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

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Abstract

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The need for improving the cost effectiveness of forest harvest residue utilization for bioenergy production has been widely recognized. A number of studies show that reducing residue moisture content presents advantages for transportation and energy content. However, previous research has not focused on the relative advantages of in-forest drying depending on the residue characteristics from different logging systems, comminution, and equipment mobilization. Residue drying curves were developed using Finite Element Analysis for two primary Pacific Northwest logging systems. These curves were applied to a case study in Oregon where mixed integer mathematical programming was used to optimize residue delivery to a hypothetical cogeneration plant with a generating capacity of 6 MW-hr. Assuming rear-steered trailers can access cable logging units, approximately 98% of the harvest residue generated by cable logging was delivered to the plant, compared with only 56% of residue generated with a ground-based system. Mainly because collection costs incurred with ground-based system residues exceed cost benefits of drier material. By considering the energy content of drier residues, the amount of oven dried metric tonnes (ODMT) needed to supply the plant can be reduced by 16% without affecting the energy output over a 24-period planning horizon. Lower ODMT demand and shifting to drier material decreases the overall production cost by 20.4%.

Keywords: Harvest residues, moisture content, logging system, cogeneration, drying

1. Introduction

60 After passage of the Energy Independence and Security Act of 2007, several initiatives have been
61 developed to improve the efficiency and economics of using forest harvest residues to produce
62 renewable energy in the Pacific Northwest, USA. The Northwest Advanced Renewables Alliance
63 (NARA) focused on production of liquid biofuels for aviation from forest harvest residues (NARA
64 2016b). Waste-to-Wisdom focused on developing methods and tools to improve feedstock for
65 biomass conversion technologies such as biochar, torrefaction and briquetting (Waste-to-Wisdom
66 2016). AHB (Advanced Hardwoods Biofuels Northwest) focused on growing hybrid poplar and
67 developing technologies for conversion into liquid biofuels and bio-based chemicals (AHB 2016).

68 In the Pacific Northwest, there are an estimated 14.4 million m³ (TPO report 2016) of forest harvest
69 residues produced annually. Of this amount, most of it is piled and burned for site preparation
70 because of the high production costs for biofuel recovery or biofuel markets that are not yet
71 developed.

72 Forest harvest residues consist of all the tree parts that are left in the forest harvest unit. This can
73 include long butts, tops, limbs, broken pieces and non-commercial species. What is left on the
74 landing or in the forest varies depending on the pulp markets. When pulp prices are high, fewer
75 small trees and tops are left as residue. When pulp prices are low, more small trees and pulp logs are
76 left as part of the residue.

77 In the Pacific Northwest, there are two primary logging systems for clear-cut harvesting using whole
78 tree yarding. One is cable logging on steep terrain (slope greater than 40%) and the second is
79 ground-based logging on more gentle terrain. Cable logging generally consists of manual felling and
80 whole tree yarding along a suspended cableway. Cable logging is an integrated biomass harvesting
81 system in the sense that the whole tree is brought to the landing. When trees arrive at the landing,
82 they are delimbed, bucked into logs, and the harvest residues are left in large piles at the landing. In

most ground-based harvest units, trees are felled using feller bunchers and forwarded whole tree by shovel yarding to the roadside landing. Whole tree shovel yarding is a partially integrated biomass harvesting system because during shovel yarding of whole trees, some branches and tops break off due to their repeated handling. The harvest residues that break off on the way to landing require separate collection, if they are to be collected. Alternatively, some trees are felled and processed at the stump (cut-to-length) either manually or mechanically, delimbed, bucked into logs at the felling site and then moved to the landing by skidder or forwarder. In these cases, residues are distributed across the harvest unit and residues are collected in a separate operation.

