Economic Estimation of the Available Biomass following Logging Operations in Western Oregon and Washington

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Abstract

A two-step method was developed to estimate the economically available biomass from forest operations in the Pacific Northwest. Step 1 measures the amount of biomass in piles from a variety of logging operations. Step 2 applies logistics models to determine the amount of biomass that is recoverable by computing the extraction costs depending on the distance from the landing. Cable units included only the biomass piles located at the landings, while ground-based units computed the collection and transport of each pile to the most cost-effective landing using geographic information system and simulation tools. This approach was applied to operations on state and private timberlands in Oregon and Washington. For the cable logging units, the average pile size was 46.7 green tonnes of residue, and this material was either on or next to the roadside landing. It produced few large piles with an average of 24.75 green tonnes per ha. For ground-based operations, approximately 54 percent of the residue in the harvest units was 90 m or less from the landing. Collection cost increases as the material is farther from the landing and ranged between about $17.6 per green tonne at distances of 15.2 m to $37 per green tonne at distances of 213 m from the landing. Depending on the distance from the landing to the bioenergy facility, it is possible to estimate how far from the landing into the forest to reach to economically collect the biomass.

Forest residuals, or logging slash, are used as feedstock to generate energy in a variety of methods. These include burned directly, often as part of a cogeneration process, or synthesized into value-added fuels by one of several processes, such as pyrolysis or enzyme-assisted distillation. The tree bole and a portion of the bark that travels to the various manufacturing centers—sawmills, pulp mills, and veneer facilities—are currently being fully exploited for a range of products, such a solid wood, pulp and paper, hog and boiler fuel, or landscaping products, that currently produce higher-value products than bioenergy. Thus, logging slash material is most commonly thought of as the feedstock for these new energy products, and they are considered more carbon friendly than some other woody biomass sources (McKinley et al. 2011). However, the small profit margins for these products require that efficient supply chains be developed to collect and comminute this material. Reliable estimates of the raw material that can be collected economically is a first step in this process for creating an efficient supply chain (Bettinger et al. 2017).

Traditionally, two methods are used to estimate the available logging slash. One is to use various allometric equations that estimate the total biomass in the various tree components for each species and then use empirically derived factors to reduce this total to predict the available feedstock. The second method estimates the amount of biomass based on the volume or area harvested. For example, a harvest of known volume will produce an estimated amount of logging slash based on localized relationships.

Both methods are flawed. Common allometric equations, such as those developed by Jenkins et al. (2004), require

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only species and diameter as the independent variables. Most do not include other variables, such as height or percent live crown, which may be able to better distinguish the available biomass in the tree and ultimately the stand. Using past recovery rates based on no more than rules of thumb may not relate to current market conditions that impact both the quantity of material available and the ability to pay for collection of the material. Both can misrepresent the available supply that leads to inferior supply chain performance.

The approach developed in this model describes a two-step method to estimate the available logging slash. Step 1 is to measure the amount of biomass in piles from a variety of logging operations because residue is typically piled after stems are processed (branches and tops removed) in order to prepare the area for planting. Step 2 applies logistics models to determine the economically available biomass by estimating the transportation costs. This approach was applied in western Oregon and Washington to estimate the biomass for a future value-added liquid fuels industry. The approach builds on the work already completed in the Northwest Advanced Renewables Alliance project, which developed a wood-based jet fuel (Zamora-Cristales and Sessions 2016). It can be used to predict the volume and collection costs for supplying bioenergy facilities with feedstock from logging slash. Figure 1 is a theoretical model of the biomass collection problem. The delivered price is set for the feedstock at the facility. The combination of collection, comminution, and transportation must be less than this price; therefore, the farther away from the plant, the lower the collection costs must be to offset the higher transportation costs. Thus, piles farther away the road may be considered as available supply only when near the facility, but those a longer distance from the plant may be able to process only the material that can be reached from the road. It is our contention that estimating the residue volume must include the spatial location of the pile

