground-cover of large woody debris, material greater than 13.7 cm (5 inches), be left on sites to promote conditions found in unmanaged forests (Forest Stewards Guild, 2013).

The presence of logging residue can provide structural features that become habitat for small animals within the harvest unit. Over 150 vertebrate species use some form of down woody debris for habitat in the Douglas-fir forests of western Oregon (Hunter, 1990). The physical structure of down logs and branches provides protection and concealment from aerial predators as well as thermal cover. Fungi and small organisms, such as grubs, associated with decaying woody debris are important food networks for many larger animals.

This sustainability study aims to answer two questions: (1) How much residual material is piled following logging versus the amount scattered on the ground after cable yarding, shovel logging, or mixed cable-shovel methods have been applied to a variety of terrain representative of commercial timber operations in western Oregon? (2) What are the location, size, and number of slash piles affected by harvesting methods in the lower portion of the Cascades, the Willamette Valley, and the Oregon Coast Range?

Six units from western Oregon were selected to be sampled: Two in the western foothills of the Cascade Mountains near Sweet Home, Oregon, two on the inland portion of Oregon's coastal range, and two on the coastal side of the coast range. Each of the unit pairs were on forestland owned by different private landowners who can recover $10 per bone dry ton through renewable energy credits to encourage their development of biomass energy (Smith et al., 2012). These units represent the type of harvest units that would likely supply raw material to a biomass conversion facility to generate the feedstock for aviation fuel.

The ground-based units were logged exclusively with shovels as this is becoming the dominant practice on private timberlands western Oregon. In the two Cascades units, one (High Deck) was harvested using ground based machinery and the other (Shot Pouch) with cable yarding. One unit (Numskull) on the inland side of the coastal range was shovel logged while the other (Fernhopper) employed a mixture of cable and shovel harvesting systems. The units on the west side of the Oregon coastal range (Four Way and Euchre Creek) were both cable yarded. The six units are representative of the type of terrain and timber harvested on a regular basis in western Oregon. The stands were predominantly Douglas-fir (*Psuedotsuga menziesii*) with some grand fir (*Abies grandis)*, western hemlock (*Tsuga heterophylla*), western red cedar (*Thuja plicata*), red alder (*Alnus rubra*), and big leaf maple (*Acer macrophylla*). Table FL-1.6 summarizes the size, slope characteristics, and the harvesting system used in each unit.

Table FL-1.6. Characteristics of harvesting units sampled in western Oregon.

Unit	Area	Slope	Harvest System:	
			Cable	Ground
Fernhopper	16.4	0-90%	30%	70%
Numskull	28.4	0-60%	100%	0%
Shot Pouch	27.0	15-60%	0%	100%
High Deck	4.0	0-15%	100%	0%
Four Way	24.6	40-70%	0%	100%
Euchre Creek	13.4	5-100%	0%	100%

4.1. Slash pile measurement

Every pile in each unit was measured with a Nikon TruPulse cruising laser rangefinder linked via Bluetooth to a SXPad with the MapSmart software; thus, a 100 % sample was performed. The pile volumes computed with the MapSmart TIN represent the shell that contains the residue; however, the solid-wood-to-space ratio is quite low. A biomass pile packing ratio of 0.2 developed by Hardy (1996) was applied to determine the weights of the residue for small- needle conifers such as Douglas-fir. Wright et al. (2010) showed similar results; they measured 63 conifer piles and computed a packing ratio of 0.19. Cross et al. (2013), in a study on the Olympic and Kitsap Peninsulas in northwest Washington, found a packing ratio of 0.38 for comminuted hog fuel to solid wood. They also developed a relationship to convert slash volume directly to dry mass or green mass using the formula (92.18 * Sqrt[Volume of the slash pile]- 4468) * density of the grindings, where the slash pile volume is cubic feet, and the density of the grindings is 9.05 lb/ft3 dry or 18.72 lb/ft3 green. Using their formula, a 25,000 cubic foot slash pile would yield a packing ratio of about 0.15 if the wood green density was 50 lb/ft3. And, using their formula, smaller slash piles would have higher packing ratios than larger slash piles. For this study, the packing ratio of 0.20 suggested by Hardy (1996) was used to convert the shell-volume in the piles to the volume of actual material.

To determine the total volumes of residual scattered slash, the total footprint area of all the piles needed to be removed from each unit's total area. The MapSmart footprint area calculation was found to be more accurate due to the inability of the operator to walk exactly at the base of the pile and the inherent lack of precision of the Trimble GeoExplorer. All the piles in each of the other four units were measured solely with a traverse and the MapSmart software.

4.2. Transects

Line transects were used to quantify the volume of slash remaining on the ground following harvesting (Warren and Olsen, 1964). In order to create an unbiased representative sample of each clearcut, five transects were placed randomly through the unit for a total of approximately 1000 horizontal feet as there was no prior estimation of the variability from previous studies on logging slash. Using a string box and calipers, the diameters (to the nearest 0.25 in) of all woody material with a diameter exceeding 0.25 inches that intersected with the line was recorded.

The purpose of the study was to measure only the solid wood that is generated from the immediate harvests. On site residues not from the logging activity, such as residual brush or snags that had fallen from previously rotations or visibly beginning to rot, were not included in the forest residue estimates. Although, bark has higher energy and nutrient values; it was not included in the measurements as the project's focus was on the solid wood for feedstock for jet fuel. Foliage was also not included. Foliage in Douglas-fir can contain more than one-half of the above ground tree nitrogen and more than one-quarter of the above ground tree calcium (Mainwaring et al., 2015).

The results show that a larger percentage of the wood is available from ground-based logging systems than from cable (Table FL-1.7). However, as the previous result showed, much of it may be too far from the landings or road junctions to economically collect and process. The total volume found from these results are similar to the produced in the total estimate with approximately 30 cubic yards per acre for cable logging units and 59 cubic yards per acre for the ground-based systems that is slightly higher than the 45 cubic yards per acre for the previous studies.

Ground-based units had an average of 72% of the biomass is piles, and cable logging units had an average 46% of the biomass in piles. However, the economics of collecting all of the material in group-base operations is unlikely as shown in the previous section. This data has been made available to NARA's Lifecycle Analysis group and Nutrient Cycling group to further address the sustainability of various aspects of the biomass collections process.