A harvest residue operation generally involves a grinder positioned at a landing or at roadside. The grinder is loaded by an excavator and as it grinds the material, a trailer is loaded through a conveyor belt. Trucks used to transport this material have lightweight chip trailers that can be 9.8 to 15.2 m long. For that reason, this operation can be challenging as these trucks need roads with larger curve radii, large turn-arounds, and have much lower gradeability than log trucks when empty (Zamora-Cristales et al. 2013). The use of all wheel drive (6 x 6) truck tractors are used by some contractors to improve gradeability and remotely steered trailer wheels are used to improve trailer tracking and reduce turn-around area. Comminution is usually carried out as a separate post-harvest operation. Integrated harvesting and simultaneous comminution of residues at the landing during logging has been attempted in the PNW and elsewhere, but equipment balancing has been challenging. Harrill and Han (2012) evaluated simultaneous comminution in an integrated harvesting of biomass and sawlogs in a stand conversion operation (biomass/sawlog ratio about 4:1) in Northern California during shovel logging, and found 41% utilization of the chipper; whereas up to 85% grinder utilization was observed with post-harvest residue collection and comminution in the same geographic area (Bisson et al. 2015). Jernigan et al. (2013), in the SE USA, experimented with simultaneous chipping during final harvests and found only 25% utilization of the chipper due to the

low biomass/sawlog ratio. They thought simultaneous comminution might have potential as long as it did not adversely affect the logging operation, but cautioned that longer term cost studies were needed. Since forest harvest residues are a minor part of the above ground biomass, equipment mobilization costs for post-harvest collection of harvest residues not reaching the landing during logging and comminution of residues can be significant for smaller harvest units. For example, at US\$ 1 000 in mobilization cost per piece of equipment, harvest units with less than 200 ODMT of total residue become less cost effective (Figure 1). To account for mobilization costs by harvesting system, we recognize distinct harvest units and model mobilization to each harvest unit.

In order to have residues ready for comminution, the residues need to be either at roadside or at the landing. For a cable unit, the trees are usually yarded whole tree, so the limbs and branches are left at the landing in piles when trees are processed into logs. With the ground-based harvest system, even though most of the trees are yarded whole tree by shovel, many of the limbs and tops need to be collected and transported to the roadside or landing at an additional cost due to breakage from rehandling, particularly those at longer distances. The residues may or may not be in piles in the field.

The effect of forest harvest residue moisture content in the economics of pricing, collection and transport has been frequently recognized by researchers (Sessions et al. 2013, Acuna et al. 2012, Ghaffariyan et al. 2013). High moisture content impacts the volume of residues that can be transported due to the weight restriction on roads and highways (Zamora-Cristales and Sessions 2015). This causes the truck trailer to reach its weight capacity before reaching its volume capacity due to the weight of water (Oregon maximum net trailer load is approximately 36.2 tonnes taking into account the weight of the empty truck and trailer), thus making transportation inefficient and uneconomical. On the other hand, when residues are very dry the trailer becomes volume limited,

caused by lower bulk density of ground material (Sessions et al. 2013). For example, a 14.6 m chip trailer, becomes volume limited when residue is lower than about 40% (wet basis).

Forest harvest residues start at high moisture content when fresh. Then, they rapidly lose moisture until wood reaches equilibrium with the environment (Simpson and TenWolde 1999). Storing the material in the harvest unit can be beneficial for drying, depending on the season in which they are collected and whether they are stored piled or scattered over the harvest unit (Belart 2016).

Evaluation of the drying process of harvest residue can be a complex process, as the drying process is often dependent on several factors including initial moisture content. One means of evaluating residue drying and wetting is the use of numerical tools, such as Finite Element Analysis (FEA), that can account for the multiple physics considerations associated with this process. FEA is a numerical technique often used to solve complex problems involving differential equations representative of changing boundary and continuum conditions (Fagan 1992). A finite element model can be constructed to predict forest residue drying rates over time using ambient condition variables such as temperature, relative humidity, wind velocity and rain in which the residues are being stored (Belart 2016). FEA works by integrating the physics phenomena such as heat transfer, laminar flow, diffusion and several assumptions such as material, fluid and thermal properties of the components (wood, water and air) over a continuum discretized with elements and nodes assigned specified degrees of freedom, boundary conditions, and physical differential equations. This tool allows the prediction of transient harvest residue moisture change over time (Belart 2016), of particular utility when coupled with experimental data.

Routa et al. (2015) determined residue moisture content changes over 35-85 weeks using constant weight monitoring in stacked wood. Sikanen et al. (2012) developed biomass drying models for whole trees based on heuristics fitting and local weather in Finland. Murphy et al. (2013) modelled

153 air-drying of small Sitka Spruce (*Picea sitchensis*) biomass logs in an off-forest site in Ireland based on
154 weather parameters. Kim and Murphy (2013) developed drying models in Oregon for Douglas-fir
155 (*Pseudotsuga menziesii* (Mirb.) Franco) and hybrid poplar (*Populus sp.*) small logs based on precipitation,
156 evapotranspiration and piece size using linear mixed effects multiple regression models, and
157 confirmed the relationship between weather and drying rates in wood. However, none has focused
158 on the deterministic use of physics to make moisture predictions or has specifically focused in forest
159 residues and the different drying rates depending on logging system operations.

