Modeling and Analysis

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Economic analysis of forest residues supply chain options to produce enhanced-quality feedstocks

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Abstract: Woody biomass feedstock that is both high quality and low cost has become increasingly important for the bioenergy and bioproducts industries. Logging generates forest residues – low-quality feedstock – and additional operations that also incur additional costs, such as biomass sorting and treetops processing (BSTP), micro-chipping, and screening, which are required to improve the feedstock's quality. Considering recent developments in technologies and BSTP to generate high-quality feedstocks, economic models were developed in this study to estimate various forest-residue logistics operational costs and to analyze the economics of delivering feedstocks to biomass conversion technology (BCT) sites near woods or power plants located far away in the form of chips, hog fuel, and bales. The results show that the cost of BSTP can vary between $30 and $82/ODMT (oven dry metric ton) based on the biomass sorting intensity. The most economical way to deliver forest residues was transporting processed stem-wood from landings to near-wood BCT sites and comminuting it into woodchips there (~$20/ODMT, assuming a one-way (32 km) road distance and no cost of BSTP at landings). Grinding slash at the landing and transporting ground-biomass (i.e., hog fuel) to a plant (< 22 km away) was more economical than transporting bales from landings and grinding at the plant. The economic feasibility of baling and BSTP requires a substantial productivity improvement or recognition and incorporation of benefits including reduced wildfire risk and improved forest health. High bulk density and strong shape of forest residues/slash bales compared to hog fuel may provide additional cost benefits during storage, for example through lower handling costs, which can be studied in the future. © 2018 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: bioenergy; forest residues; logistics; baling; comminution; economic analysis

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Introduction

Wildfires are becoming extreme and more frequent because of increased fuel loads in the forest and extended dry conditions. In the last several years wildfires have caused many deaths and have led to huge direct costs amounting to billions of dollars annually for fire suppression and property damage,[1,2] as well as indirect economic losses. For example, from 2008 to 2012, adverse health impacts[3] alone cost \$76–\$130 billion annually (in this paper, the term 'billion' refers to 10^9). Forest residues from logging operations not only pose major fire risks[4] but also cause air pollution and other adverse human health impacts.[5]

The US can sustainably produce more than one billion[1] dry Mg of biomass with about 36% of total biomass in 2040 coming from forest residues and woody energy crops.[6,7] Considering the EISA (the Energy Independence and Security Act 2007)[6] and RPS (renewable portfolio standard) mandates of different states,[8] steady growth in overseas exports,[9] growing use of pellets, briquettes, torrefied pellets/briquettes and biochar, the future US demand for forest biomass is evident. Finally, the use of forest residues in the bioenergy and bioproduct industries will create new jobs and improve the overall rural economy.[10]

Forest residue collection can incur an additional expense for the logging operation but significant cost reduction can be achieved in site preparation (e.g., \$700–\$2000/ha)[5,11] for replanting trees in the harvested area. Traditional practices adopted for harvesting forest residues produce biomass with a large ash content due to the biomass containing higher percentages of bark coming from small branches and leaves along with contamination from foreign materials such as soil during the extraction, and collection phases. However, feedstocks that are both high quality[12] and low cost are essential for the consistent production of biofuel or bioproducts[13] and the overall economic feasibility of the downstream industries.[14,15]

This study was part of a larger project referred to as Waste-to-Wisdom (WTW), a BRDI (biomass research and development initiative) grant led by Humboldt State University.[12] The WTW project investigated integrated harvesting and near-woods bioconversion of post-harvest forest residues to produce high-quality feedstock – uniform-sized particles with low contamination and low moisture content, which would meet specifications set by the biomass conversion technology (BCT) standards.[15] Kizha and Han[11] demonstrated an alternative residue-handling method during harvesting in which sawlogs and biomass trees were sorted into separate piles. The treetops (Only the top portion of trees. Wood between main stem's diameter of 15 cm and tip of the tree) were cut from the sawlogs and rather than going to waste, were delimbed to produce high-quality biomass feedstock. Biomass sorting during logging operations also helped to reduce contamination and improve the forest residues' collection efficiency.

Such biomass sorting and treetop processing (BSTP) improved the biomass quality but there was an increase in the sawlogs' total harvesting cost, resulting from additional treetops' processing and sorting.[11] Foresters and landowners who are interested in these techniques will also be interested to see the cost-benefit analysis of the BSTP regarding sawlog and biomass production, and also regarding implications for site-preparation activities and costs necessary for reestablishment. Biomass users such as biofuel and bioproducts producers may be willing to pay more for better quality biomass. Hence, it is essential to quantify the actual cost of BSTP considering sawlog cost increases, cost decreases in the site preparation for replanting, and better quality biomass produced as treetops that can receive a higher price compared to traditional logging residue feedstock.

If they are going to be removed from the site, forest residues must be comminuted into cost-effective feedstocks that can be used to produce biofuels or bioproducts.[12] This can be done either at the landing, at a near-woods BCT site, or at a plant (i.e., large biorefinery or power plant consuming biomass).[15] Comminution at the landing can help to increase the biomass bulk density and reduce the transportation cost from the landing to the plant, compared with transporting low bulk density forest residues from the landing and comminuting at the plant.

Chipping and grinding are the two primary options to comminute forest residues based on residue quality and type. Chippers produce uniform-size feedstocks from biomass, which is critical for downstream industrial operations such as drying and torrefaction. Typical woodchip size (length × width × thickness) varies between 25 mm × 19 mm × 3 mm to 200 mm × 76 mm × 13 mm depending on the woody materials inputs and chipper specifications. The quality (i.e. size uniformity) of woodchips can be further improved by using a screener if the chipper does not produce uniform materials, which could be expected for chippers using highly contaminated materials.

Micro-chipping is an alternative technology to produce highly uniform-sized materials that may not require screening before going to a dryer or torrefier. Typical microchip lengths vary between 6 and 10 mm.[13] Furthermore, microchipping can increase the feedstock's overall bulk density and reduce its transportation cost. Usually, chippers and microchippers require high-quality biomass such as processed biomass trees or treetops.[16]

Chipping low-quality forest residues such as slash (containing many small stems and leaves) may not be economical due to frequent machine breakdown and higher chipper maintenance costs resulting from the presence of contaminants.[16–18] Lower quality forest residues such as slash or highly contaminated forest residues can be comminuted using grinders such as drum grinders or tub grinders, which produce non-uniform sized materials, referred to as hog fuel.[16] Hog fuel is a suitable feedstock to power biomass boilers for heat or in power plants.[19] However, hog fuel has low bulk density and it may incur high transportation cost.[20]

Baling slash piles is another option to increase bulk density compared with hog fuel to reduce overall transportation cost. Bales can then be ground at the plant location to produce hog fuel.[21,22] A comparative study of bales and hog-fuel supply logistics can provide an insight into making a decision to adopt the most economical pathway between these two available options to deliver low-quality forest residues to a plant.