An effort was made to develop a double sampling strategy that would utilize the Timber Product Output (TPO) data collected by the University of Montana Bureau of Business and Economic Research (BBER) to estimate the recoverable harvest residues. Harvesting units that were measured by the BBER group to determine

Table FL-1.7. Total available volume and percent available volume from six units in Oregon.

System	Pile CY	Area in pile Ac	Total Area	Trans Vol. CY/Ac	Total	Percent Pile	Volume/Ac Avail
Mixed	1744.0	0.9	40.6	38.0	3254.0	0.54	43.0
Shovel	4088.0	3.0	70.2	42.0	6883.0	0.59	58.2
Shovel	597.0	0.5	9.8	21.0	796.0	0.75	60.9
Cable	2457.0	1.8	66.7	51.0	5751.0	0.43	36.8
Cable	1942.0	0.7	60.7	45.0	4630.0	0.42	32.0
Cable	970.0	0.4	33.0	25.0	1772.0	0.55	29.4

the total volume of biomass would have their piles measured by the OSU group to determine the recoverable biomass. The result would be a ratio that can be used to refine biomass estimates. However, the spatial resolution of the TPO data is maintained at the county level and thus not easily integrated with detailed collection variables at this time. A number of different models were analyzed but none yielded a meaningful result due the high variability from initial inventory, logging system and merchandizing practices.

5. DIAMETER DISTRIBUTION OF FOREST HARVEST RESIDUES

As part of a study to model forest residue moisture content over time Belart (2016) constructed and monitored forest residue piles in four primary regional climates and productive forest types of the Pacific Northwest. The four harvest units were selected near Depoe Bay, Corvallis, Dexter, and La Grande, Oregon. They represented Coastal Western Hemlock forest, low-elevation Douglas-fir forest, high-elevation Douglas-fir forest and arid Ponderosa Pine forest, respectively (Table FL-1.8). As part of the protocol to monitor environmental variables and internal drying behavior of the residue she sampled forest residues including piece diameter. Residue piles were constructed within one month of tree harvest in order to maintain green moisture content as an initial condition, with the exception of the low elevation Douglas-fir unit (WV Douglas-fir), which was constructed two months after harvest due to operation constraints. At pile construction, thirty wood samples were randomly cut (of all different diameters) from material that was going to be used to build each pile in order to determine initial moisture content. These randomly selected pieces were then cut along a set interval. The diameters inside bark and outside bark were measured. The percentage of the forest harvest residue volume in different diameter classes was quite different between over bark (Figure FL-1.17) and under bark (Figure FL-1.18).

Table FL-1.8. Site description for each unit.

Index	Site	Main species	Location	Elevation (m)	Average precipitation (mm)
Hemlock-Coast	Coast	Western hemlock	Depoe bay, OR	122	1,779
WV Douglas-fir	Valley-West	Douglas-fir	Corvallis, OR	235	1,029
Higher Elev Douglas-fir	Valley-East	Douglas-fir	Dexter, OR	984	1,384
East-P Pine	East	Ponderosa pine	La Grande, OR	1,158	457

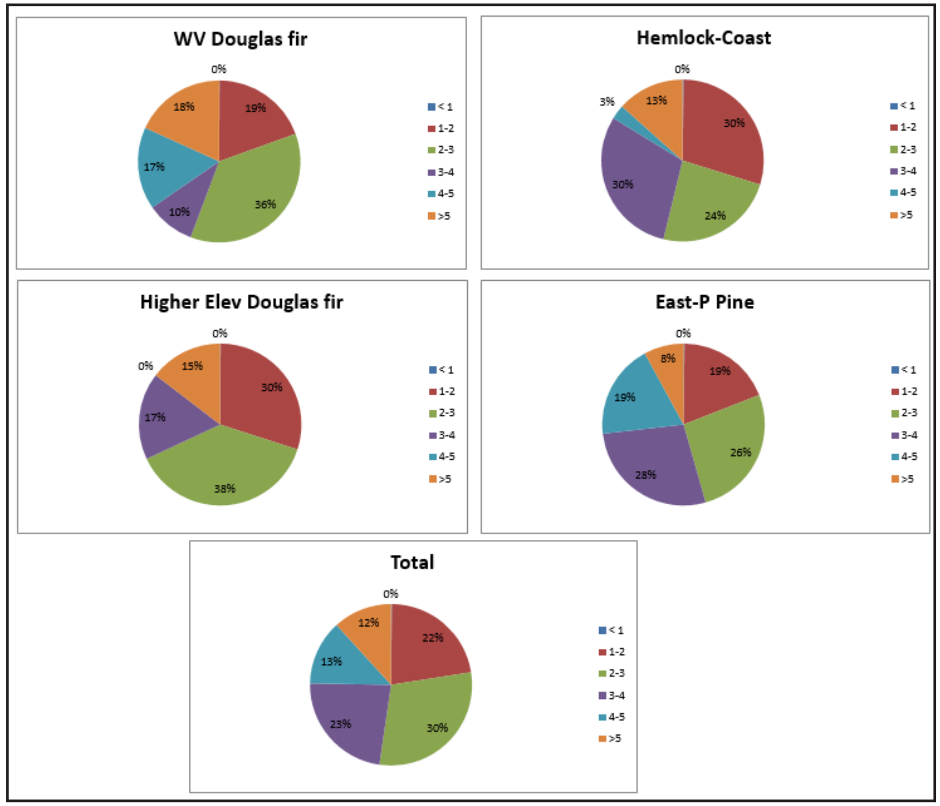

Figure FL-1.17. The percent of forest harvest residue volume in the constructed piles by diameter class (inches), measured over bark.