Literature Review

Many methods have been developed to estimate the amount of biomass available for processing. Thiffault et al. (2015) reviewed a number of biomass studies from Canada, Europe, and the eastern regions of the United States. Estimates of biomass were produced from both partial cut and clear-cut prescriptions from plantation and natural forests using a variety of harvesting equipment, and their estimates are based primarily on locally derived factors. They found that recoverable biomass estimates vary greatly between 10 and 90 percent with a mean recovery rate of 52.2 percent (Thiffault et al. 2015). Higher rates (71.6%) were observed in the Nordic countries, and the authors explain this result as being due to the region's historical emphasis on biomass fuel. In western Europe or Canada, depending on the location of processing, recovery varies between 35.6 and 60.7 percent (Thiffault et al. 2015). However, their review did not include the common logging systems used in the Pacific Northwest: cable logging, feller-bunchers, and shovel logging systems. Whole-tree harvesting is the main harvesting method in western Oregon and Washington with trees on steep ground usually cut manually and trees on flatter terrain cut mechanically. On steep-slope operations, forest harvest residues are concentrated near landings where merchandising occurs. Breakage of tops and branches during yarding on steep ground are rarely piled and are considered unavailable as supply for this study.

Shovel logging is used on the flatter ground to transport logs to the roadside. The logging slash is then piled as part of site preparation for planting and fuel reduction. Kizha and Han (2015) reported recovery from whole-tree logging using cable and shovel logging in northern California on sites being converted from mixed-species stands of conifers and hardwoods to exclusively conifers. They reported that about 60 percent of the residues were recovered from cable harvest units and 70 percent on shovel units. Recovery rates used regional allometric equations with species and diameter at breast height as the input variables 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 bone dry tons (BDT)/ha and about 157 BDT/ha on the shovel harvest units. None of these studies included the ability to estimate the volume in the unit based on the distance from the plant, only the amount that was recovered from harvesting operations.

Methodology

The study was performed on 20 logging sites harvested between 2012 and 2013 located in western Oregon and Washington. The primary tree species was Douglas-fir (*Pseudotsuga menziesii*). Although no population of harvesting units was defined, a variety of harvest units were selected as they became available throughout the year under a variety of market conditions. We believe that they represent a range of conditions likely to be encountered in the Pacific Northwest, but without a well-defined population, we cannot make inferences about these samples beyond the descriptive statistics.

The only selection rule applied to the harvest units was that each harvesting unit would be composed of only one logging system, either cable or ground based. Cable includes all forms of cable yarding, from live skyline systems to running skylines to yoaders. Ground-based systems included primarily skidders, forwarders, and shovels. These operations represent the most common practices found in Oregon and Washington on private land or state forestland. Forest harvest residue piles consisted of branches, tops, and log butts that are typically left at landings or in-unit following timber harvesting and tree processing.

The location of the piles in forest were identified using global positioning systems. All biomass piles larger than 2 m^3 were measured to determine the volume of the shell. The shell encloses the majority of the biomass piles where the individual pieces are no longer fully identifiable. This was performed using a laser range finder to determine the pile shape using a triangular irregular network model that allowed for computation of the pile volume. This measurement compared favorably to the more accurate but much more costly method using terrestrial Lidar (Long and Boston 2014). The shell volume was converted to a solid wood estimate using a packing ratio constant of 0.2 solid wood to shell volume (Hardy 1996, Wright et al. 2010). Additionally, a small sample test measurement was performed that confirmed that a packing ratio of 0.2 was appropriate for this project.

For units harvested with cable systems, only roadside piles were considered recoverable. These piles are a result of

