Original scientific paper

Modeling Harvest Forest Residue Collection for Bioenergy Production

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Abstract

Forest harvest residues are often available at roadside landings as a byproduct of the log manufacturing process. This residue is usually available for renewable energy production if desired, however there is a significant amount of residues that do not reach the landing during the harvesting process and could potentially increase the supply of forest biomass from each harvest unit. The proportion of recoverable residues depends on their collection costs, which are a function of the distance from roadside landing, terrain conditions, and collection method. In this study, a forest residue collection model using forwarders and excavator-base loaders was developed to estimate the potential cost of biomass extraction from the forest to roadside landings. At the operational level, the model calculates the potential forwarder paths to estimate the cost depending on slope, machine arrangement and distance. For the analyzed harvest unit, the use of the excavator-base loader working alone is the most cost effective system for distances of less than 50 m and two forwarders and one excavator-base loader is the most cost effective system for distances beyond 50 m. The optimal solution collection costs ranged from USD 7.2 to 27.5 per oven-dry tonne for a range of distance between 15 and 350 m. The use of one operator to trade positions as forwarder operator and excavator-base loader operator resulted in lower productivity and higher cost compared to the use of a separate operator for each machine.

Keywords: biomass, forwarder, simulation, spatial analysis

1. Introduction

Forest harvest residues are a potential source of renewable energy to generate electricity and produce liquid biofuels (NARA 2011, SENECA 2015). In whole tree logging, forest harvest residues are often available at roadside landings as a byproduct of the log manufacturing process. However, there are a significant amount of residues that do not reach the landing during logging (breakage during dragging) and could potentially increase the supply of residues from each harvest unit. In cut-to-length operations, forest residues such as tops and limbs are usually left dispersed on the ground during the delimbing and log bucking process. Forest residues could be chipped in place by mobile chippers or collected and moved to roadside for chipping or grinding at roadside points. Or, it could be bundled and bundles forwarded to roadside. In western North America neither the bundler nor the mobile chipper have been economical (Zamora-Cristales et al. 2015). Instead, the gathering of residues involves excavator-base loaders or forwarders to collect and transport the residue to roadside locations for processing. Collection costs are a function of the distance from the collection point to the roadside landing, terrain conditions, and system productivity. The farther the collection point is, the higher the biomass cost will be. Equipment balancing is important in some system configurations, where loaders and forwarders interact between different tasks that can affect the productivity of the whole collection system. Terrain conditions affect maneuverability and may prevent the forwarder from using the shortest route to reach the landing due to ridges and severe slope changes. The objective of this study was to develop a spatial simulation model to estimate the collection cost of harvest residues for different forwarder-loader configurations at the operational level. Identifying the collection cost of forest residues will help to improve biomass supply cost estimation. The scope of this paper considers harvest units with slope gradients less than 30%. The model calculates the cost of collection from different locations in the forest to the most cost effective landing. The problem to be solved is to accurately estimate the cost of collection given the distance, terrain conditions and machine productivity.

1.1 Relevant literature

Previous studies concentrate their analyses in the processing (grinding or chipping) and transportation, and very few involve the collection from the forest to the landing. Anderson et al. (2013) discussed the use of end-dump trucks to transport the material to a centralized yard; however, collection from the forest site to roadside was not discussed. In Canada, Yemshanov et al. (2014) found that forwarding biomass from the forest to the landing is inefficient given the low bulk density of the harvest residues, but the effect of cost at different distances from the landing was not discussed. Grushecky et al. (2007) evaluated extraction costs in southern West Virginia, using grapple skidders. The authors identified the extraction cost versus average extraction distance; however, the study only considered straight line average skidding distance thus not considering the effect of terrain conditions. Others have used digital terrain models to plan skid trails (Tucek 1999, Bohle 2005) and evaluate optimal landing location (Contreras and Chung 2007). Rørstad et al. (2010) developed an engineering model for estimating forest harvest residue cost using a forwarder with self-loader. Lacking actual data on harvest residues, they adjusted data from Laitila et al. (2007). Their distance from stand to landing was estimated in SGIS, but was done at a regional level. Spinelli et al. (2014) develop a simulation model to compare productivity and cost of chipping at the yarding site (not accessible for large trucks) and chipping at a roadside landing using a forwarder to transport the unprocessed residue from the yarding site to the roadside landing. Forwarding residues to the landing resulted in a more expensive operation having the forwarding distance as the most important factor affecting the cost.