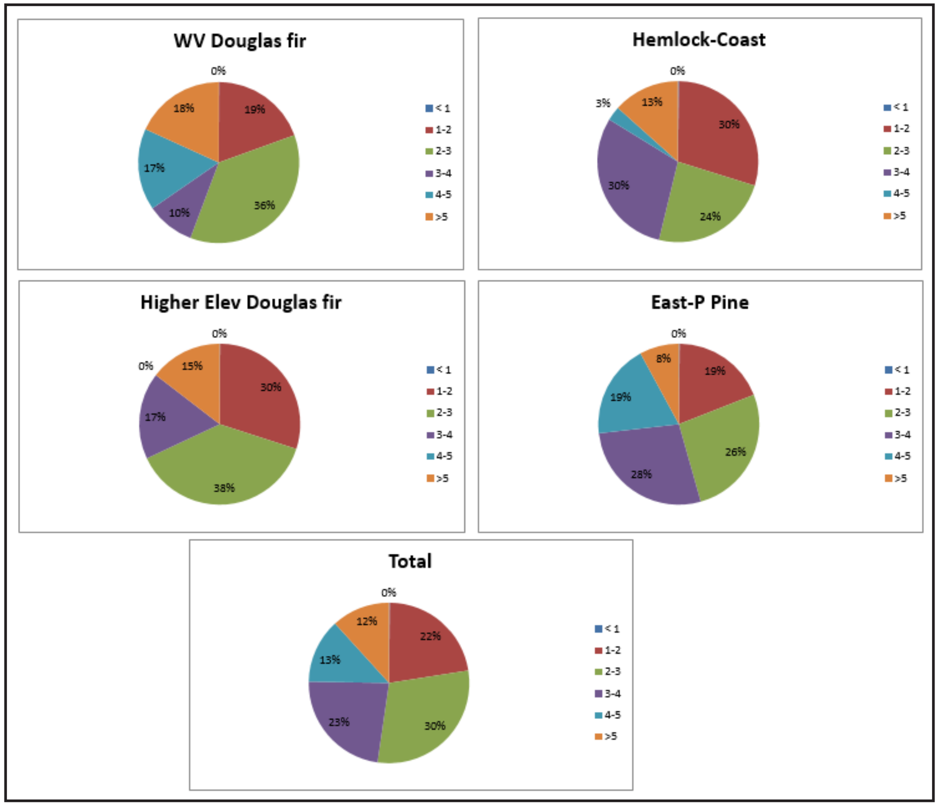

Figure FL-1.18. The percent of forest harvest residue volume in the constructed piles by diameter class (inches), measured under bark.

Belart (2016) found in a survey of standing tree branches (Figure FL-1.19) that bark proportion is greater in smaller branches. For residue utilization for liquid biofuels, the impacts of higher bark proportions are more significant than for direct combustion and illustrate the desirability of larger branches.

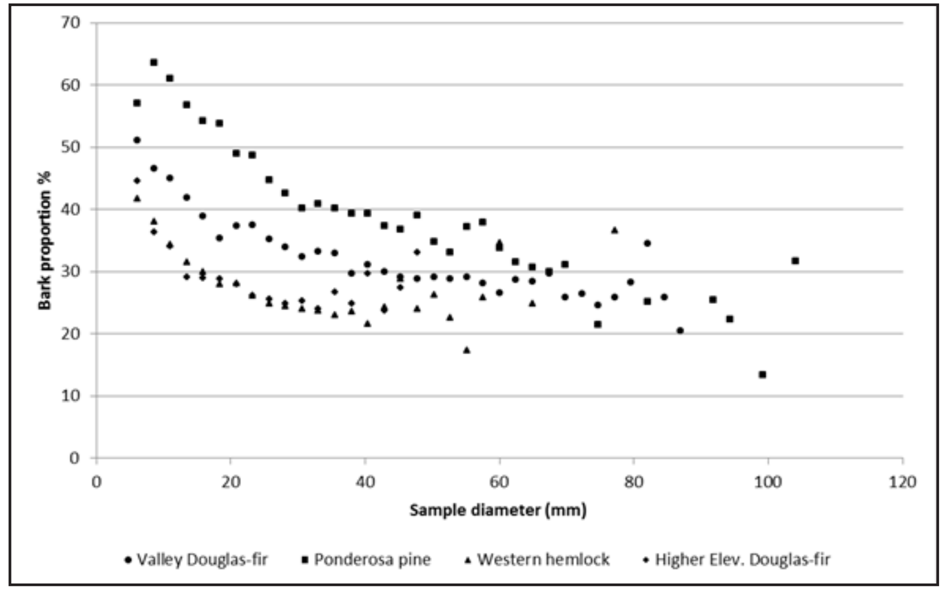

Figure FL-1.19. Branch bark proportion from Belart (2016).

6. SUMMARY AND FUTURE WORK

The results of the assessment work were:

1) The validation of tools to accurately predict the volume of the difficult to measure slash piles.

2) The development of spatially explicit model for biomass distribution for private lands in western Oregon and Washington that estimate the volume and location of harvest residues as feedstock source for bioenergy projects.

3) The development of an economic tool to estimate the volume of biomass at various collection costs.

Future work needs to address at least three areas:

1) This project emphasized the supply from western Oregon and Washington with few points on the public lands in the entire NARA region. Given the different management objective on these lands, available biomass estimates will need to be developed for these operations more explicitly as the data collected in this project did not have sufficient replication to produce meaningful results.

2) Quality of the biomass, e.g., the biomass size in the piles, remains a question. It is the large pieces of biomass that can yield the most solid wood after processing. As previously discussed, pulpwood markets will make a significant difference on the characteristics of the forest residues. Limited data characterizing volume by diameter class from limbs and tops from four sites in Oregon was collected by Belart (2016). Future work should attempt the difficult to task to understand the composition of the biomass piles as it will relate the quality of material that can be produced from each pile.

3) The pile packing ratio of 0.20 needs to be further validated. Twenty piles were checked as part of this study and the 0.20 packing ratio was a reasonable number when compared with these samples. Further industry cooperation is needed to develop this number based on the mixture of sizes, the species and method used to construct these piles.

7. MODELING LANDSCAPE DISTRIBUTION OF FOREST BIOMASS

7.1 Introduction

To support the regional biomass supply analysis by the NARA Feedstock Supply modeling team a spatial distribution of biomass by harvesting system and estimated distance to road was developed. The base resource data are FIA plots (USDA Forest Service, 2016). Regional data (digital elevation models, road networks, ownership, land cover) was collected from the primary federal and state agencies. Digital elevation models were processed to estimate the amount of forested land that could be suitable for either ground-based or cable equipment. We then combined the harvest system overlay with the road system. In cable terrain, residues were assumed to be at roadside. For ground-based systems we assumed part of the residues is generated at roadside landings and part was generated in the field at different distances from the road. The results from the analysis will be used by the NARA Feedstock modeling team to characterize the biomass collection and comminution costs for biomass generated in the vicinity of each FIA plot.