Extensive research has been performed on the individual unit operations in the forest biomass supply chain such as residue collection in the woods, compaction of residues, comminution, moisture content, and transport.[23–27] Forest residues that are typically spread around the woods are instead collected and loaded into a dump truck to be comminuted at a centralized location,[26,28] or portable grinders can be used to grind forest residues at forest landings and hauled to a concentration yard.[29] These methods are suitable for timber harvesting, where biomass and unprocessed treetops are left in the forest.[19] Bisson *et al.*[28] estimated the cost of aggregating forest residues at a centralized location at $13.80/ODMT. Comminution and transportation costs were $19.70/ODMT and $15.33/ODMT respectively, for a one-way transport distance of about 25 km.[28] In single-pass or integrated (sawlogs plus biomass) harvesting, Harrill and Han[30] illustrated that the production cost of woodchips (at a landing site) was about $30.00/ODMT despite very low chipper utilization (i.e., 41%). The delivered woodchip costs (included chipping, and hauling 67 km) from a forest thinning and a clear-cut timber harvesting operation were $38.67/ODMT and $33.36/ODMT respectively.[31]

Most of the economic analyses of biomass have been related to the woodchips' delivery from forest thinning operations,[32] second-pass harvesting of forest residues,[28] and single-pass or integrated harvesting of forest residues with sawlog harvesting.[31] Comparative and holistic analyses of different forest residues supply chain configurations are scarce and limited.[23] Producing quality feedstocks from forest residues is new but critical to producing solid biofuels and biochar at reasonable costs. The production of high-quality forest residues as processed and sorted biomass trees and processed treetops along with piles of slash was discussed in Kizha and Han[11] The advantages of the baling slash piles were presented by Dooley *et al.*[21,22] However, the broader economic impacts of these new practices and technologies have not been previously analyzed. Understanding these broader impacts should be very important for forestland owners, natural resource managers, researchers, and people involved in bioenergy and bioproducts industries.

In this study, a suite of machine-rate models was developed to estimate the cost of (a) biomass sorting and treetops processing (BSTP), (b) chipping and microchipping of processed biomass/treetops, (c) screening of woodchips, (d) grinding and baling slash piles, and (e) transportation of logs (processed biomass tree and treetops), comminuted materials, and bales. The overall total delivered costs of comminuted biomass supplied to BCT sites or power plants were estimated and compared to identify the most economical biomass delivery options in terms of woodchips/micro-chips and hog fuels. Sensitivity analysis was performed on each unit operating cost and transport cost with respect to variabilities in the input factors to identify critical inputs significantly impacting biomass delivered cost.

Methodology

Supply logistics of forest residues

A schematic diagram of the forest residues' supply logistics pathways considered in this study is presented in Fig. 1. Forest residues (material that remains after timber harvesting and other non-merchantable trees) are harvested, either comminuted or baled, and sent to either near-wood BCT sites or to power plants. At each level of the supply chain, multiple options are available to accomplish a unit operation. Previous studies of forest residues that have been harvested have assumed that no sorting had been done.[28,33] Sorting merchantable (i.e., conifers) and non-merchantable trees (i.e. hardwood and small-diameter

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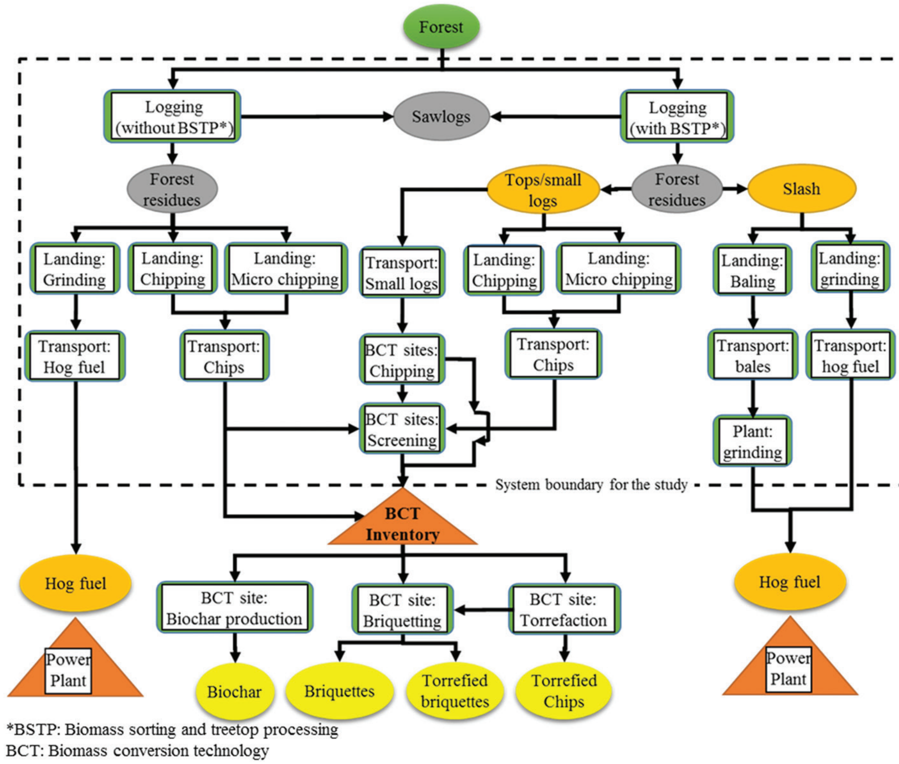


Figure 1. Forest residues supply logistics pathways – Forest residues to solid fuels and biochar.

conifers) at the landing is a proposed new practice to produce high-quality feedstock (i.e., stem wood) and forest residues slash (chunks (off-shoots), small branches, leaves, and unprocessed stems).[11,34]

This study analyzed the economics of forest residue extraction after removing the sawlogs from the stands. Two biomass streams are generated: (a) processed biomass and treetops, and (b) slash. The comminution activity can be performed at either at or close to the source, or at the demand location (e.g., BCT or an energy plant). Six options were considered involving chips and ground biomass. Short-term outdoor storage[35,36] (i.e., 1–2 weeks) of the feedstock was assumed to be at the respective BCT location but storage cost was considered to be borne by the plant or BCT facility. Option 1 is woodchips and is further divided into conventional woodchips and micro-woodchips. Option 2 is ground or baled slash piles for hog fuel. The breakdown follows:

- Opt 1.1: Chipped at landing + chip truck
- Opt 1.2: Transport logs in truck + chipping at the plant
- Opt 1.3: Micro-chipped at landing + chip truck
- Opt 1.4: Transport in log truck + micro-chipped at the plant
- Opt 2.1: Slash grounded at landing + transported in woodchip van
- Opt 2.2: Slash baled + transport in flatbed trailer + grinding at the plant

The plant delivered cost [PDC_f, \$/DOMT (Oven Dry Metric Ton)] of forest residues in the form of feedstocks (*f*) (i.e., woodchips or micro-woodchips, or hog fuel or bales) is estimated as presented in Eqn (1),

$$PDC_f = \sum_{i=1}^{I} C_i + \frac{t^b_{trip} * Tc^b}{PL^b} \qquad (1)$$

where, C_i (\$/ODMT) is the unit cost of operation (*i*) to harvest forest residues and its comminution or densification; t^b_{trip} (h/trip) is the time taken by the truck to deliver feedstocks from landing to plant and return to the base and Tc^b (\$ h^{-1}) is the hourly truck cost (including log trailer or chip van or flatbed trailer); and PL^b (ODMT/truck) is the truck payload. Screening of woodchips was considered to be optional before use at the plant. It was assumed that screening would not be necessary for micro-woodchips as the microchipping process produces fairly uniform sized feedstock. The detailed descriptions of unit operations are covered in the remaining sections here. The machine specifications and productivity of experimental studies for each unit operation are detailed in Tables 1 and 2.

Processing treetops and sorting to produce quality feedstocks

The treetops, branches and non-merchantable trees remaining at the wood yard or landing site are called forest residues. Leaves and needles have a higher ash content compared with stemwood. Forest biomass (especially treetops or non-merchantable trees) is processed to solid wood/stem and sorted into piles (to avoid contamination and enhance the efficiency of downstream operations), which can be used as quality feedstocks for further processing. During conventional timber harvest, sawlogs are produced by delimbing main stems up to a top diameter of 15 cm or so, depending on the log specifications set by the sawmill. However, delimbing operations can be extended to the tip of the main stem and delimbed tops sorted in separate piles from sawlog piles.[11] A delimbed 'processed' tree top has a large-end diameter of 15 cm and small-end diameter of about 2.5 cm. However, delimbing branches from treetops that otherwise would be left as forest residues in usual logging operations takes additional processor time and reduces the overall sawlog productivity.[11] The sorting intensity may be directly related to the productivity loss. The productivity loss due to sorting and treetop processing increases the sawlog production cost. This cost increase can be attributed to the production of high-quality forest residues through BSTP. The cost of treetops production can be estimated by knowing the treetops quantity (volume or weight) generated per unit volume/weight of sawlog production.

This study estimated the cost of BSTP and the actual cost of treetop processing and sorting as calculated in Eqns (2) and (3) respectively.

$$C_{BSTP} = \left(C_{SL,w/BSTP} - C_{SL,w/o\ BSTP}\right) * Y_{SL} \qquad (2)$$

Table 1. Machine-rate model inputs for biomass comminution and baling.

Description	In this study	Mean[c]	Lower[c]	Higher[c]
Interest rate (%)	6.00	6.00	5.00	10.00
Insurance and tax (%)	3.00	3.50	1.30	7.00
Labor ($/SMH)[a]	17.73	17.73	12.24	25.51
Labor fringe benefits[a] (% of labor)	35.00	46.00	33.00	59.00
Fuel use (l/SMH)	See Table 2	0.12	0.09	0.26
Lube and oil (% of fuel cost)	38.50	38.5	36.80	43.70
Machine use (SMH/year)	2160	2160	2000	2300
Fuel cost ($/l)[b]	0.61	0.88	0.61	1.05

[a]US average wage and benefits for logging operators in 2016.
[b]Average off-road diesel price from 2012 to 2017.
[c]Data from previous studies.[11,30,32,33,37,38,39,40–42]

Table 2. Input parameters specific to equipment used in biomass comminution and baling.

	Power (kW)	Purchase price ($)	Salvage value (% of PP)	Economic life (years)	Utilization (%)	Repair and maintenance (% of depreciation.)	Fuel use (l/kWh)	Productivity (ODMT/hr)
Loader chipper or grinder (John Deere 2954D)[a]	145	432 268	20.0	10	80.0	80.0	0.16	—
Chipper (disc)[b]	650	457 696	20.0	5.00	80.0	100.0	0.12	40.90
Chipper (drum)[c]	570	406 841	20.0	5.00	80.0	100.0	0.11	37.95
Grinder (tub)[d]	470	522 780	20.0	5.00	90.0	90.0	0.15	12.45
Grinder (drum / horizontal)[b]	783	661 116	20.0	5.00	85.0	100.0	0.13	38.04
Micro-chipper[b]	570	522 790	20.0	5.00	80.0	100.0	0.13	33.49
Screener (deck screen)[e]	97	385 000	20.0	8.00	85.0	100.0	0.12	31.30
Screener (star screen)[e]	55	150 000	20.0	8.00	85.0	30.0	0.12	13.40
Front end loader with bucket[f]	76	104 490	32.1	10.00	85.0	100.0	0.26	—
Small baler[g]	37	132 223	20.0	7.00	85.0	50.0	0.12	2.82
Large baler[g]	194	355 986	10.0	7.00	85.0	50.0	0.12	9.23

[a]11; [b]43; [c]32; [d]44; [e]45; [f]39, 41; [g]21, 22

$$C_{TT} = \frac{C_{BSTP} * Cf_{TT}}{Y_{SL} * f_{FR} * f_{TT} * \rho_{SL}} \quad (3)$$

where, C_{BSTP} = cost of BSTP per hectare of forest land (\$/ha); Y_{SL} = sawlog yield from unit forest land (m^3/ha); C_{TT} = cost of treetop processing and sorting (\$/ODMT); Cf_{TT} = fraction of total BSTP cost due to treetop processing and sorting; $C_{SL,w/TTP\&S}$ = cost of sawlog production with treetop processing and sorting (\$/m^3); $C_{SL,w/o\ TTP\&S}$ = cost of sawlog production without treetop processing and sorting (\$/m^3); f_{FR} = fraction of total tree biomass as forest residues (including treetops, branches, etc.); f_{TT} = fraction of only treetops in the total forest residues; ρ_{SL} = density of treetops (ODMT/m^3).