The model proposed here, on a harvest unit basis, is based on field collected data, and considers system configurations not previously documented in the literature. A GIS-based raster system is used to limit the travel of the forwarder to gentle terrain when possible or at least to minimize the travel on steep slope zones although this may require traveling through a longer trail. It assumes that rubber-tired vehicles are permitted on the forest harvest site. Beginning in the 1960s, some landowners in western Oregon and western Washington stopped using rubber-tired skidders on compactable, high site forest soils, preferring cable logging to protect soil productivity (Fisher 1999). In the early 1970s, excavator-base loaders were introduced for yarding logs and trees to roadside. The excavator-base loader (shovel) equipped with wide tracks (low ground pressure) and high clearance makes one pass across the harvest site limiting soil disturbance. The high productivity of this one man system for yarding and loading led to its quick adoption throughout the region. Concern over using rubber-tired vehicles lingers; some forest managers remain concerned about potential post-harvest site damage from high tonnage rubber-tired forwarders collecting low value harvest residues after the forest site was protected using the one pass shovel logging method.

1.2 Collection systems

The collection of forest biomass requires concentrating the scattered residues at collection points. In the Pacific Northwest, USA this is usually performed by an excavator-base loader. If the residues are close to the landing (usually less than 50 m), they can be collected using an excavator-base loader that swings the residues directly to the landing. At longer distances, the use of alternative and more productive equipment, such as forwarders, are used to access the material and transport it to the landing. Forwarders are equipped with a self-loading grapple crane that allows the forwarder to operate independent of a dedicated loading machine. The conventional forwarder was designed for loading logs, not forest residues. Using the self-loading system for forest residues can be challenging due to the limited visibility of the operator while putting the material in the bunk and the limited reach and capacity of the loading boom. In biomass recovery operations in the Pacific Northwest, USA, forwarders are sometimes loaded using excavator-base loaders equipped with fully rotating grapples that facilitate the handling of residues. Once the forwarder is fully loaded, it returns to the landing and unloads. Equipment balancing is important to keep all equipment elements producing to optimal capacity. The farther the collection point is from the landing the more expensive it is to collect the residue because the forwarder has to spend more time traveling, thus decreasing the forwarder productivity (Fig. 1). The use of two forwarders per loader help to minimize the impact of the distance on forwarding productivity, however traffic along the trails can cause machine interference. Once the material is at the landing, it is commonly processed using grinding to increase the bulk density of the material and facilitate transport and further handling. Other equipment such as off-highway dump trucks with skidder tires could be used to move the residues;

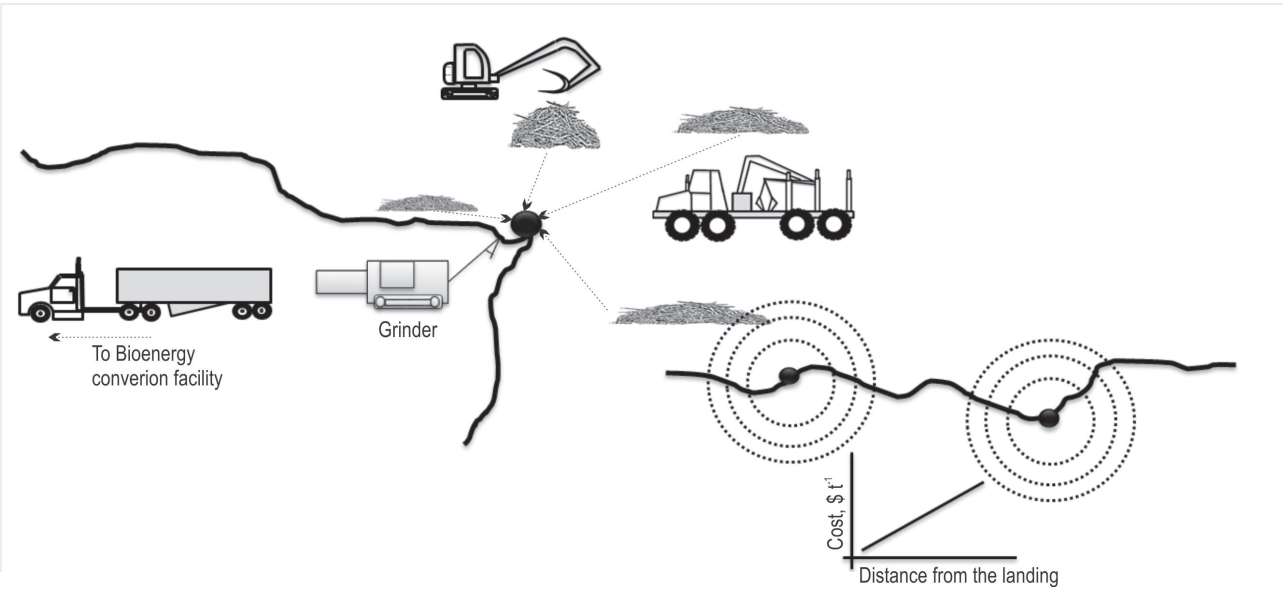

Fig. 1 Description of the forest residue collection problem

however, the use of this equipment on forest soils could cause more soil compaction compared to the multi-axle forwarders using wheel tracks.