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

164 Processing residues with lower moisture content is advantageous for improved energy production.
165 Cogeneration plants need fewer residues to generate the power if they are in a drier state. Many
166 companies in the Pacific Northwest (For example, Seneca Sustainable Energy LLC in Eugene,
167 Oregon and Evergreen BioPower LLC in Lyons, Oregon) pay for feedstock on a dry tonne basis,
168 and at least one varies payment per dry tonne based on moisture content. Other studies have
169 recognized the importance of moisture content (Acuna 2012, Ghaffariyan et al. 2013) but have not
170 considered the effect of spatial distribution of forest harvest residues, logging method on residue
171 pile characteristics, and the mobilization costs for comminution. Because drying rates and costs
172 differ between the two logging systems, it is important to understand the difference in economic
173 value of harvest residue from those two different sources. Cable yarding often results in large,
174 “green” piles at the landing that dry slowly. With ground-based systems, residues are often not piled
175 or placed in smaller, dispersed piles which dry quickly. A decision maker is confronted with a choice

of which residue piles to utilize and what should be the management strategy. We focus on a case study in northwest Oregon to satisfy the feedstock supply for a cogeneration plant.

2. Methodology

To investigate the implications of drying from each system, an optimization problem was formulated using mixed integer linear programming. The objective of the problem was to minimize the cost of harvest residue collection, processing and transport to a cogeneration plant to produce electricity. Since a case study was needed to develop the problem, data from clear-cut harvest units over Linn and Marion Counties (Oregon) was employed. This hypothetical plant is located in Lyons, Oregon since it is the logical delivery location for the case study area and it currently possesses forest industry infrastructure, including a cogeneration plant. The delivered feedstock moisture content is a variable to be determined in joint consideration of transport and power generation requirements by an entity that both owns forest land and a power generating facility. The specific objectives of this study are the following:

- Determine drying rates for up to two years for forest harvest residues generated from cable and ground-based logging systems in the area.
- Determine the optimal harvest residue delivery to a hypothetical cogeneration plant located in Lyons, Oregon.
- Determine production costs of residue generated from cable and ground-based logging systems.
- Determine the cost effectiveness of expressing the plant demand as a function of moisture content of delivered residues

2.1 Data set

The data used to perform this analysis consisted of approximately 944 ha of regeneration harvests (clear-cuts) within Marion and Linn counties in Oregon, and was provided by J. Clark and J. Butteris of the Oregon Department of Forestry (personal communication, 2016). These 138 harvest units were harvested between 2003 and 2015 totaling 549,310 m³, where 87% of the total gross m³ were Douglas-fir. The average yield for the harvest units was 580 m³/Ha and 35% of the forest units were yarded with a cable system.

The date of each truck load delivery was provided and used as a start date in which the harvest residues became available for processing and transport or in-forest storage. Additionally, spatial data was provided, including road networks that allowed distance calculation to a hypothetical cogeneration plant located in Lyons, OR. Harvest volume was provided in MBF (Scribner Decimal C, long-log west side scaling rules) and converted into m³ (Spelter 2003). The amount of generated harvest residue was calculated using a factor of 0.12 ODMT/m³ (Lord 2009, Washington DNR 2012). All the material was treated as if it were Douglas-fir and all harvest units with a residue volume below 68 ODMT were excluded from the analysis.

2.2 Mathematical formulation

Two mathematical models were developed. Both are mixed integer programming problems with the objective of minimizing the sum of fixed and variable cost of delivered forest harvest residue to a cogeneration plant over a 24-month period. The hypothetical cogeneration facility is located in Lyons, Oregon with a generating capacity of 6 MW per hour. The first model, referred to as the baseline scenario, assumes a constant biomass to energy conversion. The second model, referred to as the energy-based demand model, assumes a variable biomass to energy conversion based upon the moisture content of the delivered material.