The experimental study by Kizha and Han[11] described the sawlog, and biomass production cost without and with sorting (moderate and intensive). The detailed descriptions of stand and site, logging operations, equipment, and productivity are provided in Kizha and Han.[11] The sawlog production costs were \$40.81/m^3, \$42.25/m^3 and \$44.75/m^3 of sawlog wood for the base case (conventional logging operations without treetop processing), and for the moderate, and intensive sorting with treetop processing respectively. Moderate sorting was defined as treetops being processed and sorted into conifer and hardwood piles by the processor and separated from the slash. Intensive sorting had forest residues processed and sorted into five categories: processed conifer tops, unprocessed conifer tops, processed hardwood tops, unprocessed hardwood tops, and slash.[11] Only 15–25% of the increase in the sawlog production cost came from sorting biomass trees and the rest (75–85% of the total production cost increase) came from the processor used in in the logging operation. This increase in the cost can be attributed to additional treetop processing and subsequent sorting.

A treetop makes up only a small portion of a tree's mass, so the amount (volume or weight) of treetops generated was much less than the amount of sawlogs that were produced. The fractional volume of treetops was about 16–40% of the total forest residues.[34] The remainder was made up of non-merchantable wood. The fraction (ODMT basis) of forest residues to total forest biomass at the forest stand can vary from 17 to 33% depending on logging type, tree species, and age.[46] Eckardt[37] mentioned that the logging residues volume percentages compared with total merchantable wood were about 10% for hardwood, 15% for mixed wood, and 20% for softwood. In this study the fraction of total tree biomass as forest residues (f_{FR}) was 25%; the fraction of only treetops[34] in the total forest residues (f_{TT}) was 30%, and the density of treetops (ρ_{SL})[47] was 0.510 ODMT/m^3.

Estimating machine cost using rate models

In this study, a chipper (using a drum or disc chipper) and a micro-chipper were used to comminute processed biomass (non-merchantable trees and treetops). Woodchips' technical feedstock specifications, such as particle size distribution and percentage of fine particles, are essential for better handling of inbound logistics and smooth operation of a chemical/thermal plant.[48,49] A screener was therefore considered to screen the woodchips produced from chippers. However, a micro-chipper produces consistently sized woodchips that do not require screening. Slash piles were considered to be either ground or baled at the landing site. Slash generated from the logging operations was comminuted using a grinder[43] or baled using a forest residues baler[21] and delivered to a bioenergy plant for grinding into hog fuel. Detailed descriptions of forest residues baling process and equipment performance are given in Dooley *et al.*[22] Biomass comminution operations were performed at the landing or at the plant locations.

Unit operation cost estimates can be calculated by either the machine rate or by discounted cash flow methods.[50–52] In this paper, we used machine rate models to estimate forest residues logistics operation costs. Machine-rate models are useful if only limited information on capital and operating costs is available. Machine-rate models offer much simpler calculations than discounted cash flow models, and if the machine-rate models are constructed using a capital cost recovery factor to estimate the annual fixed ownership cost of capital, they produce cost estimates that are close to those derived from discounted cash flow methods using the same limited information.[51]

The cost of each operational component can be broadly segregated into fixed / ownership costs, operating costs, and labor costs. Fixed-cost components are estimated based on equipment purchase price, salvage value, economic life, interest rates, insurance, taxes, and other miscellaneous fixed costs.[53] Variable-cost components are fuel and lubricant usage and maintenance (includes replaced tires/tracks). Wages and employee benefits (health insurance, social security, and various compensations) constitute labor costs. Annual machine use (scheduled machine hours – SMH), the machine's overall utilization rate, which is used to calculate productive machine hours (PMH), and machine productivity, significantly affect the overall unit operation cost.[39] The unit operation cost can be expressed in terms of dollars per hour (per SMH or per PMH) or dollars per unit output (volume or mass). In this study, the cost of unit operations is estimated as dollars per hour (PMH) and then converted to unit output basis, i.e., dollars per ODMT. For a unit operation (i) using multiple pieces of equipment, hourly costs for each piece of equipment (m) are added assuming a common productivity for the specific unit operation. For example, a wood chipper requires a loader to feed biomass and it was assumed that the loader was used for the chipper only. An optimized system with balanced productivities among different pieces of equipment and dependent operations was beyond this study's scope.

The unit cost of an operation (i) by a set of machines/equipment (m) is generally expressed either as dollars per PMH or dollars per ODMT (Eqn (4)) considering the biomass productivity ($Pr_{i,m}$, ODMT/h) of the unit operation. Hourly machine cost (C_i, \$/PMH) includes fixed ($F_{i,m}$, \$/PMH) and variable cost ($V_{i,m}$, \$/PMH) (Eqn (5)). Fixed cost (\$/PMH) includes an annuity or annualized capital charge (ACC_m), annual cost of insurance and taxes ($I\,\&\,T_m$), and yearly storage and licensing ($S\&L_m$) (Eqn (6)). SMH_m and U_m are scheduled machine hours (SMH) in a year and the machine utilization rate expressed as a percentage ranging from 80 to 100%, respectively. ACC_m is (Eqn (7)), the capital that must be recovered each year from initial investment cost less than the present value of salvage at the end of the economic life at the annual interest rate (r_{int}).[51] The capital recovery factor (CRF_m) for each piece of equipment (m) was estimated (Eqn (8)) considering the interest rate (r_{int}) and the equipment's economic life (T). Equations (9) and (10) show estimations of annual insurance and tax, and average yearly investment (AYI_m).[53] Salvage value (SV_m) was considered to be a fixed percentage of the equipment purchase price.

$$C_i\left(\$/ODMT\right) = \frac{C_i\left(\$/PMH\right)}{Pr_{i,m}} \quad (4)$$

$$C_i = \sum_{m=1}^{M} F_{i,m} + V_{i,m} \qquad \forall m = 1\ to\ M \quad (5)$$

$$F_{i,m} = \frac{ACC_m + I\,\&\,T_m + S\,\&\,L_m}{SMH_m * U_m} \quad (6)$$

$$ACC_m = CRF_m * \left(PP_m - \frac{SV_m}{\left(1+r_{int}\right)^T}\right) \quad (7)$$

$$CRF_m = \frac{r_{int} * \left(1+r_{int}\right)^T}{\left(1+r_{int}\right)^T - 1} \quad (8)$$

$$I\,\&\,T_m = AYI_m * r_{ins\&tax} \quad (9)$$

$$AYI_m = \frac{PP_m * \left(1-SV_m\right) * \left(T+1\right)}{2*T} + SV_m \quad (10)$$

Each component of the variable cost (related to machine cost) and labor cost was estimated using Eqns (11)–(16). Variable cost (V_m, \$/PMH) includes costs related to fuel (Fu_i, \$/PMH), oil, and lubricants ($O\&L_i$, \$/PMH), repair and maintenance ($R\&M_i$, \$/PMH), labor and benefits ($L\&B_i$, \$/PMH) (Eqn (11)).