Thus, at least five systems can be used alone or in combination:

⇒ System 1 – Excavator-base loader, working alone
⇒ System 2 – Forwarder self-loading
⇒ System 3 – Forwarder loaded by excavator-base loader
⇒ System 4 – Two forwarders loaded by one excavator-base loader
⇒ System 5 – As above, but the loader is manned by the forwarder operators, in turn

The time and productivity of each system, *s*, can be defined by:

$$T_s = a_s + b_s x \quad (1)$$

$$P_s = \frac{60}{T_s} L_s \quad (2)$$

$$C_s = \frac{Cost_s}{P_s} \quad (3)$$

Where:

T_s time per trip in minutes, as the fixed component of the trip not related to distance
b_s time per ton-km
x travel distance in km
P_s productivity in tonnes per hour
L_s load per trip in tonnes
$Cost_s$ cost per unit time (hours)
C_s cost per unit volume in dollars per tonne.

The objective is to find the system or combination of systems that minimizes total collection cost including mobilization costs.

2. Material and methods

The analysis for modeling forest residue collection starts at the forest unit by identifying the boundaries, potential spatial location of residues and candidate landings. In this model, a grid-type approach is used to cover the entire unit and estimate the cost of each potential residue location to the roadside landings. A point every 30 m is generated and stored to represent the location of the forest residue (Fig. 2).

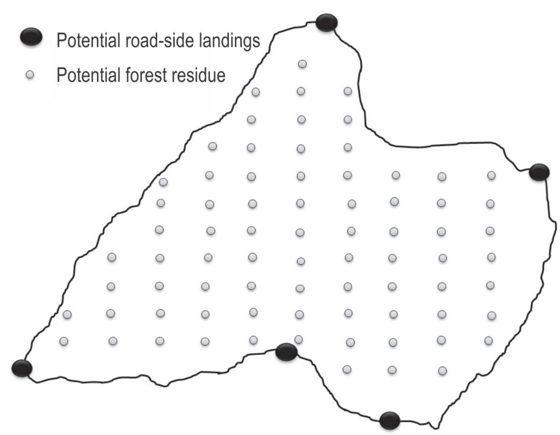

Fig. 2 Spatial description of the residue collection problem from different locations within the harvest unit to potential roadside landings

Landing locations are typically selected by their accessibility for trucks and available turnarounds. In this model, we selected all the logging landings and loading points as potential candidates for roadside residue concentration. The main criteria for establishing a residue landing is that it has to provide good access for chip vans and enough space to place residue and processing equipment. Chip vans compared to log trucks have several limitations depending on road characteristics such as trailer low ground clearance and less traction in the rear axles when traveling empty among others (Sessions et al. 2010, Zamora-Cristales 2013). Once the unit boundaries, potential landings and concentration points were defined, we developed a computerized GIS model to design the forwarder trails given the terrain conditions.

2.1 Computerized identification of forwarder trails

Forwarder trails need to be identified to accurately estimate the forwarding cost. Assuming an average forwarding distance for the entire harvest unit could lead to underestimating or overestimating the cost depending on the assumed distribution of residues among candidate roadside landings. Assuming a straight line distance from the collection point to the landing could also lead to misleading results, given that in actual conditions operators tend to avoid difficult terrain or abrupt edges when traveling in the forest, thus traveling longer paths. To create the computerized forwarder trails, a 10 m digital elevation model (DEM) was used to derive a slope raster image to create the feasible paths. All the spatial data processing was made using ArcMap 10.0 (ESRI 2012). The slope raster image allowed us to analyze potential areas that will be difficult for the forwarder to travel on. The slope raster image was then reclassified to clearly separate areas with slopes greater than 30%. Once the slope raster images were reclassified, we created a cost distance raster image to estimate the cost of each pixel to each of the potential landings. Then, a cost path raster image was created to calculate the least cost path from each harvest residue location to the most cost-effective landing. Once the least cost paths were created, we converted them into a vector polyline for further processing, using the network analyst extension to create the optimal forwarder paths. Finally, a kriging technique (Oliver 1990) was used to create a continuous cost map that clearly shows the cost of collecting the residues at different distances.