2.2.1 Baseline

The costs are due to fixed components (equipment mobilization) requiring binary variables and variable components (material transport) that are represented as continuous variables. The fixed cost is charged once when equipment is mobilized to the harvest unit to grind residues, as a result of residue volume flow to the plant. The variable cost is the sum of collection (if a unit is harvested with a ground-based system), comminution and transportation costs per ODMT of harvest residue produced. The objective function (Eq. 1) was set as follows:

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

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

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

The wood demand is based on a common rule of thumb of 0.91 ODMT per MW-hr (US DOE 2011, eXtension 2011, Shelly 2010) and is typical of biomass with moisture content of 40-55%, but actual yield will depend on system efficiency (US DOE 2011). The consumption of the plant was estimated at 43 105 ODMT/yr based on 330 days of operation and 24 hours per day during the year. The plant supply will consist of 63% forest harvest residues and 37% bark and other industrial mill residues.

The data set included volume harvested from 2003 to 2015, leaving a smaller amount of harvest residues available at the beginning of the study period because an unknown amount of residues would have been available from harvests before the planning horizon began. To fill this data gap, four months of average forest harvest residue (6 168 ODMT) was made available for the first four

242 periods as a “dummy” unit to provide initial stock. Eq 2. specifies the demand of the cogeneration
 243 plant and Eq 3. limits the harvest residue capacity from each harvest unit.

$$244 \quad \sum_i Volume_{ij} = Demand_j, \forall i, j \in \mathbb{N} \quad (\text{Eq. 2.})$$

$$245 \quad \sum_j Volume_{ij} \leq Capacity_i, \forall i, j \in \mathbb{N} \quad (\text{Eq. 3})$$

246 Additionally, another constraint (Eq. 4) is specified to ensure that the mobilization cost will be
 247 included in the objective function for the period the harvest unit is accessed to retrieve harvest
 248 residues, defined as:

$$249 \quad M * MOB_{ij} - Volume_{ij} \geq 0, \forall i, j \in \mathbb{N}, MOB_{ij} \in \mathbb{Z}_2 \quad (\text{Eq. 4})$$

250 Were M is a large number to trigger the binary variables. Since none of the units have enough
 251 volume to keep the equipment working for longer than a month, a constraint (Eq. 5) was needed to
 252 ensure the residue is processed and delivered in only one period, defined as:

$$253 \quad \sum_j MOB_{ij} \leq 1, \forall i, j \in \mathbb{N} \quad (\text{Eq. 5})$$

254 Finally, a minimum volume of 200 ODMT in the harvest unit is required to move in the equipment
 255 and operate. This constraint was set to avoid having equipment stay in a unit for a very small volume
 256 in order to avoid another move-in cost that would be charged if there is residue delivery in the same
 257 unit on nonconsecutive months. This function is specified as:

$$258 \quad Volume_{ij} - M * W_{ij} \leq 0, \forall i, j \in \mathbb{N}, W_{ij} \in \mathbb{Z}_2 \quad (\text{Eq. 6})$$

$$259 \quad Volume_{ij} - 200 * W_{ij} \geq 0, \forall i, j \in \mathbb{N}, W_{ij} \in \mathbb{Z}_2 \quad (\text{Eq. 7})$$

The associated constants are described in Table 1. The decision variables of this problem are:

- $Volume_{ij}$ Continuous variable, volume of forest residue processed and transported to plant from unit i in period j (ODMT)
- MOB_{ij} Binary variable [0,1] triggering mobilization cost when material is processed and transported to plant from unit i in period j .
- W_{ij} Binary variable [0,1] to ensure there is a minimum volume flow on unit i in period j .

2.2.2 Energy-based demand

A cogeneration plant requires specific amounts of feedstock to generate power depending on its moisture content. Heat energy rates per wood mass burned in a boiler were developed assuming 33% conversion of the net boiler output to electricity and recoverable Btu per green kg from Ince (1979) and fit with a polynomial function (Figure 2). In order to implement this energy-based residue demand, the mathematical formulation of the problem had to be modified. The first part was to calculate the energy content of the residue on each unit at each point in time, defined in (Eq. 8).

$$0.0001 * 100 * mc_{ij}^2 - 0.0014 * 100 * mc_{ij} + 0.7291 = Energy_{ij} \quad \forall i, j \in \mathbb{N} \quad (\text{Eq 8.})$$