Various input factors affect fuel consumption in comminution equipment, including biomass type, moisture content, size of products, and knife sharpness.[14,54] Wide variations in specific fuel usage were reported in the literature, i.e., 0.09 and 0.20 L/kW-h based on the type of machine and factors related to machine load.[30,33,38,55] If fuel consumption records were not available, an empirical equation (Eqn (12)) was used to estimate hourly fuel usage by a machine based on its gross power (hp_m), load factor (lf_m), and type of fuel ($sf_m = 0.2023$, and 0.2917 for diesel, and gasoline respectively).[56] The load factor can vary from 0.38 to 0.7 based on loading on the machine, i.e., low and high. A median load factor value of 0.54 was used for average loading on the engine to estimate fuel consumption by powered equipment.[53]

$$V_m = Fu_m + O\,\&\,L_m + R\,\&\,M_m + L\,\&\,B_m \quad (11)$$

$$Fu_m = sf_m * hp_m * lf_m \quad (12)$$

The consumption of oil and lubricants depends on many factors similar to fuel consumption. Bilek[51] and Sessions[56] used a detailed calculation for estimating the usage of oil and lubricants based on the crankcase oil capacity and oil requirements for hydraulics. To simplify, and if machine specifications are not available, a certain percentage of the fuel cost is often considered as oil and lubricant cost ($O\&L_m$, \$/PMH) (Eqn (13)). Repair and maintenance cost ($R\&M_m$) varies with many factors including type of manufacturer, size, operational conditions, etc. However, it is often assumed (Eqn (14)) as fixed percentage (RMF_m) of annual straight-line depreciation cost (D_m).[52] Equations (15) and (16) represent the estimation of labor cost ($L\&B_m$) and productive machine hours (PMH_m), respectively. $L\&B_m$ was estimated considering the labor required to operate a machine ($LRPE_m$), hourly wage (W_m), wage benefits (WB_m), scheduled machine hour (SMH_m), and machine utilization (U_m). Tables 1 and 2 present the inputs and assumptions used to estimate the cost of machine use and feedstocks production costs.

$$O\,\&\,L_m = OLf_m * Fu_m \quad (13)$$

$$R\,\&\,M_m = RMF_m * \frac{D_m}{PMH_m} \quad (14)$$

$$L\&B_m = \frac{LRPE_m * W_m * (1+WB_m)}{SMH_m * U_m} \quad (15)$$

$$PMH_m = SMH_m * U_m \quad (16)$$

The move-in and move–out costs of the machines were not considered for cost analysis, as they are highly variable and dependent on the contract.[26]

Estimating biomass transportation cost

Truck/trailers are usually the available options for transporting forest biomass.[57,58] Log and container trailers or chip vans are used to haul larger-size forest biomass (e.g. trees, logs, and poles) and comminuted biomass (e.g., hog fuel and chips) respectively.[59] Chip trucks can be loaded either from the back (directly from chipper or grinder) or from the top (using belt conveyor or front-end loader).[46] A significant portion of daily working hours for a truck in the short distance hauling can be spent on biomass loading and unloading.[39,60] Moreover, biomass trucks on the forest roads travel at very low speeds.[34] Annual operational miles for forest industry trucks hauling short distances[61] are significantly less than for long-distance hauling trucks.[42] Hence, biomass transport cost (Tc^b) was estimated on an hourly basis and was then converted to dollars per ODMT biomass based on hourly truck feedstock delivery capacity. In this study, tractor and trailer are considered as two independent units for estimating transport cost (due to a significant difference in lifecycle mileage and other cost inputs such as the cost of replacing tires). All relevant fixed (AFC_a^b) and variable (AVC_a^b) costs components are accumulated on a yearly basis and divided by productive machine hour (PMH) in that year to calculate hourly truck transportation cost (Eqn (17)). The PMH on a day (PMH_d) and annual (PMH_{Yr}) basis were estimated considering Eqns (18) and (19) respectively. It was assumed that only full truckloads of material are delivered from sources to demand locations.

The loading and unloading times for each trailer are different and specific to trailer type and feedstock, i.e., 28 min/log trailer (for treetops and biomass logs),[11] 56 min/chip van (chips, microchips, and hog fuel)[39,41] and 88 min for small (72 min large bales).[39] A truck can only make a specific number of trips ($N_{Trip/day}$, Eqn (20)) in a day based on daily scheduled machine hours (SMH_d), tuck utilization (U^b), and total time for a trip (t^b_{trip}). Equation (21) is used to estimate $N_{Trip/day}$ considering transport distance (D_{av}), loading time (t^b_{lo}), travel speed of a loaded truck (V_{lo}), unloading time ($t^b_{the\ ulo}$), and the travel speed of an empty truck (V_{ulo}). There are many cost components such as tire cost, oil changes, brake replacement cost, etc. that depend on the annual truck mileage. Hence, annual mileages (D_{Yr}) for trucks and trailers for specific feedstock types were estimated using Eqn (22).

$$Tc^b = \frac{\sum_a \left(AFC_a^b + AVC_a^b\right)}{\mathrm{PMH}_{Yr}}, \quad a = \left[1(tractor), 2(trailer)\right]; \quad \forall b \in B\left(\log trailer, chip\, van, flatbed\right) \quad (17)$$

$$\mathrm{PMH}_{Yr} = \mathrm{WD}_{Yr} * \mathrm{PMH}_d \quad (18)$$

$$\mathrm{PMH}_d = t^b_{trip} * \mathrm{N}_{\frac{trips}{day}} \quad (19)$$

$$\mathrm{N}_{Trip/day} = Int\left(\frac{\mathrm{SMH}_d * U^b}{t^b_{trip}}\right) \quad (20)$$

$$t^b_{trip} = t^b_{lo} + \frac{D_{av}}{V_{lo}} + t^b_{ulo} + \frac{D_{av}}{V_{ulo}} \quad (21)$$

$$\mathrm{D}_{Yr} = \mathrm{WD}_{Yr} * \mathrm{PMH}_d * \frac{V_{lo} + V_{ulo}}{2} \quad (22)$$

Fixed cost and variable cost were estimated as described in Eqns (23) and (28) respectively. Fixed cost (AFC_a^b) included annualized capital charge ($AFC_{Cap_a}{}^b$), insurance ($AFC_{Ins_a}{}^b$), license ($AFC_{lic_a}{}^b$), and miscellaneous ($AFC_{Mis_a}{}^b$) costs (Eqn (23)). The truck and trailer life can be specified in terms of lifecycle mileage ($D_{life_a}{}^b$) or lifecycle years ($T_{life_a}{}^b$). The lifecycle years (T_a^b) for tractors / trailers were calculated by dividing lifecycle mileage by annual mileage. However, this calculation may overshoot the recommended lifecycle years (10 years for tractor and 20 years for trailers) due to very low annual mileage.[39] This is common for trucks and trailers used in biomass logistics or forestry operations due to lower travel speeds and a large portion of working hours (in a day) spent waiting during loading and unloading activities. Despite the lower mileage, these units still incur heavy wear and tear.