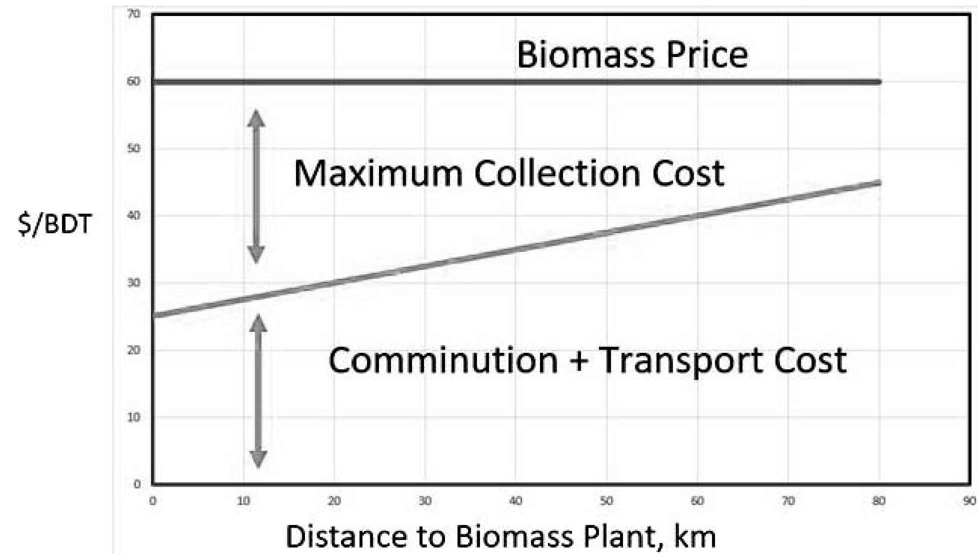

Figure 1.—Conceptual example of the maximum collection cost that could be incurred as a function of truck transport distance to the biomass plant for a given biomass price at the plant.

the merchandising on the landings and contain tops, branches, and cull pieces. Currently, there is no attempt to collect this residue on steep slopes in the Pacific Northwest region. For ground-based units, we could simulate the collection and transport of each residue pile to the roadside for grinding.

The second part of the model estimates the cost to collect, process, and transport the biomass. It begins by determining the lowest-cost route to transport the material to the roadside. Geographic information system layers that contained the pile locations were combined using the overlay function with a slope raster that was derived from a 10-m pixel digital elevation model. The slope raster allowed us to calculate feasible operational routes (e.g., avoiding areas with abrupt changes in slope that will not allow the machine to pass over them) to move the residue to the nearest landing using ground-based equipment. A travel impedance value representing operational difficulty and potential environmental impact was assigned to each pixel varying from a value of 10 for a 30 percent slope to a value of 1 for a 0 percent slope. Then all the potential landings were identified that provide access to chip vans, have enough space to place the grinder, and allow the trucks to be loaded. The potential routes from each pile to each candidate landing were determined using a shortest path algorithm, using the impedance values to model the cost to cross the pixel. The algorithm selected the best route from the pile to the nearest landing. For example, if the slope were constant, the model would select a shortest distance. It may avoid a pixel with high impedance value by selecting a longer route. Once potential distances from each pile to the landing were calculated, the information was incorporated into a model developed to optimize forest biomass operations (Zamora-Cristales et al. 2015).

For each pile, the forwarding option depended on the distance to the landing (Zamora-Cristales and Sessions 2016). For residue piles located at 45 m (150 ft) or less from the landing, the residues were assumed to be transported to the landing using one excavator-based loader. From 45 to 90 m (150 to 300 ft), one forwarder, loaded by an excavator-based loader was used. For distances longer than 90 m (300 ft), two forwarders were used to collect the residues, loaded by the one excavator-based loader. Forwarding costs were calculated for fresh material using a combination of both the excavator and the forwarder costs that were computed for a volume-limited machine rather than a weight-limited machine (Zamora-Cristales et al. 2013, 2015). Examples for Oregon are shown in Figure 2, while an example for Washington is shown in Figure 3.

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 position for loading. This is a best-case scenario for the operation. Grinding costs of $10.60 per green tonne were calculated from previous work (Zamora-Cristales et al. 2016). If large delays occur due to waiting for trucks, a new cost will need to be computed, and a larger intercept value will be added to the comminution component of Figure 1. Transportation cost from the landing to the bioenergy facility is not considered in this study because our main focus is on understanding the effect of pile location and distance from the landing on the economically available supply.

Results and Discussion

Results are presented for the ground-based and cable units. For ground-based units, the cost of collection depending on the location of the material from the landing plus grinding costs were calculated. For the cable units, only grinding costs were reported because all piles were exclusively located at the landings following yarding and log merchandising operations.