7.2 Harvesting Systems

Two main harvesting systems (ground-based and cable-based) are used for most logging operations in Pacific Northwest forests (Figure FL-1.20). Ground-based systems (typically shovel logging) are generally utilized when slopes are less than around 30% for safe productive work (Conway, 1976; MacDonald, 1999). Cable-based systems are generally employed on steeper slopes. Usually, ground-based systems are more cost effective if conditions are suitable (Lousier, 1990; Jarmer et al., 1992). When utilizing cable systems, the residuals are primarily located at a landing site where trees are processed after whole tree yarding.

Figure FL-1.20. A skyline cable-based logging system (left) ground-based system using a shovel loader (right). Photos courtesy of Michael Berry and Komatsu.

Alternatively, ground-based logging systems such as shovel logging typically disperse a larger volume of residuals in the field with a smaller fraction located at roadside. Usually residues are not moved directly to roadside but are moved to discrete landings along the roads for comminution. This is important, as the distance to roadside is the primary collection cost driver and subsequent barrier to sustainable utilization. Studies suggest that residuals, which are piled and within 150 feet of roadside, cost roughly $5-10/ BDT compared to $20-30/ BDT for material that is further from roadside (Zamora and Sessions, 2016). For ground-based harvesting systems, two logical distance bands are the area within 300 feet of a road and the area outside of 300 feet. If residues are to be transported less than 300 feet, the least expensive method is by excavator. For harvest units with residue collection distances greater than 300 feet adding one or more forwarders loaded by an excavator can be more economical if the equipment is available.

7.3 Use of FIA Plots

The NARA biomass supply model relies on the Forest Inventory and Analysis (FIA) database for the description of forest characteristics. In order to project when and where forest biomass residues will be created, the NARA biomass supply model simulates commercial timber harvest to meet regional product demands using a variant of the Timber Assessment Market Model developed by Adams and Haynes (1980). The NARA biomass supply model allocates the volume of commercial timber harvest that will occur at each plot center in each time period considering timber characteristics, logging costs, and transport distances. In the NARA biomass supply model, forest harvest residues are a byproduct of the timber harvest, they do not drive it. To develop the supply, the quantity of biomass and cost of delivered biomass must be calculated. Prior to the development of the procedures described here, the NARA biomass supply model assumed all forest harvest residues at a plot point are available on truck at the same average cost. The procedures described here incorporate the topography in the vicinity of the plot point with the goal of improving cost estimates through identification of the percentage of area by harvesting system.

7.4 Land Classification

The objective is to present a methodology that can be used to refine the average cost of moving forest biomass to roadside. From a modeling perspective we need to answer the following key questions:

1) What harvest method is likely to be used at a specific location?

2) How many acres of forested land within state and private ownership classes are in close proximity to existing roads?

3) How much and where is the area available for near term harvesting on a per FIA plot basis?

We concentrate on classifying state and private forest land that is likely to be harvested within the next 25-35 years (i.e., not recently harvested) and falls into one of the following four categories: cable-based, ground-based within 150 feet of road, ground-based between 150 and 300 ft of a road, and ground-based beyond 300 ft of a road. Our contribution is to develop a methodology for incorporating spatial data to further refine the collection costs input to NARA's supply chain economic model. The information provided will be customized to meet these input requirements. We discuss how the model is applied (via point and sample dataset) in western Oregon and will be extended over the entire NARA region. We also present how the model compares to Oregon Department of Forestry (ODF) historical harvest data while exploring its limitations and overall implications to the NARA cost model.

7.5 Methods

ArcGIS 10 geospatial software and the Python programming language were used to manipulate and automate data processing (ESRI, 2015). Key input data included: FIA point locations (USFS), Regional Road Networks (State), Digital Elevation Models (USGS DEMs), Protected Areas Data (USGS) and Global Forest Change (2000-2013) mapping data (Hansen et al., 2013a). The process was broken up into distinct phases including 1) pre-filtering the data, 2) spatial processing and discretizing, 3) road data processing and 4) land cover change analysis designed to answer the key questions related to estimating the underlying harvesting method, land type, road offset and land availability questions. The general methodology is based on sampling a 1250-acre area around the FIA point location, subdividing this acreage into 50ac subplots which were then analyzed to estimate a harvesting method and subsequent residual collection criteria related to road offset distance and area availability (Figure FL-1.21). Each subplot was then assigned an estimated harvest unit type, which became the basis for the analysis.

First the data was filtered. Residuals are assumed to be solely a by-product of commercial logging operations. As such, the NARA project is primarily interested in productive sites from state and private land ownership classes rather than federal sites where production is limited. Only forested state and private FIA points were selected for analysis. Once the FIA points were filtered, the point data was then

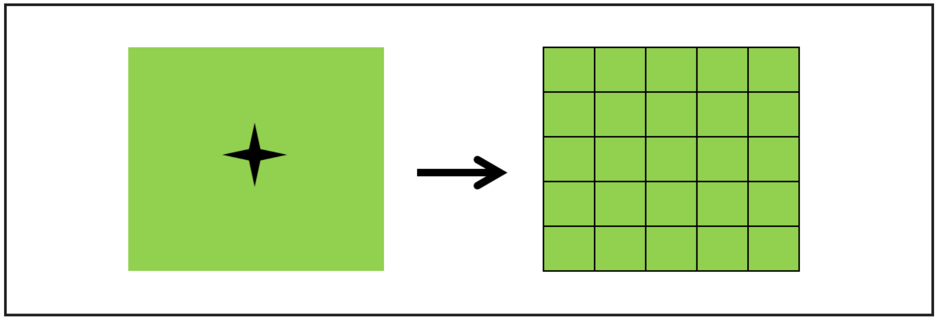

Figure FL-1.21. Conceptual model of land area discretizing (rasterizing)

used in conjunction with state specific DEM data to create a square buffer/ DEM raster around the point encompassing 1250 acres. The FIA DEM raster file was used as the input file for the slope function, which output the percent slope at each point within the dataset. This raster file was then reclassified into two segments depending on the percent slope (<30%, >30%). This reclassified raster dataset was then split (discretized) into twenty-five 50-acre subplots. The 25 individual raster files were then reclassified in accordance to their percentage of either likely ground-based systems (<30%) or cable-based systems (>30%) based on area majority. At this point the land is effectively reclassified in accordance with harvesting method with discrete raster and shape files for each of the 50-acre subplots.

Once the individualized 50-acre subplot data was generated, road data is imported into the system and manipulated with a similar process being utilized to separate the data into the desired 1250-acre units (namely data masking). The plot level shapefiles were then buffered with a 300 ft. offset to determine approximate area available adjacent to the roadway. Finally, only the ground-based system plots were then compared to the road offset shapefiles to determine approximate areas within the 300 ft. buffer.