An appropriate lifecycle year for a truck/trailer (T_a^b) was estimated (Eqn 24), which was then used to estimate the capital recovery (CRF), salvage value (SV_a^b) and annual average capital investment ($AYI_{Inv_a}{}^b$). Equation (25) was used to estimate annual capital charge ($AFC_{Cap_a}{}^b$) considering purchase price (PP_a^b), salvage value, lifecycle year, and annual discounted rate (r_{int}). Annual insurance cost ($AFC_{Ins_a}{}^b$, Eqn (26)) was assumed as a specified percentage / fraction (Ins_{frac}) of (estimated

Table 3. Assumptions and inputs for the calculation of transportation cost using log trucks, chip vans, flatbed trucks, and trailer combinations.

Notation	Description	Comments
a, b	*a* = (1: tractor, 2: trailer) *b* = (1: log truck for treetops, 2: chip van for woodchips /hog fuel, 3: for bales)	
Tc^b	Total truck transport cost per hour ($/hour) for biomass with a trailer (*b*)	
AFC_a^b	Annual fixed cost for trucks (*a*) or trailer (*b*)	
AVC_a^b	Annual variable cost for trucks (*a*) or trailer (*b*)	Varies with truck mileage
PMH_{Yr}	Productive machine hours in a year (h $year^{-1}$)	
PMD_h	Productive machine hours in a day (h day^{-1})	
WD_{yr}	Working days in a year (days $year^{-1}$)	
t_{trip}^b	Total time required for a truck to supply biomass to demand site and return back to the landing (h/trip)	
t_{lo}^b	Loading time of biomass to a trailer (h/load)	t_{lo}^1 = 14 min (assuming same as loading logs in log trucks)[11] t_{lo}^2 = 1.83 min per chip/hog fuel bucket load (5 m^3)~ 37 min[41] t_{lo}^2 = 1 min per bale (44 and 36 min for small and large bales respectively for a truck)[39]
t_{ulo}^b	Unloading time of biomass to a trailer (h/unload)	t_{ulo}^1 = same as loading time t_{ulo}^2 = Assumed 50% of unloading time (self-unloading trailer)[62] t_{ulo}^3 = same as loading time
D_{av}	Average trip distance between supply and demand (km h^{-1})	Average distance between landing site and 5 BCT locations in this study
V_{lo}	Speed of the truck with biomass in trailer (km h^{-1})	32 km h^{-1}[63] average speed from landing to BCT
V_{ulo}	Speed of the truck without biomass in trailer	Assumed same as loaded
$N_{Trip/day}$	Number of trips a truck daily performed between supply (i.e. landing) and demand point (i.e., BCT).	Estimated using Eqn (21)
U^b	Truck/tractor utilization (%)	Assumed 85%[43]
D_{Yr}	Average distance traveled by trucks in a year (km $year^{-1}$)	Calculated using Eqn (23)
AFC_a^b	Total annual fixed cost ($ $year^{-1}$)	Calculated using Eqn (24)
$AFC_{Capa}^{\ b}$	Capital cost ($ $year^{-1}$)	Calculated using Eqn (25)
$D_{lifea}^{\ b}$	Life of truck or trailer in km (km)	$D_{life1}^{\ b}$ = 1207008 km[40,42] $D_{life2}^{\ b}$ = 2414016 km[40]
$T_{lifea}^{\ b}$	Life of truck or trailer in years (year)	$T_{life1}^{\ b}$ = 10 years[39] $T_{life2}^{\ b}$ = 20 years[39]
T_a^b	Life of truck in terms of years (year) used in the calculation	Estimated using Eqn (26)
$AFC_{Insa}^{\ b}$	Insurance cost ($ $year^{-1}$)	Calculated using Eqn (27)
Ins_{frac}	% of Av. annual investment ($AYI_{Inva}^{\ b}$)	5.95%[61] or $4643 per year cost for an average annual capital investment of $78 000.
$AYI_{Inva}^{\ b}$	Average *yearly* investment($ $year^{-1}$)	Estimated using Eqn (28)
$AFC_{lica}^{\ b}$	License and registration cost ($ $year^{-1}$)	$2225/year[61]
$AFC_{Misa}^{\ b}$	Miscellaneous fixed cost ($ $year^{-1}$)	$2000/year,[61] It includes union fee, citation, etc.
AVC_a^b	Annual variable cost ($ $year^{-1}$)	Estimated using Eqn (29)
$AVC_{Fuela}^{\ b}$	Annual fuel cost ($ $year^{-1}$)	Estimated using Eqn (30)
P_{fuel}	Average fuel price ($ L^{-1})	$0.75/L, avg. US diesel price for last 5 years
m_{ilo} & m_{iulo}	Mileage in loaded and unloaded trucks (km L^{-1})	2.17 km L^{-1}[61]

Table 3. (Continued)