Ground-based systems available residue and cost

The ground-based units were divided according to the geographic distribution. The western Oregon harvest units have an average pile size of 7 green metric tonnes (7.7 green short tons [GT]; Table 1). The number of piles per harvest unit averaged 42. The piles were located at various distances from the landings from 0 to 240 m. The volume in each of

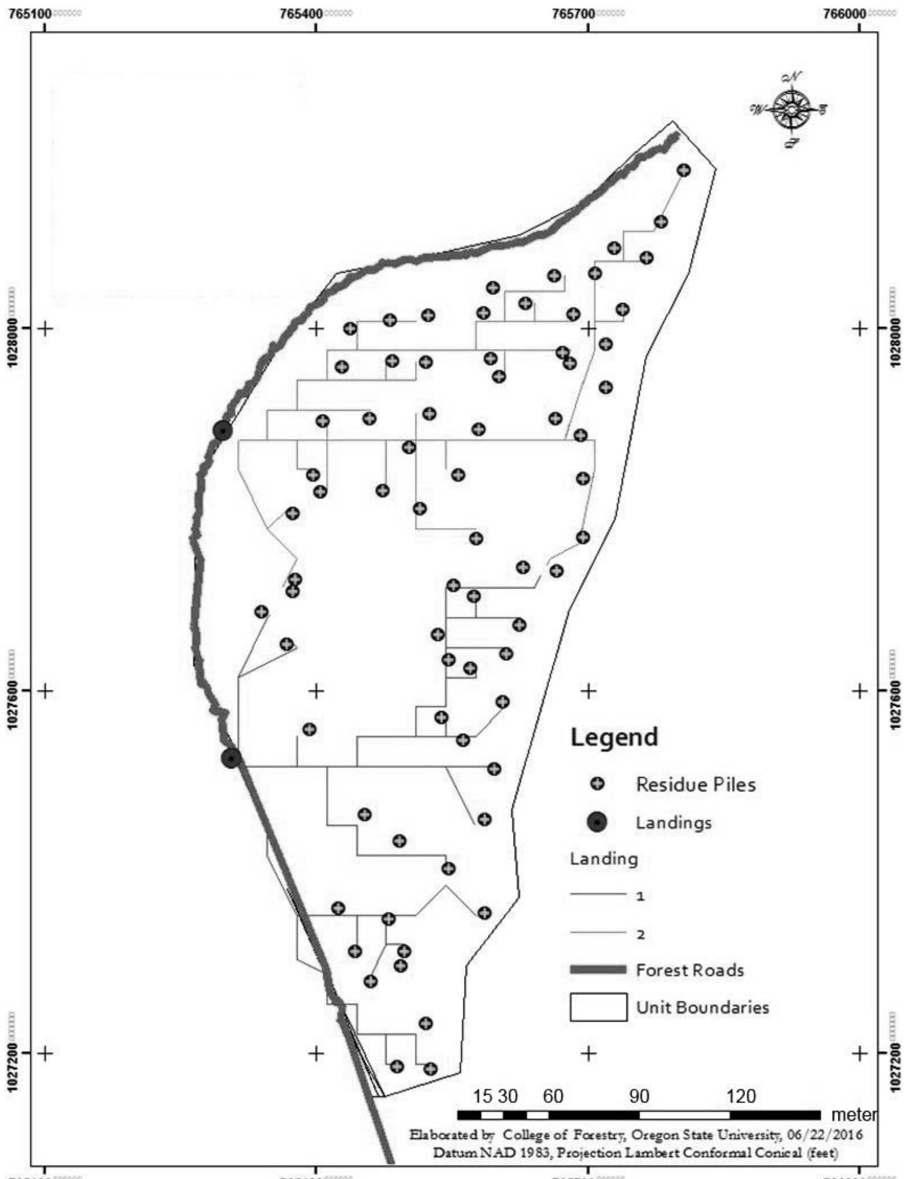

Figure 2.—Geographic information system analysis to determine available logging slash from ground-based logging system in Oregon.

the harvest units varied from 226 to 793 green metric tonnes (249 to 872 GT) of logging slash. A feller-buncher was used in all but one of the units. The use of the excavator shovel was the preferred method for transporting the trees to the landings. The available piled residue per hectare was 86.5 green tonnes (95.3 GT). Pile size varied from 2.45 to 15.9 green tonnes (2.7 to 17.2 GT).