Recently harvested lands were removed from the landbase since they will not form part of the near term residue supply. The Global Forest Change dataset (Forest Cover Loss Layer) was utilized as a supplemental data layer. Similar to the other processing features, this dataset was sub-sampled and matched at the subplot level and then combined with harvesting system data. This permitted determination of the land area available for future harvests within each harvest class.

7.6 Application and Results

We applied and compared the model results to actual harvest units in Oregon with data provided by the Oregon Department of Forestry (ODF). This was done to modify and compare this method before extrapolation to the entire NARA region. In this section, we illustrate the methodology as applied to 1) a single FIA plot and 2) a series of 39 FIA plot locations in the Astoria region of northwest Oregon for comparison.

7.6.1 State Forest Comparison – Single Plot Example

For illustrative purposes and to provide an example of the actual output to be delivered to NARA, the analysis was applied to a single FIA plot (Figure FL-1.22) located in northwest Oregon (45° 24' 3.19" N, -123° 33' 18.84" W).

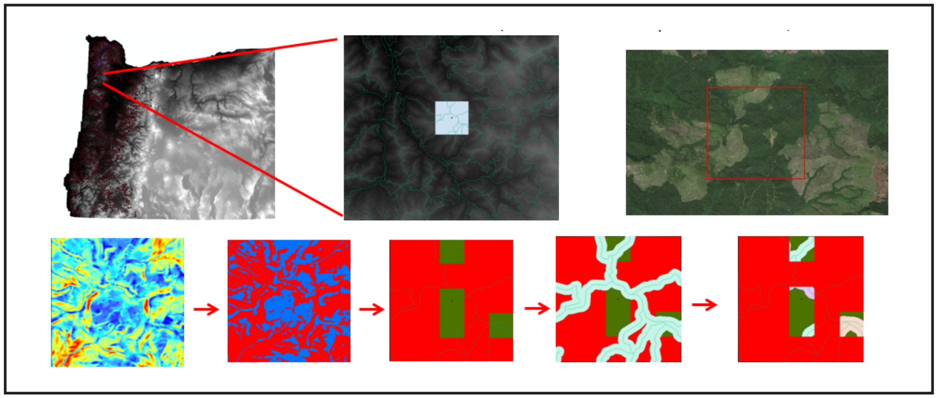

Figure FL-1.22. Example of proposed methodology: FIA plot location, point envelope, Google Earth aerial imagery, slope manipulation, reclassification and discretization, road system 300 ft. offset buffer overlay.

It is important to note that on a per-plot basis the individual results will vary. ODF harvest units are predefined, irregular and tailored towards the site terrain and local logistics beforehand, while the model is a blanket interpretation of the area cut into pre-defined segments based on slope. While the results on a per-plot-basis are highly variable it is anticipated that from a system-wide view the method provides a realistic representation when aggregated. When reviewing a single plot we can also qualitatively see the efficacy of the land available and harvesting unit approximations. When viewing the land from an aerial perspective, we see a clear correlation of land available for harvest from the ground cover change layer when compared to actual aerial imagery (Figure FL-1.23). Additionally, we see that (in this case) the model harvest unit does a good job at approximating ground-based systems as the dominant area (middle of the unit, Figure FL-1.23). Overall, for this point, the model over-predicted ground-based operations by roughly 8% (Table FL-1.9). An over-prediction like this would provide a more conservative approximation of accessible residuals in the sense that a fraction of ground-based residues are not at roadside and must be collected as opposed to residues from cable-based harvesting systems at roadside. The NARA input is the percent of the private or state forested land within the 1250 acre sample that has not recently been harvested and falls into one of the following four categories: 1) cable-based, 2) ground-based within 150 ft of road, 3) ground-based between 150 and 300 ft of a road, and 4) ground-based beyond 300 ft of a road (Table FL-1.7). NARA would apply those land area percentages as part of the biomass cost estimation process.

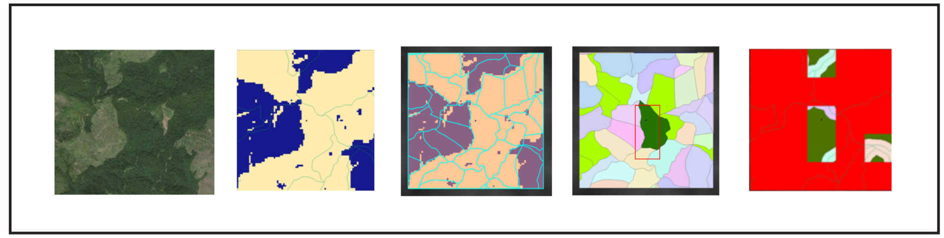

Figure FL-1.23. Comparison of ODF harvesting systems with model projections. Google Earth Overlay, Global Forest Change Layer, ODF Harvest Unit separation, ODF Harvest Unit (Dark Green is 70% ground, light green is less than 40%, all others are cable system).

Table FL-1.9. Example Comparison of ODF vs. Model projections for a single 1250ac Plot (45° 24' 3.19"N, -123° 33' 18.84"W). Model NARA Input File generated based on available land area only.

		ODF Total	Model Total	NARA Input (Of Available)
Harvesting System	Ground-Based Systems	8%	16.00%	
	Cable-Based Systems	92%	84.00%	
Land Cover Availability	Ground-Based Available		50.99%	
	Cable-Based Available		65.87%	87.15%
	% Available Overall		63.49%	
Ground-Based Systems Area	Ground-Based 150 ft Offset		20.72%	2.66%
	Ground-Based 300 ft Offset		41.43%	2.66%
	Ground-Based Other		100.00%	7.53%

7.6.2 State Forest Comparison

The methodology was compared to 39 FIA plot locations which represented approximately 48,750 acres (Figure FL-1.24). With this data, we compared and analyzed the overall harvesting system allocation by overall area as well as review information from a per-plot-basis. We can see that, similar to the single plot example, the composite data compares favorably with the ODF data where cable-based system area was underestimated by 0.59% and ground-based systems area overestimated by 5.86% (Table FL-1.10). When reviewing the ODF harvest unit data compared to the model on a per-plot basis we see that the average overestimation towards ground-based system is roughly 6% with a standard deviation of about 25% (Figure FL-1.25).