Where mc_{ij} is the moisture content (wet basis) of harvest residue of unit i in period j and $Energy_{ij}$ is the amount of energy, MWh-ODMT, of unit i in period j . Finally, the original demand equation (Eq 2.) needs to be modified to make the amount of ODMT demanded at each period vary, depending on the average moisture content of the delivered material. Then $Demand_j$ is the sum of energy demanded in period j in MW-h/month.

$$\sum_i Volume_{ij} * Energy_{ij} = Demand_j, \quad \forall i, j \in \mathbb{N} \quad (\text{Eq 9.})$$

281

282 2.3 Solver

283 For this study, a commercially available optimization model solver (Lingo® v16.0.28) was used. This

284 solver allows importing volume and cost data to the Lingo platform from Microsoft Excel and the

285 mathematical formulation can be written in Lingo language. The solution time will depend on the

286 difference between the current best integer and current best partial integer solution that the user

287 wants to achieve. This difference is known as the gap. Approximately 2 minutes of computing time

288 was necessary on an Intel Core 2 PC (Windows 7 Enterprise, 3 GHz, 8 GB RAM) to produce less

289 than a 1% gap with both models. In other words, the solutions were within 1% of the optimal

290 solution.

291 2.4 Moisture content

292 Finite element models to predict forest residue drying rates for four different climates in Oregon

293 were created, generated and calibrated with field samples (Belart 2016). Those models focused on

294 piled residue and were calibrated with data collected in the field; however, moisture content data was

295 also collected for scattered residue using samples of the same dimensions as the ones in the piles (30

296 cm long, approximately 3.8-4.3 cm in diameter). Since the geographic location and species provided

297 in the harvest data-set are similar to the Valley-East Douglas-fir unit used to build and calibrate that

298 Finite Element Analysis model, the input conditions were used to determine the drying rates for the

299 piled residue of the study area. In addition, the same model with a flat pile was used to estimate the

300 drying rates for scattered residues. After running an initial model, the model was calibrated with data

301 obtained from the field.

The original FEA models were set to run for only one year. However, since we wanted to have the residue available for one full year for each unit, independent from the harvesting date, the models were set to run for two years, starting at different months. The same weather data was used for the second year under the assumption that both years would have the same weather pattern. Since the starting date for storage provided in the data set is the date in which the loaded trucks were delivered, a 50% moisture content (wet basis) was considered as the initial moisture on each month (Belart 2016). Each model component was specified with material properties found in the literature (Table 2).

As residue is stored, various decomposition and degradation processes ensue. Ghaffaryian et al. (2003) in their model assume material loss and deterioration over time. Losses can result from changes in specific gravity as wood decomposes and the loss of biomass components such as needles separating from the branches. Nurmi (2014) studied pine and birch whole tree storage and concluded that significant losses in dry mass of pine only occurred after more than one year of storage. Significant losses in dry mass of birch occurred after only one drying season. For our anticipated storage times we assume no mass loss of wood. Harvest residue samples cut after 23 and 48 weeks of storage in piles primarily of Douglas-fir in western Oregon showed no significant differences between the mean specific gravity of samples obtained at those different times (t-test p-value = 0.2677). We assume needles separate from the residues either in storage or during handling and comminution. Needle fall increases the value of the harvest residue as a fuel and benefits nutrient retention in the harvest unit.

2.5 Costs

For the purpose of this exercise, the cable logging comminution operation consists of a horizontal grinder, an excavator loading the grinder and a 13.7m chip trailer for transportation. Both the

grinder and excavator need to be mobilized with one lowboy trip each. The ground-based logging collection and comminution operation consists of a horizontal grinder, an excavator loading the grinder, two forwarders and a loader loading the forwarders. The productivity and cost effectiveness for this system was evaluated by Zamora-Cristales and Sessions (2016). They compared self-loading forwarders with forwarders being loaded by excavators to transport forest harvest residues and determined that using excavators was more efficient and cost effective. Mainly, because a self-loading forwarder cannot always completely fill the bunk due to visibility and maneuverability reduction, an excavator can load the forwarder faster and increase its load volume (Zamora-Cristales and Sessions 2016). For this study, the grinder and two excavator-loaders need to be mobilized with three lowboy trips. It was assumed that the forwarders were close enough to the operation to be self-mobilized. A mobilization cost of \$1000 per lowboy load was used based on actual costs from seven biomass operations in western Oregon conducted by the authors.