2.2 Simulation model

For system 1, the excavator-base loader worked alone; in system 2, one forwarder worked alone. A simple time study determined the production coefficients as there was no significant effect of equipment interaction. However, systems 3–5 depend upon equipment interactions (Fig. 3). A simulation model was created in a Rockwell Arena software environment (ROCKWELL 2015). System 3 is represented by one forwarder loaded by the excavator-base loader. The simulation model in this system starts when one of the forwarders is moving unloaded to the forest residue collection point. At the collection location, the excavator-base loader is simultaneously concentrating material for the forwarders. As the forwarder arrives at the collection point, the excavator-base loader proceeds to load it as long as there is enough piled material. If not enough material is available for the forwarder to be loaded, the forwarder has to wait. After the forwarder is loaded, it travels back to the landing and unloads the residue. System 4, two forwarders loaded by one excavator-base loader is similar to system 3, except that only one forwarder is allowed to travel along the trail at a time, thus minimizing interference along the trail. System 5 includes the use of two forwarders loaded by one excavator-base loader. This

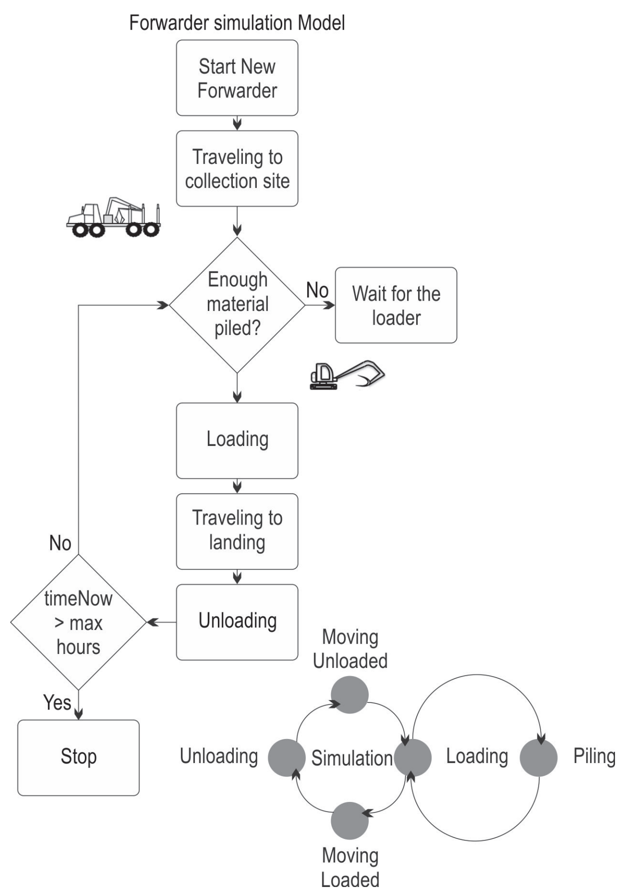

Fig. 3 General description of the simulation model

system is different from the other systems in the sense that the same operator operates the forwarder and the loader. This is similar to sharing a log loader among truck drivers. This system is only feasible if the material is already concentrated so the excavator-base loader is only used for loading the forwarder. As the forwarder reaches the collection point, the operator moves to the excavator-base loader and proceeds with loading the forwarder.

For the purpose of determining production rates, a time study was undertaken to calculate average time per swing of the excavator grapple, time per swing of the forwarder grapple, volume in the excavator grapple, volume in the forwarder grapple, load on the forwarder, and speed of the forwarder. During the time study the number of grapple loads per forwarder load of each type of grapple was recorded and each individual forwarder load was put into an end-dump truck and weighed at the mill yard.

2.3 Study site

Source data for the simulation model was collected from a residue collection operation. We performed a time and motion study on a harvest unit located 24.5 km southwest of Springfield, Oregon, USA (43°53′59″N, 122°47′9″W). Douglas-fir (*Pseudotsuga menziesii*) forest residues were dispersed over a 16.7 ha unit following whole tree harvest by shovel logging. Residue consisted of branches and tops with an average diameter ranging from 5 to 15 cm (μ=5.96 cm and σ=2.80 cm). Average piece length was 1.2 m. A Caterpillar 564 forwarder with a maximum load capacity of 13,608 kg was used for the test. A Kobelco SK290 LC hydraulic excavator-base loader was used to concentrate the residue at the loading points and load the forwarder except for the system where the forwarder self-loaded. A GPS Visiontac VGPS-900 was placed in the forwarder to track the movements of the machine when collecting the residues. Each forwarder load was then placed in a 90 m^3 end-dump truck and transported to a local mill, where the material was weighed. A total of 180 wet tonnes were collected and transported as part of the study. Thirty forwarder cycles were recorded and data processed. Samples for moisture content were taken from each load and transported to the laboratory for moisture content estimation using standard ASTM D4442 for direct moisture content measurement of wood and wood-based materials.