The harvest units located in Washington had an average pile size of 18 green metric tonnes (20 GT), with an available piled residue of 81.1 green metric tonnes/ha (38.8 GT/acre) (Table 2). Compared with the Oregon units, current practices in Washington created larger residue piles. The volume per pile was 7.4 green metric tonnes (8.0 GT) in Washington compared with 5.8 green metric tonnes (6.4 GT) per pile for Oregon. The piles are distributed from 0 to 225 m from the landings. The logging slash produced, based on the harvest area, was similar in both states, Oregon producing 87.1 tonnes/ha and Washington 83.2 tonnes/ha. This is somewhat surprising because western hemlock (*Tsuga heterophylla*) 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. The green tons of residue per cubic meter of harvest in Oregon (0.21) was about 24 percent higher than the green tons of residues per cubic meter of harvest in Washington (0.17). Differences in pulp markets are probably the contributing factor, but this demonstrates how a dynamic system is needed to estimate the available logging slash. During 2012 to 2013, mill-delivered pulpwood prices in western Oregon (Oregon Department of Forestry 2016) averaged less than 50 percent of the price of mill-delivered pulpwood in western Washington (Washington Department of Natural Resources 2016), and the higher pulp prices encourage greater recovery of pulpwood during logging. Delivered chip prices to pulp mills in Oregon were also about 40 percent