Grinding cost was obtained from NARA (2016a) at 21 US\$/ODMT at 60% utilization and 0.94 US\$/l for diesel and average productivity of 32 ODMT/PMH. Transportation cost was calculated based on a 13.7 m trailer with a volumetric capacity of 99 m³, a maximum payload of 25 tonnes and a ground material dry bulk density of 160 kg/m³ (Zamora-Cristales and Sessions 2015). These calculations are based under the assumption that the trailers can access all the harvest units.

As the moisture content of the material changes over time, the truck load was limited by either weight (when wetter) or volume (when drier). Transportation hourly cost was calculated based on 8% of the time on dirt road, 15% on gravel road and 77% highway and different costs for travel loaded and unloaded (110 US\$/hr and 95 US\$/hr, respectively). Additionally, 3.2 US\$/ODMT was added to account for an unloaded truck waiting for one hour in order to keep the grinder utilization high, since typically the grinder needs to wait for trucks to turn around or the road standard does

not allow transit for more than one vehicle at a time. Since we assume that all trucks can access all units, a rear steered axle trailer was used to transport residues from cable units at a higher cost, and a standard trailer for ground-based units. The total truck cost is 103 US\$/hr per traveling hour for the standard trailers (NARA 2016a) and 126 US\$/hr for the steerable rear trailers (Zamora-Cristales et al. 2015) with an average speed assumed at 48.3 km/hr based on the proportion of road surfacing and loaded/unloaded travel time.

Collection cost was considered to be zero when the harvest units were yarded with a cable system and 24 US\$/ODMT on ground-based units (Zamora-Cristales and Sessions 2016) using two forwarders and one loader with a harvest residue average distance to roadside of 156 m (Zamora-Cristales and Sessions 2016). Distance from each harvest unit to the cogeneration plant was calculated from the centroid of each timber sale to Lyons, Oregon using ArcGIS 10.4.1.

2.6 Drying curves

Forest harvest residue dries rapidly during the first weeks in the harvest unit and then reaches equilibrium with ambient conditions. This is similar to what Pettersson and Nordfjell (2007) found, their harvest residue MC fell from 50 to 29% in only three weeks. Scattered residue left after a ground-based logging operation in this particular harvest unit (assumed typical of Valley East Douglas-fir) can reach moisture contents as low as 10% (wet basis) during the summer months, and can re-moisten up to 30% (wet basis) during the winter (Figure 3 a)). When residue is left piled at the landing on a cable logging operation, it does not reach as low a moisture content as if it was scattered. Also, the piled residues gain moisture during the winter, although the piled residue has less moisture fluctuation over time compared to scattered residue (Figure 3 b)). These drying behaviors serve as inputs for the case study.

3 Results

371 3.2 Baseline

372 After economic optimization of the problem, the results indicate that all the residues from the
373 previous year are used to help supply the power plant during the first four monthly periods (January
374 to April of year 1). Then, the excess residue produced in May and June is left to dry to supply the
375 deficit in August and September (Figure 4). A total of 75% of the available harvest residue is
376 processed and delivered to the cogeneration plant in Lyons, Oregon. The average round-trip
377 distance for the cable logging units is 72 km and 32 km for ground-based units.

378 In the baseline scenario, using a 13.7 m trailer and 160 kg/m³ material bulk density, 98% of the
379 volume harvested by cable system is processed and delivered to the plant, and only 56% of the
380 volume harvested with a ground-based system is delivered to the plant. The average round trip
381 distance of the material left in the harvest units is 87 km.

382 The average moisture content (wet basis) of the residue for both cable and ground-based harvest
383 systems for the two-year period is 34%. The majority of the residue is left to dry for one month,
384 especially the material harvested with a cable system. Very little volume is left to dry for more than
385 four months (Figure 5), probably because the single trailer becomes volume limited and there is little
386 advantage to letting the material dry for much longer. Additionally, material is needed to cover
387 volume gaps in preceding periods.