Notation	Description	Comments
$AVC_{Oil_a}^{b}$	Annual cost engine oil change ($ year^{-1})	Estimated using Eqn (31)
$Dist_{oil}$	Average mileage for oil change (km)	16 000 km[61]
OCI_{oil}	Number of days between oil change (days)	4 weeks[61]
PP_{oil}	Price of an engine oil change	$242.89/oil change @ 23 liter[61]
$AVC_{Tire_a}^{b}$	Annual tire cost ($ year^{-1}) for truck or trailer	Estimated using Eqn (32) for truck Estimated using Eqn (33) for trailer Price of new tire ($PP_{Tire,new}$)= $465.78[61] Price of retreaded tire ($PP_{Tire,Retreaded}$)= $174.67[61]
AVC_{Tire1}^{b}	Annual tire cost ($ year^{-1}) for truck	Estimated using Eqn (32) for truck
$N_{Tire_{1,Str}}^{b}$	Number of steering tires replaced in a year from tractor	Estimated using equation Eqn (34) considering number of steering tires in trucks ($N_{StrTire}$=2)[61] and life of a steering tire ($TiLi_{Str}$), 40 000 km[40] All steering tires must be replaced with new tires.
$N_{Tire_{1,Dri}}^{b}$	Number of drive tires replaced in a year from tractor	Estimated using Eqn (35) considering number of drive tires in a truck ($N_{DriTire}$), annual travel distance (D_{Yr}) and life of drive tire ($TiLi_{Dri}$,)
$N_{Tire_{2,Tra}}^{b}$	Number of trailer tires replaced in a year from trailer	Estimated using Eqn (36) considering number of drive tires in a truck ($N_{DriTire}$), annual travel distance (D_{Yr}) and life of drive tire ($TiLi_{Dri}$,)
$N_{StrTire}$, $N_{DriTire}$, $N_{TraTire}$	Number of steering and drive tires in a truck (no./truck) Number of tires in a trailer (no./trailer)	$N_{StrTire}$ = 2 $N_{DriTire}$ = 8 $N_{TraTire}$[40,61]
$AVC_{L\&M_a}^{b}$	Annual cost of repair and maintenance ($ year^{-1})	Estimated using Eqn (37)
LM_a^b	Lube and maintenance cost ($ km^{-1})	RM_a^b =0.041 $ km^{-1} assuming ($2880/year for lube, $1200/year for hose and light, $600/year for brakes for an annual mileage of 114 588 km year^{-1}[61]
$AVC_{Adm_a}^{b}$	Annual cost of administration for a truck	Estimated using Eqn (38)
C_{adm}	Cost of administration per truck per day ($/day/truck)	C_{adm}, cost incurred due to accounting, scheduling, dispatching and other activities to operate trucks[61]
$AVC_{Labor_a}^{b}$	Annual labor cost ($ year^{-1})	Estimated using Eqn (39)
CL_{Driver}	Hourly cost of driver's wage	$20.81 (at March 2017) hourly median wage (range = $13.50–$29.70)[64]
FB_{Driver}	Fringe benefits (% of wage)	35% of wages[61,64]

using Eqn (27)). Miscellaneous fixed costs ($AFC_{Mis_a}^{b}$) such as license fees, utilities, parking, etc., are included in the estimation of transport costs (mentioned in Table 3).

$$AFC_a^b = AFC_{Cap_a}^{b} + AFC_{Ins_a}^{b} + AFC_{lic_a}^{b} + AFC_{Mis_a}^{b} \quad (23)$$

$$T_a^b = Min\left(\frac{D_{life_a}^{b}}{D_{Yr}}, T_{life_a}^{b}\right) \quad (24)$$

$$AFC_{Cap_a}^{b} = \frac{r_{int} * (1+r_{int})^{T_a^b}}{(1+r_{int})^{T_a^b} - 1} * \left(PP_a^b - \frac{SV_a^b}{(1+r_{int})^{T_a^b}}\right) \quad (25)$$

$$AFC_{Ins_a}^{b} = Ins_{frac} * AYI_{Inv_a}^{b} \quad (26)$$

$$AYI_{Inv_a}^{b} = \frac{(PP_a^b - SV_a^b) * (T_a^b + 1)}{2 * T_a^b} + SV_a^b \quad (27)$$

Annual variable costs (AVC_a^b, Eqn (28)) included the cost of fuel ($AVC_{Fuel_a}^{b}$), oil change ($AVC_{Oil_a}^{b}$), tires ($AVC_{Tire_a}^{b}$), lube and maintenance ($AVC_{L\&M_a}^{b}$), administration ($AVC_{Adm_a}^{b}$), and labor ($AVC_{Labor_a}^{b}$). Annual fuel cost ($AVC_{Fuel_a}^{b}$) was estimated using Eqn (29) and includes annual travel distance (D_{Yr}), average fuel mileage (loaded = mi_{lo}, unloaded = mi_{ulo}), and fuel price (P_{fuel}).

Recommended engine oil changes occur after specified travel distance ($Dist_{oil}$, i.e. 16 000 km) or once every four weeks.[61] The annual oil cost ($AVC_{Oil_a}{}^{b}$) was estimated by multiplying number of oil changes $\left(Max\left(\frac{D_{Yr}}{Dist_{oil}}, \frac{365}{OCI_{oil}}\right)\right)$ by the price per engine oil change (PP_{Oil}), as mentioned in Eqn (30). Tire life is normally expressed in transport distance, i.e. 65 000–80 000 km. Except for tractor steering tires, which must be new, worn-out tractor and trailer tires can be replaced with either new or retreaded tires. Retreaded tires have about 20% less life at a 50% lower price compared with new tires.[40] Annual costs of tractor tires ($AVC_{Tire1}{}^{b}$), and trailer tires ($AVC_{Tire2}{}^{b}$) were estimated as shown in Eqns (31) and (32) respectively. Equations (33)–(37) describe the estimation of the number of new and retreaded tires required for the trucks and trailers. Annual lube and maintenance (e.g., brake replacement, hose, and lights) cost ($AVC_{L\&M_a}{}^{b}$) was estimated by multiplying total annual mileage and unit cost of lube and maintenance (\$ km^{-1}) (Eqn (38)). Additional costs ($AVC_{Adm_a}{}^{b}$) required to manage accounting, scheduling, dispatching of trucks were treated as administration costs (C_{adm}) for a truck (Eqn (39)). Wages (CL_{Driver}) for truck drivers constitute a significant portion of total transport costs.[39,40] The annual labor cost ($AVC_{Labor_a}{}^{b}$) was estimated (Eqn 40) including fringe benefits (FB_{Driver}). The detailed descriptions of variables, and input parameters and their values used in the cost model are listed in Table 3.