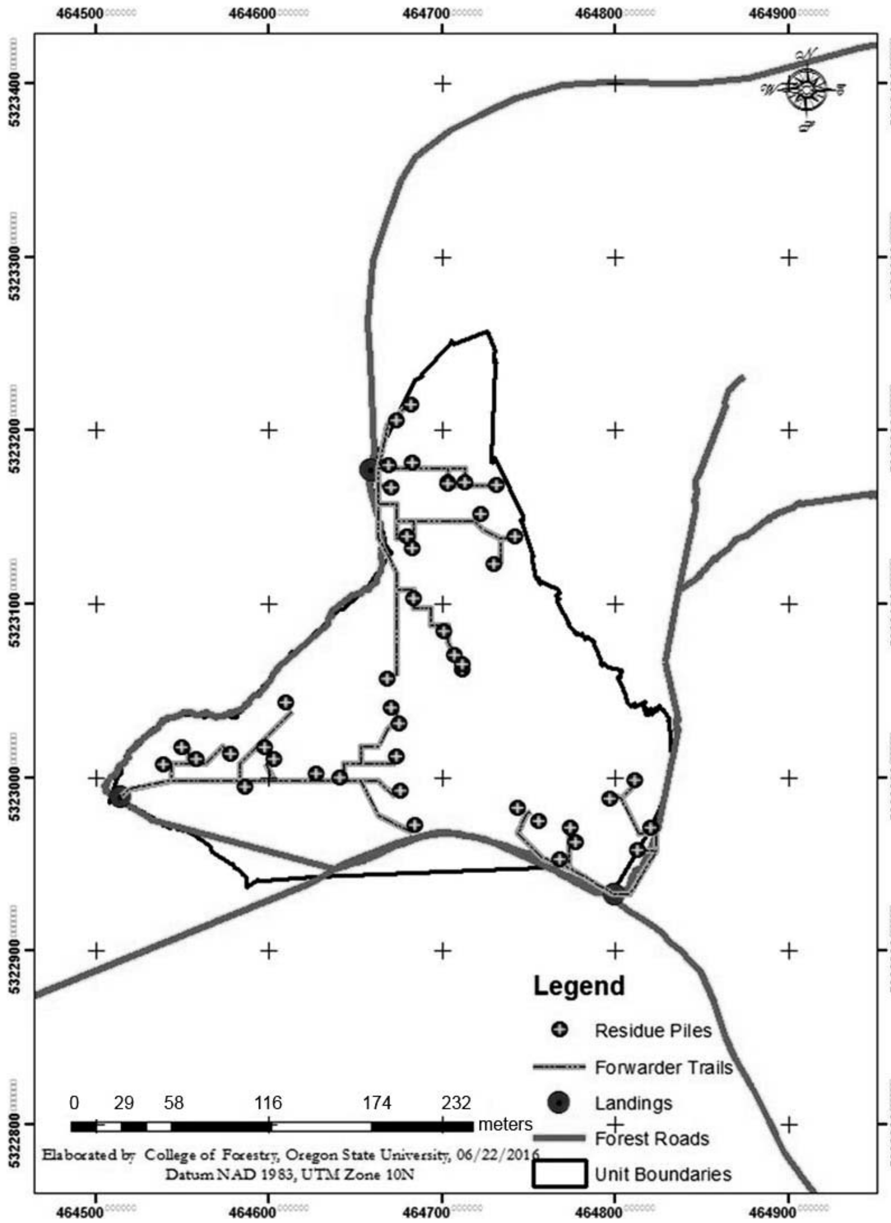

Figure 3.—Geographic information system analysis to determine available logging slash from ground-based logging system in Washington.

lower than those in Washington during the study period. Weaker pulp prices would increase the amount of material that remains following harvesting; however, there is no method to predict where it might be located after piling operations.

The impact of distance on available residue can be seen in Figure 4; approximately 23.4 percent of the residue was available at 45 m (150 ft) or less from the nearest landing for collection with an excavator loader, 35.6 percent of the residue was available at 45 to 90 m (150 to 300 ft) from the

Table 1.—Descriptive statistics of forest harvest residues in Oregon ground-based harvest units.[a]

	Shovel logging system						
Species	PSME/THSE	ABGR/PSME/ACMA	PSME	PSME	PSME	PSME	Average
Mean (green tonnes/pile)	3.2	8.2	6.2	10.0	6.4	8.1	7.0
Count (no. of piles)	71.0	12.0	127.0	16.0	16.0	15.0	42.8
Sum (green tonnes)	226.3	98.6	792.6	159.8	102.6	122.1	250.3
Piled residues (green tonnes/ha)	75.3	79.1	89.0	106.7	65.0	107.7	87.1
Piled residues (green tonnes/m^3 harvest)	0.22	0.41	0.13	0.28	0.17	0.23	0.21

[a] Species codes: PSME = Douglas-fir; THSE = western hemlock; ABGR = grand-fir; ACMA = big leaf maple.

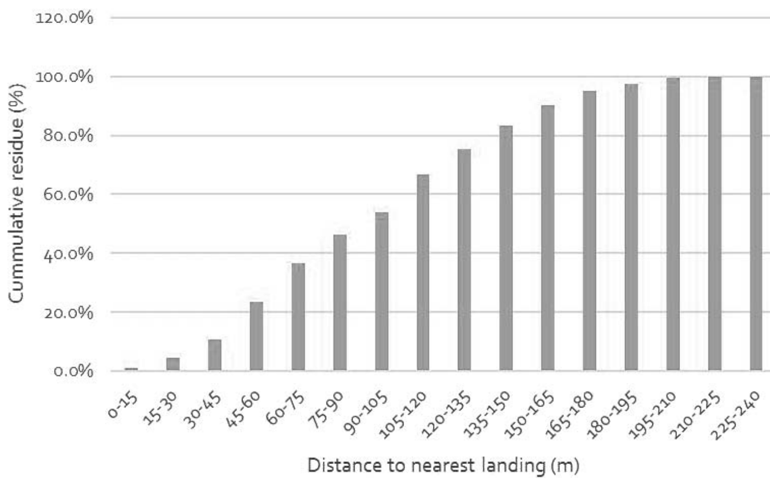

Figure 4.—Cumulative residue by distance from the landing in Oregon ground-based harvest units.

nearest landing for collection using one forwarder and one loader, and the remaining 41 percent of the material was available for collection with two forwarders and one loader for material located at more than 90 m (300 ft) from the landing.

The collection and grinding cost of the material will range from $17.93 per green tonne ($16.30/GT) at 15 m (50 ft) or less to $37 per green tonne ($33.70/GT) at 229 to 244 m (750 to 800 ft) from the landing (Fig. 2). While research has demonstrated that there is little difference in cost per dry tonne between grinding fresh versus aged residue (Zamora-Cristales et al. 2016), the transportation cost is very sensitive to changes in moisture content. Ideally, the material needs to be below 35 percent moisture content (wet basis) to favor the economics by increasing the amount of delivered dry material per truck per trip. At 35 percent moisture content, the costs will range from $27.60/BDT ($25.10/BDT) to $57.70/BDT ($51.80/BDT) for distances of 226 to 244 m (740 to 800 ft).