388 3.3 Energy-based demand

389 After implementing the harvest residue demand depending on its energy content, the total amount
390 of volume delivered to the plant is reduced by 16% (8 874 ODMT in the two-year period) without
391 affecting the energy needs to keep the plant generating electricity at the same level as the baseline

scenario. In terms of harvest systems, the ground-based system volume delivered to the plant is reduced by 32% and the cable system by 5% (Figure 6).

The amount of volume delivered to the plant is not only reduced when the demand for harvest residues is based on energy content, but it also changes the number of drying periods of the residue in the field, shifting towards longer drying times. There is a minimal amount of residue processed and transported immediately after harvesting, and residue volume is shifted towards 2, 3 and up to 6 drying periods (months) compared to the baseline scenario (Figure 7).

By recognizing the value of drier material, the problem shifts towards delivering material with lower moisture content. In the first two periods, the average moisture content is the same for both cases, probably because there is a smaller pool of harvest units to choose from. However, as more harvest units become available, the average moisture content starts decreasing, especially in the last two warmer months, July and August. During fall season (September and October), the average moisture content of delivered residues drops down by up to 30% (Figure 8).

3.4 Cost analysis

3.4.1 Baseline

The largest proportion of the variable cost in a ground-based unit is collection (24.3 US\$/ODMT). This can be avoided in a cable unit because the material is already at the landing (Figure 9). Even when the average truck transportation cost for the cable system is 17.8 US\$/ODMT and transportation for the ground-based harvesting system is 11.3 US\$/ODMT, the higher residue drying rates achieved on a ground-based system are not enough to offset the collection cost. The difference between both systems is 17.7 US\$/ODMT.

413 The total cost for the operation is US\$2 700 326 (50 US\$/ODMT) over the two -year period. The
414 objective function gap is 0.7%, meaning the total cost of the optimal solution cannot be lower than
415 99.3% of this (integer) solution.

416 3.4.2 *Energy-based demand*

417 Since collection and comminution costs are assumed constant, only the amount of residue volume
418 and harvest units chosen in the energy-based scenario differ from the baseline scenario, resulting in
419 transportation cost averaging 0.7 US\$/ODMT lower than baseline conditions. When the cost is
420 separated by harvesting system, the cost is 1.0 US\$/ODMT lower for the cable system and 0.5
421 US\$/ODMT lower for the ground-based system (Figure 10).

422 When compared with the baseline scenario, the total cost of the operation during the 24 periods is
423 20.4% lower (US\$550 947 lower). The average cost for the operation is 47 US\$/ODMT.

424 4 Discussion

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

432 The amount of forest residue available for this case study is enough to supply 63% of feedstock for
433 a 6 MW-hr cogeneration plant in Lyons, OR. The majority of the residue coming from a cable
434 system operation is delivered to the plant (98%), even when the cable units are further from the

plant and have a lower drying rate. The ground system units are closer to the plant, but the collection cost is too high to have those units be more cost effective than the cable units.

For both cases, piled and scattered residue, moisture decreases rapidly during the first month. For that reason, most of the residue is left to dry for the first month for the baseline scenario. This result is different from what Acuna et al. (2012) found. Their results indicated that they should have left the residues to dry for 7 to 8 months. However, they had multiple types of feedstocks to supply the plant such as whole trees and delimbed stems with higher storage costs than harvest residues. Currently, since harvest residues are usually left to dry for burning in the fall, storage cost was not considered in our case study.

In terms of variable cost, the ground-based units are 46-48% higher compared to units harvested with a cable system. The main reason for this difference is the collection cost that needs to be incurred when the residue is scattered over the unit. This makes the overall cost in the ground-based units too high, even when these units have an advantage in terms of material moisture (drier than cable) and distance to the plant (lower transportation cost).

When the plant demand is based on the residue moisture content and its effect on the plant energy recovery, the amount of material needed to obtain the same output of energy is reduced by 16%. This is caused by energy losses due to the vaporization of water contained in the wood during the combustion process (Bowyer et al. 2003). For that reason, drier residues make energy production more efficient. Most of this reduction occurred in the ground-based units (32% reduction), mainly because of the collection cost. As expected, when drier material becomes more attractive from the demand point of view, there is an additional incentive to let material dry in the field for longer time. Almost no fresh material is taken to the plant in the energy-based demand scenario (Figure 7). This material is left to dry for at least one period, and as more harvest units become available, material

starts shifting towards more drying periods. Since there is no cost to let the material dry, this presents an added benefit to the value of drier material.