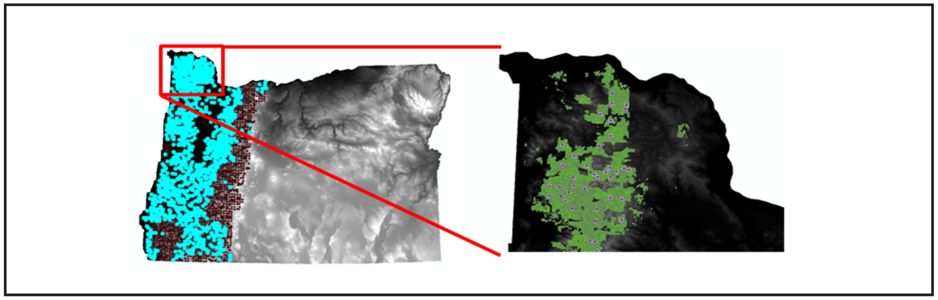

Figure FL-1.24. Oregon State Forest Validation Zone, Northwestern Oregon

Table FL-1.10. Comparison of ODF vs. Model projections for 39 points where data is available.

	ODF	MODEL	DIFFERENCE
Ground-Based Systems	25.42%	31.28%	5.86%
Cable-Based Systems	69.31%	68.72%	-0.59%
Helicopter	5.27%		

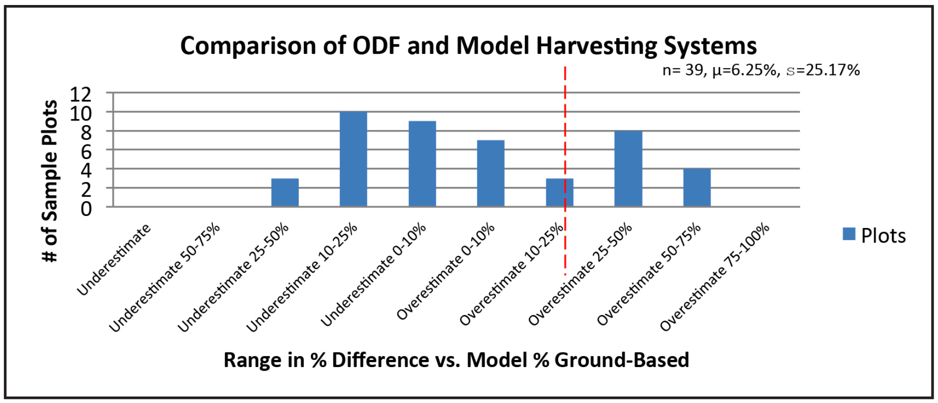

Figure FL-1.25. Comparison of ODF and modeled harvesting systems for the 39 FIA plots (1250 acre area each) based on % difference of model predicted ground-based area. Data normalized to exclude helicopter and non-harvest areas.

It is likely the model over-predicts ground-based systems due to broader terrain characteristics that favor cable-based operations (i.e. raised road system along a ridge adjacent to milder slopes). Conversely, the model may under-predict due to its inability to capture situations where ground-based systems are used to harvest easily accessible timber near roads to supplement the cable operation.

7.6.3 NARA Region Summary

We applied the methodology to the four-state NARA region and passed the results for 6000 FIA plots to the Feedstock Supply modeling team. Table FL-1.11 shows a consolidated view of each State within the NARA region (forested private and state lands). Over 6000 FIA plots were analyzed contributing to a land area of nearly 8 million acres. Overall, there is a higher percentage of area using ground-based logging systems (60-70%) when compared to cable-based systems (30-40%). This is likely due to the fact that private land ownership classes are generally concentrated around more easily accessible with more gentle terrain when compared with federal lands. Additionally, we see regional differences in road coverage and residual accessibility. These results suggest that on average 22-25% available land area in Oregon/Washington correspond to a ground-based road offset of 300 ft. where Idaho has around 18% and Montana approximately 6%. These percentages relate to road costs/infrastructure and regional timber management practices. We also see approximately 10% of the land area had a land cover change during the time period (2000-2013) [thus ~90% available], this in itself would signal a mean rotation age of approximately 100 years. This seems high as industrial forest landowners in western Oregon and Washington are often on 45-55 year rotations. On the other hand, the land base includes riparian, other protected zones, less productive zones, and non-industrial forest landowners who often have goals other than timber production. Also, our land base may include non-forested acres even though FIA indicated the plot to be forested.

Table FL-1.11. Regional Summary of Model Generated Data (OR, WA, ID, MT). Results show ground-based systems by road offset and cable-based systems by % area for the whole region and that which is available (not recently harvested). Model NARA Input File generated on a per FIA plot basis.

		PERCENT OF TOTAL AREA				PERCENT OF AVAILABLE AREA				
REGION	# PLOTS	*G1 - 150'	G2- 300'	G3- REST	%C	%AVAIL	*G1 - 150'	G2- 300'	G3- REST	%C
OR	1973	9.36%	9.36%	47.71%	33.57%	87.24%	11.14%	11.14%	43.88%	33.83%
WA	2093	10.26%	10.26%	51.81%	27.67%	87.61%	12.16%	12.16%	47.76%	27.92%
ID	675	7.94%	7.94%	45.47%	38.64%	89.83%	9.02%	9.02%	43.29%	38.67%
MT	1419	2.54%	2.54%	66.79%	28.14%	92.27%	2.86%	2.86%	66.29%	28.00%

G1= GROUND-BASED SYSTEMS % LAND AREA 0-150' ROAD OFFSET
G2= GROUND-BASED SYSTEMS % LAND AREA 150-300' ROAD OFFSET
G3= GROUND-BASED SYSTEMS % LAND AREA > 300' + OFFSET
C= CABLE-BASED SYSTEMS % LAND AREA
% AVAIL = LAND AREA THAT HAS NOT BEEN RECENTLY HARVESTED
*Approximated as ½ of the calculated 300' buffered area

7.7. DISCUSSION

This methodology provides a framework for estimating residual accessibility on a landscape scale. Overall, this method provides a simple, logical framework for estimating operating harvest system and associated landscape harvest residue accessibility and distance from roadside characteristics on a spatial scale; an improvement over the current method. There are a number of limitations:

1) This method uses a simple discretization technique that cannot characterize all the dimensions of an actual harvest unit such as size, placement, method, road logistics or a combination of methods in a specific area. The logic in our method uses assumptions of harvest unit size, harvest system selection, and harvest system homogeneity within the harvest unit. In this study, the plots were assumed to be squares surrounding the projected FIA plot centroid. In reality, FIA plots are not delineated in this fashion, with the point reflecting the centroid of a spherical area. Additionally, since the FIA point placements are 'fuzzed' to begin with, the actual area (and thus residual quantities) is only approximate.