In Oregon, approximately 54 percent of the residue in the harvest units was 90 m (300 ft) or less from the landing. Thus, there is a potential of recovering that material using only the excavator loader (Fig. 4), the least costly collection system. However, the cost increases rapidly at that distance because at least three swings (with a 15-m [50-ft] boom) will be needed to move the material to the landing (Fig. 5).

The distribution of volume with distance from harvest units from Washington's Olympic Peninsula followed a similar pattern to western Oregon (Fig. 6): 35.1 percent of the piles were available at less than 45 m (150 ft) from the landing, 25.7 percent of the material was available at 45 to 90 m (150 to 300 ft), and 39.2 percent was available at distances of more than 90 m (300 ft) (Fig. 7). Similar to the Oregon harvest units, 60 percent of the material was available at distances of 90 m (300 ft) or less from the landing.

Cable logging harvest units' available residue

For the cable logging units, the average pile size was 46.7 green tonnes (51.4 GT) of residue. An average of 24.75 green tonnes per hectare (11 GT/acre) were found in piles. Average unit size was 26 ha (65 acres). All of the cable logging units were hand felled, and we found an average of 0.14 green tonnes per cubic meter of harvest. The larger piles, compared with those found in ground-based systems, are the result of processing the trees at or around the harvest landings. The steep terrain associated with these harvest units does not permit recovering material left in the harvest unit that is produced from the breakage during falling or yarding activities.

The data gathered from Oregon and Washington reflect current piling practices. As bioenergy markets mature, alternative methods of residue handling during harvesting may develop. Jacobson and Filipsson (1999) reported that harvesters could concentrate stems so that pile size could be increased. Pile size increased, and approximately 87 percent of the residues reached the piles, but productivity of the harvester was reduced.

Table 2.—Descriptive statistics of available material available in Washington Olympic Peninsula in ground-based harvest units.[a]

	Shovel logging system						
Species	PSME/TSHE	PSME/TSHE	PSME/TSHE	PSME/TSHE	PSME/TSHE	PSME/TSHE	Average
Mean (green tonnes/pile)	8.1	14.1	9.8	46.8	19.9	10.2	18.1
Count (no. of piles)	71.0	12.0	127.0	16.0	16.0	15.0	42.8
Sum (green tonnes)	355.8	408.1	176.6	468.1	219.0	264.8	315.4
Piled residues (green tonnes/ha)	74.5	140.0	121.2	60.8	71.2	31.3	83.2
Piled residues (green tonnes/m^3 harvest)	0.15	0.28	0.21	0.14	0.17	0.06	0.17

[a] Species codes: PSME = Douglas-fir; THSE = western hemlock.

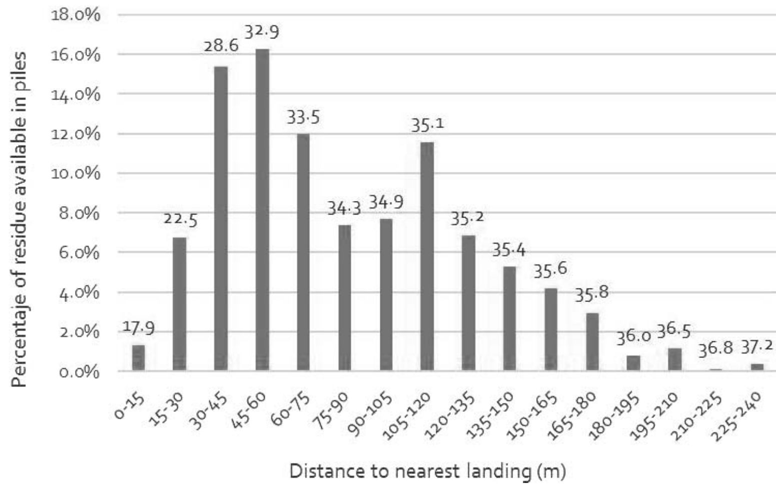

Figure 5.—Cost (number on top of the bar chart) and volume distribution of logging slash by distance group from ground-based units from Oregon.