2.4 Cost estimation

The forwarder and the excavator-base loader costs were estimated by adapting Brinker's (2002) machine rate method and validated with the actual contractor costs. All the costs were expressed in USD 2015 dollars. Hourly costs include depreciation, insurance/taxes, and interest, labor, repair and maintenance, fuel and lubricants and profit and risk (10% of total hourly costs). Fuel cost was estimated to be \$0.8 l^{-1}. If the machine is operating (forwarding/loading/piling) then the cost included all previously listed items. If the machine is idling, (e.g. forwarder waiting for the loader) then only interest, insurance/taxes, labor cost and profit and risk are included. Profit and risk is included in the idling time to recognize the opportunity cost of being not productive in addition to interest on average investment. In this study, depreciation due to use is considered negligible when the machine is not operating since the parts are not wearing out. Depreciation due to obsolescence is considered low for relatively new forest machinery in the Pacific Northwest region and depends more on the hours of use rather than the year of manufacture (Personal Communication, Larry Cumming, Peterson-Pacific Industries, December 9, 2016). Our accounting approach offers advantages over the scheduled/productive hour approach when dynamic equipment balancing decisions are being made. Mobilization costs were based on a fixed rent rate of \$100 per hour for a lowboy truck. It was assumed that one machine is transported per truck and it takes 8 hours to complete delivery of the machine (rates in the region are calculated from the time the truck leaves the yard until it returns).

2.5 Supply economics

We estimated the impact of collection cost on the amount of residue that could be supplied. This was performed by integrating the collection costs with the processing and truck transportation cost. Transportation costs were calculated for a truck equipped with a drop-center (possum-belly) trailer with a capacity of 100 m^3. The truck-trailer combination has a maximum allowable legal weight of 40,823 kg. It was assumed residue is evenly distributed at each collection point defined in the GIS grid (30 meter) with a biomass volume of 42.43 dry tonnes per ha in 16.7 ha, giving a total of 707.6 dry tonnes of residues. With the transportation cost, we ran a sensitivity analysis to evaluate the amount of residue that could be economically feasible depending on the distance from the harvest unit to the bioenergy conversion facility. As the distance from the forest to the bioenergy facility increases the transportation cost increases, thus limiting the amount of harvest residue that could economically be recovered. We set four potential prices, \$50, \$60, \$70 and \$80 dollars per oven-dry tonne in order to estimate the maximum collection cost to break even. Grinding cost and productivity were extracted from Zamora-Cristales (2013) for a Peterson 4710B horizontal grinder.

Table 1 Forwarder and excavator-base loader hourly costs, USD

Item	Operating costs		Waiting cost	
	Forwarder CAT 564	Loader Kobelco SK290 LC	Forwarder CAT 564	Excavator Loader Kobelco SK290 LC
Purchase price, $	361,160	280,000	–	–
Ownership costs				
Depreciation cost, $ h^{-1}	38.52	29.87	–	–
Annual interest, $ h^{-1}	16.37	12.69	16.37	12.69
Annual insurance and taxes, $ h^{-1}	12.04	9.33	12.04	9.33
Annual productive machine hours, h	1500	1500	1500	1500
Hourly ownership cost, $ h^{-1}	66.93	51.89	28.41	22.03
Variable costs				
Labor, $ h^{-1}	33.75	33.75	33.75	33.75
Repair and maintenance, $ h^{-1}	23.11	17.92	–	–
Fuel and lubricants cost, $ h^{-1}	16.41	16.32	–	–
Hourly variable costs, $ h^{-1}	73.28	67.99	33.75	33.75
Profit and risk, $ h^{-1} (10% of hourly variable and ownership cost)	14.02	11.99	14.02	11.99
Total cost, $ h^{-1}	154.23	131.87	76.18	67.77

3. Results and discussion

3.1 System costs

Moisture content of the samples was estimated in 44% (wet basis). Hourly operating and waiting costs for the forwarder and excavator-base loader are shown in Table 1. Labor cost was included in the excavator-base loader cost although in the case of the one operator system simulation only the cost of one operator was counted.

Results from the time and motion study are shown in Table 2. If the forwarder is self-loading, then it is difficult to completely fill the bunk. Additionally, it took more time to load the forwarder due to the reduction in visibility and maneuverability. Loading the forwarder with the excavator-base loader resulted in significant decreases in time and increased load volume (Fig. 4), however this affected the time for the loader to concentrate residue at the forwarder collection points. The unloading time was consistent with the load size and was considerably faster than self-loading by the forwarder because the material is partially pushed out of the bunks instead of grabbed and unloaded. The excavator-base loader spent 12.6 (δ=0.4) minutes in average to pile 7.6 t of wet residue at the concentration points. During this time, the excavator-base loader spent 0.6 minutes per swing, with an average grapple load size of 0.36 t of wet residue.