2) For analysis purposes, we chose a 1250 acre plot to be representative of the FIA area. This design was primarily chosen due to overlapping areas (with larger plots), irregular point placement and to standardize the size. In reality, an FIA plot typically represents a 6000-acre area (though there are plot variants). We assume this sample to be characteristic of the broader area.

3) We assume a 50-acre harvest unit subplot throughout the study as this correlates well with the Pacific Northwest practices, industry norms and the data obtained from our ODF sample. In our 39-plot sample, we see a harvest unit average of 52 acres. However, a standard deviation of 27 acres with the overall range in excess of 100 acres illustrates the highly variable nature of the data. Additional sensitively analysis by varying harvest unit size showed best results when using a 50-acre model harvest unit size (Table FL-1.12).

4) We used a 30% cutoff to differentiate ground-based systems (<30%) and cable-based systems (>30%) based following classifications used by Conway (1976), Dykstra (1996, and MacDonald (1999). While this is the often used, there has been a trend toward using ground-based equipment on steeper slopes. Additional sensitivity analysis showed that this variable (as expected) was particularly sensitive to estimated system choice with 30% being a fairly accurate representation (Table FL-1.13).

5) In conjunction with the slope indicator, we used a simple slope majority rule to denote likely harvesting method. While this will likely explain many logging practices employed, it will not account for combinations of harvest systems used within any given harvest unit. From the 39 ODF plots, we saw that nearly 48% of all actual harvest units used a combination of harvest systems with an average of 30% difference between ground and cable-based logging systems.

6) We used regional road network data. Temporary dry season spur roads, not on the regional road network data, would shorten collection distances on ground-based units. To the extent that these occur, the method here would underestimate the area close to roadside.

Table FL-1.12. Comparison of ODF vs. Model projections for 39 points. Percent difference of ground-based systems compared to observed (normalized for no helicopter or other system utilization) when varying individual harvest unit size (25ac, 50ac, 140ac).

	25ac Model	50ac Model	140ac Model
AVG % Difference	7.41%	6.25%	7.16%
Standard Deviation	23.60%	25.17%	27.83%

Table FL-1.13. Comparison of ODF vs. Model projections for 39 points (normalized for no helicopter or other system utilization) when varying the harvest slope indicator (20%, 30%, 40%).

	ODF Values	20% Model	30% Model	40% Model
Ground-Based Systems	25%	16%	31%	51%
Cable-Based Systems	69%	84%	69%	49%
Helicopter / Other	5%			

This paper presents a simple, logical technique to estimate the spatial area that can contribute to harvest residual extraction. The model is designed to provide input percent areas to the NARA economic model in an effort to further refine the estimated collection costs portion of this model.

Future work to enhance this model could focus on three areas.

1) We believe the largest source of error is related to harvest unit configuration. In order to improve the process, more sophisticated rules could be developed to reconfigure the harvest units to follow watershed boundaries, topographic contours and roadways.

2) Additional data such as soil stability, vegetation type, riparian areas and other sensitive areas could be added to better approximate land available, systems constraints and subsequent residual locations.

3) It would be beneficial to have a greater number of comparison zones (points) in a variety of conditions and States to further refine and test key assumptions regarding slope delineation, harvest unit system cutoff and harvest unit size.

8. SUMMARY COEFFICIENTS FOR NARA FEEDSTOCK MODELING

1) For regional feedstock modeling, each FIA point was classified as ground-based harvesting or cable-harvesting using the methodology of Section 7 applied to each FIA point.

2) The proportion of area within 150-ft, 300-ft, and beyond 300-ft for ground-based units varied by FIA point using the methodology of Section 7 applied to each FIA point.

3) For cable units, 46.5% of the available slash volume as determined by the FVS projections of the tree list under the relevant silvicultural prescription was assumed to be recovered (removed). This percentage comes from NARA field studies conducted under NARA Task FL-1. It compares to 50% used in the Billion Ton-Update report (US DOE, 2011) as a conservative rule for sustainability.

4) For ground-based harvest units, 67.2% of the available slash volume as determined by the FVS projections of the tree list under the relevant silvicultural prescription were assumed to be recovered (removed). This percentage comes from NARA field studies conducted under NARA Task FL-1. It compares to 70% used in the Billion-Ton Update report (US DOE, 2011) as a conservative rule for sustainability.

9. LITERATURE CITED

Adams, D.M. & Haynes, R.W. (1980). The 1980 softwood timber assessment market model: structure, projections, and policy simulations. *Forest Science Monographs,* 26(3), 22.

Akhtari, S., Sowlati, T. & Day, K. (2013). The effects of variations in supply accessibility and amount on the economics of using regional forest biomass for generating district heat. *Energy*, 67, 631-640.

Belart, F. (2016). Forest Harvest Residue Moisture Management in the Pacific Northwest, USA. Ph.D. dissertation. Oregon State University, Corvallis, OR. 146p.

Berg, E.C., Morgan, T. A., Simmons, E.A, Zarnoch, S. & Scudder, M. G. (2016). Predicting Logging Residue Volumes in the Pacific Northwest. *Forest Science,* 62(5), 564-573

Conway, S. (1976). Logging Practices, Principles of Timber Harvesting Systems. San Francisco: Miller Freeman, 419p.

Cross, J., Turnblom, E. & Ettl, G. (2013). Biomass Production on the Olympic and Kitsap Peninsulas, Washington: Updated Logging Residue Ratios, Slash Pile Volume-to-Weight Ratios, and Supply Curves for Selected Locations. USDA Forest Service PNW-GTR-872. Pacific Northwest Forest Research Station. 31 pp.

Dykstra, D.P. (1996). Chapter 5: Extraction. FAO model code of forest harvesting practice. Available online at http://www.fao.org/docrep/v6530e/v6530e08.htm; last accessed May 28, 2015.

ESRI (2015). ArcGIS 10. ArcGIS for Desktop. Available online at www.esri.com/software/arcgis/; last accessed May 28, 2015.

Forest Stewards Guild (2013). Forest Biomass Retention and Harvesting Guidelines for the Pacific Northwest. https://www.forestguild.org/node/9. Last accessed January 28, 2017.