The changes in moisture content, quantity, and origin of the harvest residues delivered to the plant result in a lowered transportation cost that averages 0.7 US\$/ODMT compared to the baseline scenario. This cost could be further reduced if a double trailer was to be used for harvest units further from the plant. Double trailers present an advantage compared with single trailers since they have larger volumetric capacity (Zamora-Cristales and Sessions 2015). The total cost of the operation during the 24 periods is 20.4% lower than when energy recovery in the plant is not considered. This is a result of having the plant demand being driven by the harvest residue energy content as a function of its moisture content instead of assuming a fixed 0.91 ODMT/MW-hr at 50% moisture content.

5 Conclusions and Future Work

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

For the baseline scenario (24 periods), the longest residue storage was seven months, and the majority of the material was stored for only one month. Under the circumstances of this study, letting the material dry for a longer time does not seem beneficial.

Since fuel value is inversely related to moisture content, grindings with lower moisture content are more valuable at the plant. In our case study, 16% fewer ODMT of residues are required to generate

a fixed power output. This approach incentivizes longer drying times in the field and can result in a more accurate estimate of operation cost (20.4% lower) than the baseline scenario of 0.91 ODMT/MW-hr.

The conclusions are limited to a specific area. However, drying rate schedules can be derived for other climate regions in the Pacific Northwest and can be used to investigate the effects of forest residue. For the purpose of a case study, we assumed a fixed residue recovery rate per merchantable unit of harvest using both cable and ground-based logging systems. Studies in progress by the authors and others suggest the recovery rates may differ between harvest systems. Kizha and Han (2015), for example, found 70 percent recovery rate from ground-based sites and 60% from cable-logged sites in Northern California. We also assumed that all cable harvest units required use of the more expensive self-steering trailer. Not all cable units will require self-steering trailers and 6 x 6 truck tractors. However, as cable harvest units were chosen over ground-based units, using less expensive trucks on some cable units probably would not have affected the biomass utilization schedule for this example. Opportunities for integrating biomass/sawlog production hold potential for reducing collection and comminution costs. Lastly, the effect of feedstock moisture content will be affected by the efficiency of the specific plant (US DOE 2011). Specific design features may favor operation in specific moisture content ranges to achieve complete combustion.

The future trajectory for biomass for energy is unclear. Cogeneration of biomass for electricity and steam using forest harvest residues for part of the furnish is done in at least two mills in western Oregon under a biomass subsidy of about \$5.5 per dry tonne, where the industrial cost of electricity is about 6.5 cents per kilowatt-hr. Industrial cost of electricity in neighboring California is 14.0 per kilowatt-hr and about 11-12 cents nationally. Much will depend on future costs of energy substitutes.

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Table 1. Definition of constants used in the mathematical formulation.

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

Table 2. Material properties of model components.

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

¹Based on 1,520 (kg/m³) cell wall density (Bowyer et al. 2003), ²Hardy (1996), ³Simpson and TenWolde (1999), ⁴Monteith and Unsworth (2008), ⁵TenWolde et al. (1988) Wilkes equation, ⁶Nield and Bejan (1998), ⁷Welty et al. (2008)

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Figure Captions

Figure 1. Relationship between mobilization cost and total harvested biomass based on actual mobilization costs to seven harvest units in Oregon studied by authors using three lowboy trips to mobilize for ground-based harvest units and two lowboy trips to mobilize for cable units.

Figure 2. Rate of wood (ODMT) per MW-hr needed at the energy plant depending on wood moisture content.

Figure 3. Drying curves for Douglas-fir a) scattered residue and b) piled residue at different stand harvesting months, based on modeling of Valley East Douglas-fir empirical data.

Figure 4. Harvest residue volume available and delivered to the plant on each period over the two years.

Figure 5. Number of drying periods for delivered harvest residue volume by harvesting system for baseline scenario.

Figure 6. Available and delivered residue volume by harvest system during 24 periods.

Figure 7. Number of drying periods for delivered harvest residue volume by harvest system for energy-based demand scenario.

Figure 8. Average moisture content (wet basis) of delivered harvest residue per period.

Figure 9. Collection, comminution and transportations costs for the cable and ground-based harvesting units.

Figure 10. Transportation cost by logging system for the baseline and energy-based scenarios .

a)

b)

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