For the harvest unit analyzed, simulation results suggest that the use of two forwarders and one loader could be the most productive system (Fig. 5) at longer distances. The productivity of this system is maintained until it reaches a distance from the landing of 255 m after which the excavator-base loader wait time is increasing. Using the same operator for both the forwarder and the loader will maintain productivity but it requires the operator to move between machines increasing the forwarder waiting time. The self-loading system appears to be the least productive of the forwarder systems due to the longer loading time

Table 2 Time and motion study results for forwarder productivity in wet tonnes (t) from 30 recorded cycles

Item	Mean	SD
Forwarder self-loading, min load^{-1}	8.9	2.5
Forwarder self-unloading, min load^{-1}	5.1	2.8
Excavator loading forwarder, min	5.2	1.3
Forwarder self-unloading excavator loaded, min	6.9	1.3
Travel loaded speed, km h^{-1}	3.0	1.0
Travel unloaded speed, km h^{-1}	4.2	0.8
Forwarder load, excavator loaded, t	7.6	1.2
Forwarder load size self-loaded, t	4.8	0.2

Fig. 4 a) Forwarder being loaded by the excavator-base loader; b) Forwarder traveling to the landing

compared to the excavator-base loading system and the reduced payload due to difficult visibility and grapple maneuverability when loading the forwarder.

The most cost effective option for distances less than 50 m from the roadside landing to the collection point is the use of the excavator-base loader working alone. Between 50 and 100 m, the use of one forwarder loaded by the excavator-base loader is the most cost effective system. Beyond 100 m, the two forwarders loaded by a single excavator-base loader is the most cost efficient and its comparative advantage grows with distance (Fig. 6). Although the system that uses the same operator for both machines is highly productive, it has higher cost because the residues would need to be pre-piled before forwarding operations can begin. The self-loading forwarder has the highest per unit cost due to the longer collection time and smaller load size (Table 2). Fig. 6 shows cost as a function of distance. If the average collection distance for the harvest unit was greater than 50 m and less than 70 m, then mobilization costs would probably determine if the excavator-base loader would be used alone or in combination with a single forwarder. This decision will depend upon the mobilization cost per unit volume that is a function of the amount of residual material available. In this example, we assumed a mobilization cost of $800 per machine ($100 h^{-1} of low-

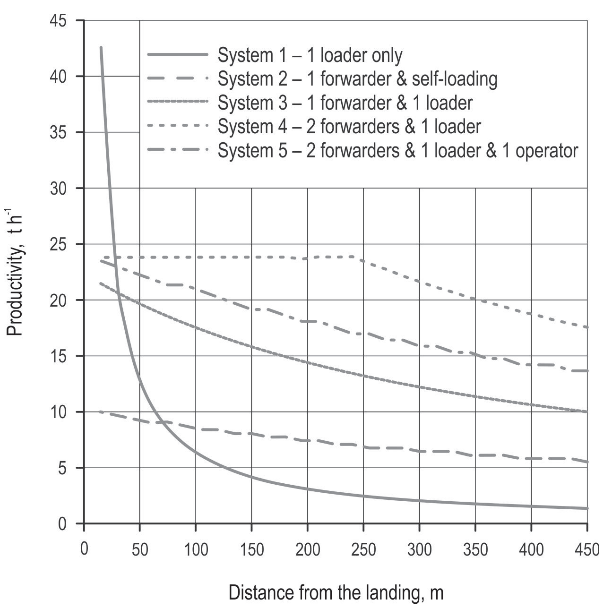

Fig. 5 Productivity in oven dry tonnes per hour for each of the analyzed options

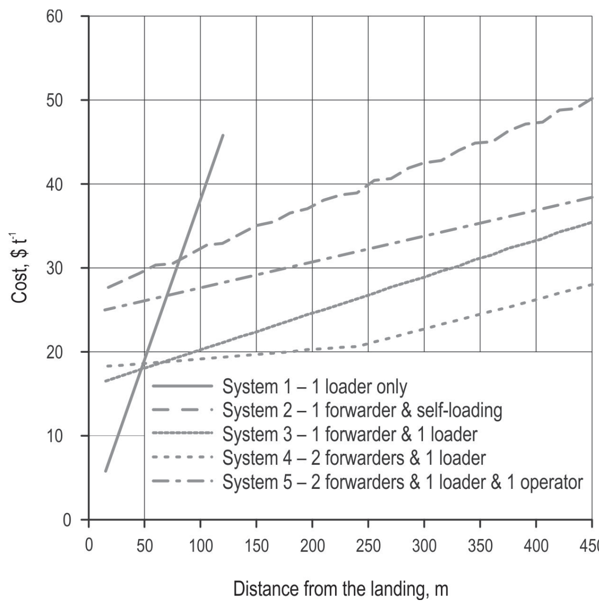

Fig. 6 Collection cost in USD per oven dry tonne as a function of the distance from the roadside landing (mobilization costs are not considered)

Table 3 Collection cost for each system in the 16.4 ha harvest unit of study (707.6 dry tonnes) and the optimal solution considering a combination of systems 1, 3, and 4 (this includes mobilization cost)

System	Cost, $	Cost, $ t^{-1}
System 1: Excavator-base loader	42,994	60.8
System 2: Forwarder self-loading	26,399	37.3
System 3: Forwarder loaded by excavator-base loader	17,613	24.9
System 4: Two forwarders loaded by one excavator base- loader	16,447	23.2
System 5: Two forwarders loaded by one excavator base-loader sharing operator	22,630	32.0
Optimal Solution, System 1<50 m; 50 m<System 3<70 m; System 4>70 m	16,180	22.9

boy cost, contracted for 8 hours). This gave a cost of 1.1, 2.3 and 3.4 dollars per oven dry tonne for one, two and three machines respectively. This cost assumes that 707.6 oven-dry tonnes are available and recoverable. In all cases, the excavator-base loader would be used to directly collect residues until at least the point where its marginal costs exceeded the marginal cost of the alternatives. Cost for harvesting the unit under study are shown in Table 3.