Gan, J. & Smith, C.T. (2006). Availability of logging residues and potential for electricity production and carbon displacement in the USA. *Biomass and Bioenergy*, 30(12), 1011-1020.

GEO Enterprise (2013). Oregon Geospatial Enterprise Office. http://www.oregon.gov/GEO/Pages/index.aspx. Last accessed September 16, 2016.

Hakkila, P. (1989). Utilization of residual forest biomass. Springer Series in Wood Science. Springer-Verlag. 568 pp.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. & J. Townshend, R. G. (2013a). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, 342 (6160), 850-853.

Hardy, C.C. (1996). Guidelines for estimating volume, biomass, and smoke production for piled slash. Gen. Tech. Rep. PNW-GTR-364. Portland, OR: U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Research Station. 17 p.

Howard, J. O. (1981). Ratios for estimating logging residue in the Pacific Northwest. *Research Paper, Pacific Northwest Forest and Range Experiment Station, USDA Forest Service*, (PNW-288).

Hunter, M.L. (1990). Wildlife, Forests, and Forestry. New Jersey: Prentice Hall. 363 p.

Jarmer, C.B., Mann, J.W. & Atkinson, W.A. (1992). Harvesting timber to achieve reforestation objectives. In: S.D. Hobbs, S.D. Tesch, P.W. Owston, R.E. Stewart, J.C. Tappeiner and G.E. Wells (Eds). Reforestation Practices in Southwestern Oregon and Northern California. Forest Research Laboratory (FRL), Oregon State University. USA. Pp 202-230.

Kizha, A. & Han, H.-S. (2015). Forest residues recovered from whole-tree timber harvesting operations. *European Journal of Forest Engineering*, 1(2), 46-55.

Kumar, A., Cameron, J.B. & Flynn, P.C. (2003). Biomass power cost and optimum plant size in western Canada. *Biomass and Bioenergy*, 24, 445-464.

Long, J.J., & Boston, K. (2014). An evaluation of alternative measurement techniques for estimating the volume of logging residues. *Forest Science*, 60(1), 200-204.

Lousier, J. D. (1990). Impacts of forest harvesting and regeneration on forest sites. Land Management Report 67. Victoria: British Columbia Ministry of Forests. 90 p.

MacDonald, A. J. (1999). Harvesting systems and equipment in British Columbia. [Victoria]: British Columbia, Ministry of Forests, Forest Practices Branch.

Mainwaring, D., Maguire, D. & Harrison, R. (2015). Forest productivity, feedstock removals, and implications for nutrient flux and sustainability [Powerpoint Presentation] NARA Annual Meeting, Spokane, Washington. Retrieved from https://nararenewables.org/documents/2016/09/forest-productivity-removals.pdf

Morgan, T. A. & Spoelma, T. P. (2008). California logging utilization: 2004. *Western Journal of Applied Forestry*, 23(1), 12-18.

Nilsson, B., Nilsson, D. & Thörnqvist, T. (2015). Distributions and Losses of Logging Residues at Clear-Felled Areas during Extraction for Bioenergy: Comparing Dried- and Fresh-Stacked Method. *Forests,* 6(11), 4212-4227.

Nurmi, J. (2007). Recovery of logging residues for energy from spruce (Pices abies) dominated stands. *Biomass and Bioenergy*, 31, 375-380.

ODF (2016). Log prices for domestically produced logs delivered to a mill by region. Oregon Department of Forestry. http://www.oregon.gov/ODF/Working/pages/TimberSales.aspx. Last accessed November 29, 2016.

Perez-Garcia, J., Oneil, E., Hansen, T., Mason, T., McCarter, J., Rogers, L., Cooke, A., Comnick, J. & McLaughlin, M. (2012). Washington Forest Biomass Supply. Washington Department of Natural Resources, University of Washington, College of the Environment, School of Environmental and Forest Sciences and TSS consultants, U.S. Department of Agriculture, Forest Service 183.

Simmons, A.E, Erik, C., Berg, C.F., Micah, G. & Scudder, C.F. (2015). NARA Logging Utilization [poster presentation]. Retrieved from http://www.bber.umt.edu/pubs/forest/util/NARALoggingUtilPoster2015.pdf. Accessed August 12, 2016.

Smith, D., Sessions, J., Tuers, J., Way, K. D. & Traver, J. (2012). Characteristics of Forest-Derived Woody Biomass Collected and Processed in Oregon. *Forest Products Journal*, 62(7/8), 520-527.

Thiffault, E., Béchard, A., Paré, D. & Allen, D. (2015). Recovery rate of harvest residues for bioenergy in boreal and temperate forests: A review. *WIREs Energy Environ*, 4, 429–451. doi:10.1002/wene.157

USDA Forest Service (2016). Forest inventory and analysis and plot design: Sampling and plot design. FIA Fact Sheet Series. Last accessed September 17, 2016. https://www.fia.fs.fed.us/library/fact-sheets/data-collections/Sampling%20and%20Plot%20Design.pdf

US DOE (2011). *U.S. Billion-Ton Update*: *Biomass Supply for a Bioenergy and Bioproducts Industry*. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

WA DNR (2016). Log prices for domestically produced logs delivered to a mill by region. Washington Department of Natural Resources. http://www.dnr.wa.gov/programs-and-services/product-sales-and-leasing/timber-sales/timber-sale-querylog-prices. Last accessed November 29, 2016.

Warren, W.G. & Olsen, P.F. (1964). A line intersect technique for assessing logging waste. *Forest Science*, 10(3), 267-276.

Wright, C. S., Balog, C. S., & Kelly, J. W. (2010). Estimating volume, biomass, and potential emissions of hand-piled fuels. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Zamora-Cristales, R. & Sessions, J. (2016). A collection model for forest biomass residues. *Croatian J. of Forest Engineering*, 3(2), 287-296.

Zamora-Cristales, R., Sessions, J., Boston, K. & Murphy, G. (2015). Economic Optimization of Forest Biomass Processing and Transport in the Pacific Northwest USA. *Forest Science*, 61(2), 220-234. http://dx.doi.org/10.5849/forsci.13-158

Zamora, R, Sessions, J. & Marrs, G. (2017). Economic implications of grinding, transporting and pretreating fresh versus aged forest residues for biofuel production. *Can. J. For. Res.*, 47, 269–276. doi: org/10.1139/cjfr-2016-022.