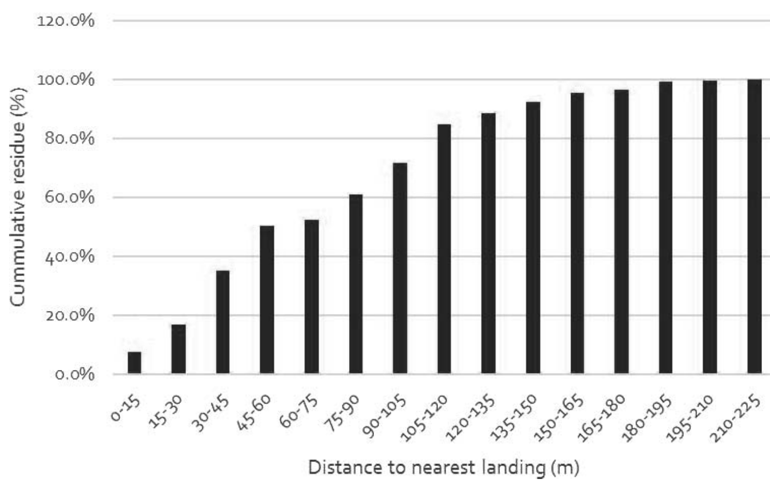

Figure 6.—Cumulative residue by distance from the landing in Washington ground-based harvest units.

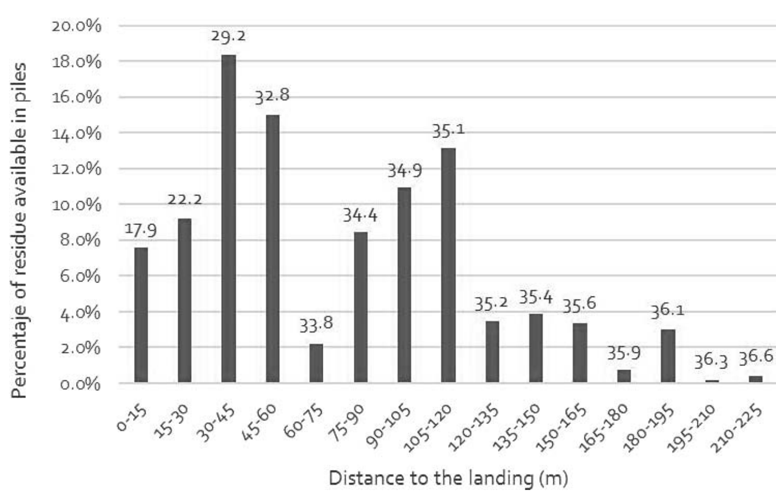

Figure 7.—Cost (number on top of the bar chart) and volume distribution of logging slash by distance group from ground-based units from Washington.

Conclusions

Measured residue per hectare was similar in Washington and Oregon on ground-based harvest units, but the piled harvest residues per cubic meter harvested from Washington were lower than those from Oregon during the study period. This appears related to pulpwood prices prevailing during the study period. Higher pulpwood prices encourage greater log utilization during harvesting, leaving less residues. Steep units harvested with cable methods produce fewer green tonnes per cubic meter harvested compared with the study units harvested with ground-based equipment. Collection cost significantly increases as the material is farther from the landing. For ground-based harvested units, collection cost ranged between about \$17.60 per green tonne (\$16/GT) at distances of 15.2 m (50 ft) from the landing to \$37 per green tonne (\$34/GT) at distances of more than 213 m (700 ft) from the landing. Depending on the transportation distance of the material from the landing to the bioenergy conversion facility, it is possible to estimate how far from the landing it is economically feasible to collect the material. The key is in considering operational constraints along the supply chain. For example, harvest units that are very close to the conversion facility may have lower transportation cost compared with those that are farther (Fig. 6), so the savings can be used to collect more material at distances farther from the landing (as in Figs. 2 and 4).

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