3.2 Application to the trail network

For each potential residue spatial location a least cost path to landing was determined. The processing of the digital elevation model, residue and landing locations resulted in the optimal location of the forwarder trails (Fig. 7) according to a slope-weighted shortest path to the closest landing. The forwarder trails were designed to avoid traveling over abrupt changes in slope and steep areas (<30% in slope) by penalizing cost rasters on steeper slopes. The total length of forwarder trails was 8660 m, occupying about 15% of the harvested area. In Fig. 7a, costs were assigned using the results of Fig. 6 resulting in what we define as the optimal system cost. At shorter distances (less than 50 m), the excavator-base loader was used, at distances between 50 and 70 m, one forwarder and one excavator-base loader was used and for longer distances greater than 70 m, the two forwarder and one excavator-based loader system was used.

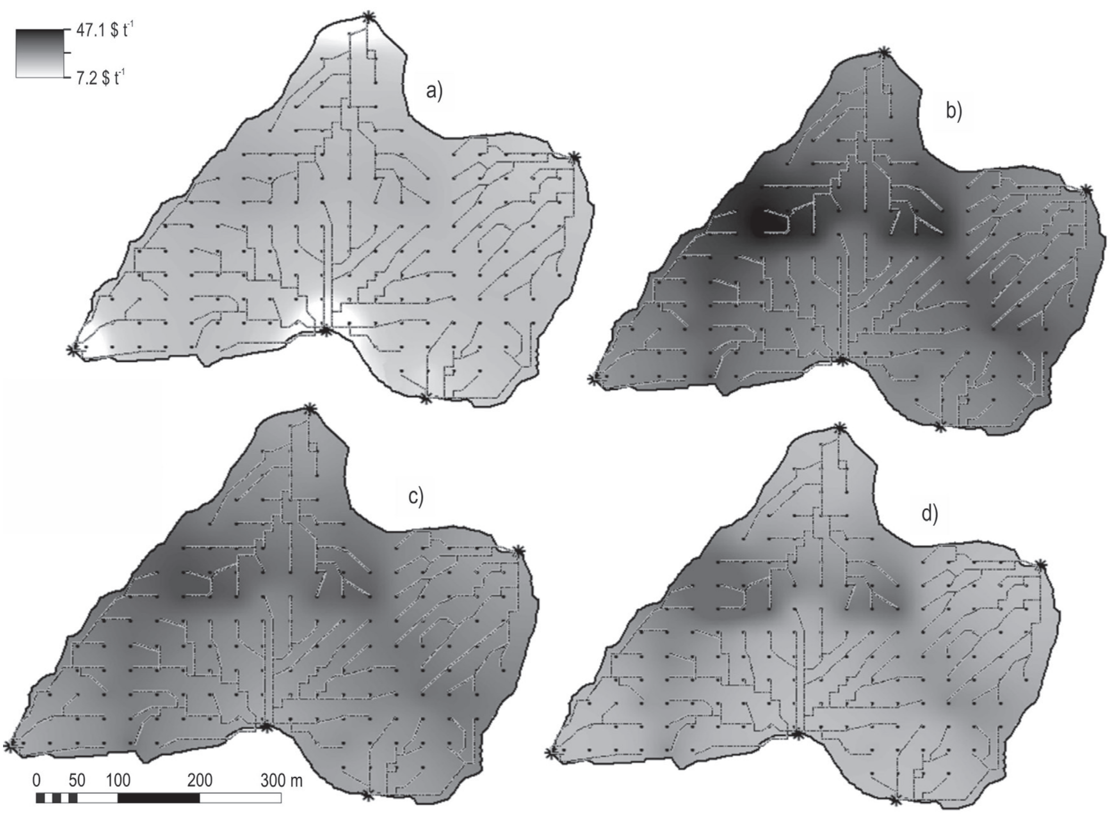

Fig. 7 Cost raster map for: a) optimal costs; b) one forwarder self-loading; c) one forwarder, one loader; d) two forwarders one loader (optimal costs combine the excavator-base loader working alone at short distances with the two forwarders and the excavator-base loader working together at longer distances)

Figs. 7b-d show the cost mapping if the self-loading forwarder (system 2), one forwarder and one excavator-base loader (system 3), and two forwarders and one excavator-base loader were used (system 4) without using the excavator-base loader working alone at the shorter distances. Average forwarding distance using this harvest unit was 156.4 m. On the other hand, using the straight line method, the average forwarding distance for the same unit would be 124.5 m. The straight line average forwarding distance is 20% less than the actual distance calculated using the raster method, thus underestimating the forwarding cost.

As the collection cost varies over the harvest unit, it is possible that, depending on price and the transportation cost to the bioenergy facility, not all of the residues will be delivered to the landing, but may either be left piled or burned in place. Assuming no other forest management benefit to the landowner (for example, reduced disposal costs, added available planting space, reduced fire risk), the percentage of biomass that could be available as a function of the distance from the forest to the bioenergy facility is shown in Fig. 8. At distances longer than 60 km no residue could be economically recoverable at a gate price of \$50 t^{-1}. Similarly at \$60 t^{-1}, the maximum transportation distance is 100 km. This procedure can be adapted for different processing and other transportation configurations to evaluate potential biomass availability from an economical point of view and can include other forest management benefits to the owner such as avoided disposal costs, increased planting space, or reduced fire risk.

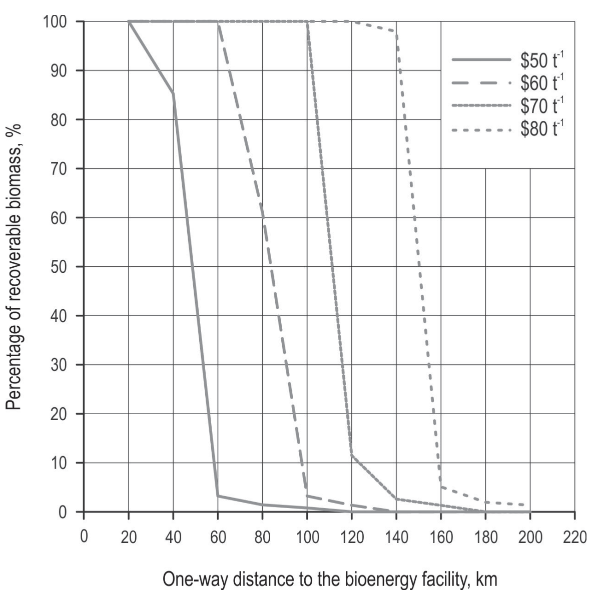

Fig. 8 Non-roadside biomass available per oven-dry tonne at different potential prices at the bioenergy facility gate

4. Conclusions

The utilization of forest residues offers an additional, but low value product from the forest. In order to provide economic value, the collection model must be well rationalized. A number of methods can be used to collect forest residues. Currently in the Pacific NW, USA, only residues close to the landing are utilized and those are primarily collected by an excavator-base loader working alone. We have demonstrated that a number of methods can be used to collect residues. For the conditions in our simulation, the excavator-base loader is the least expensive option within 50 m, between 50 and 70 m a combination of one forwarder and one excavator-base loader is the most cost effective option and beyond 100 m, a combination of two forwarders loaded by an excavator-base loader is the least expensive option with collection costs increasing modestly up to 240 m. However, if the total forwarding distance is less than 100 m, it is possible that excavator-base loader working alone may still be the lowest total cost option due to mobilization costs to bring in a forwarder. The mobilization cost to move the machinery (forwarders and loader) to the site is a fixed cost, thus it is important to have a significant amount of biomass available at the unit to justify the transport and placement of the machinery, especially for systems that require the use of two forwarders. The excavator-base loader would always be used to forward the closest material regardless of the system used at longer distances. The model developed in this research could be adapted and used in other conditions. The only required input for the GIS trail identification is the use of the digital elevation model. Additionally, the model can be extended by adding other land features such as streams. In this simulation the only physical barrier for the forwarder was ground slope.

It was assumed that the use of forwarders would be permitted. In this example, forwarder trails covered 15% of the area. Depending on soil considerations, forwarder trails could be reduced by increased piling by the excavator-base loaders. This could be represented by larger pixels. An alternative analytical modeling approach could be mathematical programming that includes soil compaction and mitigation methods and permits direct control of the area in forwarder trails.

Regardless of the collection system, there is a price point at which some residues in a harvest unit will not be recovered suggesting that there is a tradeoff between off-road collection distance and on-road transportation cost. Including other forest management benefits such as avoided disposal costs will increase economic collection distances.

Acknowledgements

This research was funded by the Northwest Renewables Alliance (NARA). NARA is supported by the Agriculture and Food Research Initiative Competitive Grant 2011-68005-30416 from the US Department of Agriculture, National Institute of Food and Agriculture. We also want to thank Lane Forest Products, and TOPS Weyerhaeuser for giving us access to their operations and operational assistance.

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Received: May 24, 2015
Accepted: December 18, 2015

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