$$AVC_a^b = AVC_{Fuel_a}{}^{b} + AVC_{Oil_a}{}^{b} + AVC_{Tire_a}{}^{b} + AVC_{L\&M_a}{}^{b} + AVC_{Adm_a}{}^{b} + AVC_{Labor_a}{}^{b} \quad (28)$$

$$AVC_{Fuel_a}{}^{b} = \frac{D_{Yr}}{\frac{1}{mi_{lo} + mi_{ulo}}} * P_{fuel} \quad (29)$$

$$AVC_{Oil_a}{}^{b} = PP_{Oil} * Max\left(\frac{D_{Yr}}{Dist_{oil}}, \frac{365}{OCI_{oil}}\right) \quad (30)$$

$$AVC_{Tire1}{}^{b} = \left(N_{Tire1,Str}{}^{b} + N_{Tire1,Dri,new}{}^{b}\right) * PP_{Tire,new} + N_{Tire1,Dri,Retread}{}^{b} * PP_{Tire,Retread} \quad (31)$$

$$AVC_{Tire_2}{}^{b} = N_{Tire2,Tra,New}{}^{b} * PP_{Tire,New} + N_{Tire2,Tra,Retread}{}^{b} * PP_{Tire,Retread} \quad (32)$$

$$N_{Tire1,Str,new}{}^{b} = N_{StrTire} * \frac{D_{Yr}}{TiLi_{Str,New}} \quad (33)$$

$$N_{Tire1,Dri,new}{}^{b} = \left(N_{DriTire} * \frac{D_{Yr}}{TiLi_{Dri,new}}\right) * Pct_{New} \quad (34)$$

$$N_{Tire1,Dri,Retread}{}^{b} = \left(N_{DriTire} * \frac{D_{Yr}}{TiLi_{Dri,Retread}}\right) * \left(1 - Pct_{New}\right) \quad (35)$$

$$N_{Tire2,Tra,New}{}^{b} = \left(N_{TraTire} * \frac{D_{Yr}}{TiLi_{Tra,New}}\right) * Pct_{New} \quad (36)$$

$$N_{Tire2,Tra,Retread}{}^{b} = \left(N_{TraTire} * \frac{D_{Yr}}{TiLi_{Tra,Retread}}\right) * \left(1 - Pct_{New}\right) \quad (37)$$

$$AVC_{L\&M_a}{}^{b} = L\&M_a^b * D_{Yr} \quad (38)$$

$$AVC_{Adm_a}{}^{b} = PMH_{Yr} * C_{adm} \quad (39)$$

$$AVC_{Labor_a}{}^{b} = SMH_d * WD_{Yr} * CL_{Driver} * \left(1 + FB_{Driver}\right) \quad (40)$$

Results and discussion

Cost of treetops processing and sorting

Processing treetops and sorting increased the overall sawlog production cost by \$1.40–\$3.94/m^3 depending on the sorting intensity. Treetop processing and sorting took additional time and reduced the productivity of sawlog production (i.e. 13% and 27% for moderate and intensive sorting respectively). The increase in sawlog production cost was mainly due to the additional processing operation (removing branches of trees from the treetops) (i.e., 75–86% of total sawlog production cost) among all unit operations during the harvesting of timber in the stand.[11] This production cost increase in sawlogs represents the cost of processing the treetops.

The small increase in sawlog production cost (per unit volume) results in a relatively large cost for treetops (per unit volume). Most of a tree's recoverable biomass is in its sawlog portion (i.e., the base large diameter end towards small diameter end, ~15 cm). Treetops have less mass compared with the sawlogs and were estimated to be 2.7–13.3% the weight of total sawlogs produced. This relative difference means that a small increase in sawlog unit production cost results in a large increase in treetop unit production costs.

The estimated costs of processing treetops are illustrated in Fig. 2. Treetop processing costs are based on the difference between sawlog production costs without sorting, and with sorting (moderate and intensive) as mentioned in Kizha and Han[11] and the estimated volume of treetops generated per unit volume of sawlog production. The processed treetops cost was $30/ODMT or $24/green metric ton (~50% MC) considering moderate sorting during logging operations. For intensive sorting, the processed treetops cost was $82/ODMT or $64/green metric ton (~50% MC). The treetops cost produced through only moderate sorting was similar to the cost of processed biomass ($27.5/ODMT[11]) trees. However, treetops produced through intensive sorting was about three times that of the processed biomass trees ($29.5/ODMT) as presented in Kizha and Han[11]

The amount of sawlogs that can be harvested in the Pacific Northwest states i.e., Washington, northern California, and Oregon, were 235, 207, and 200 ODMT/hectare respectively.[25,65] The cost of sorting and treetop processing was estimated (Eqn 1) to be about $586–$1603, $564–$1544 and $666–$1822 per hectare of forest land in Washington, California, and Oregon respectively, based on the type of sorting (moderate or intensive) trees during logging (estimated biomass only from treetops was 15–18 ODMT/ha). The results illustrated that sorting and treetop processing may most likely be economically favorable for timberlands with lower compared to higher sawlog yields, assuming unit sawlog production cost remains the same irrespective of yield. This translates to increasing cost of logging with increasing sawlog yields per unit forest area.

Forest-land owners might be interested to know the breakeven sawlog yield, where the increase in the sawlog production cost will be compensated by benefits (i.e., savings during replanting, selling biomass to an energy plant, etc.) from implementing biomass sorting and treetop processing during logging operations. If logging residues were not used, the total cost of post-harvest management (including 'making piles and burning' or 'mastication') and site preparation for replanting was about $700–$2000/ha on an industrial timberland.[5,11] Moreover, pile burning negatively impacts air quality and increases the risk of wildfire. Producing good-quality feedstocks was the sole objective of the sorting biomass and processing of treetops. However, the large cost incurred due to processing treetops and sorting may increase the overall price of feedstocks, which may impact the economic viability of the production of bioenergy and bioproducts. Generally, logging residues remain in the forest and collection of logging residues spread across a harvesting site with a dump-truck for comminution incur a cost ($13.8/ODMT[28]) and it may also produce lower-quality feedstocks. The proposed forest residues management practice, i.e., BSTP, will reduce the cost of collecting residues and provide better quality biomass.

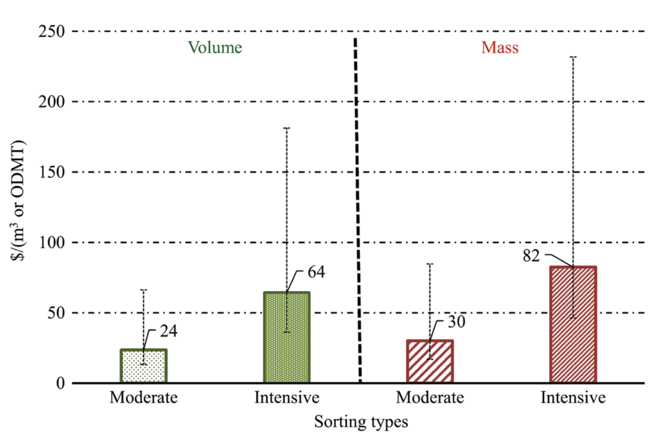


Figure 2. Estimated cost of treetop processing and sorting (error bars: standard error of mean).

Biomass comminution, screening, and baling

The estimated comminution, screening, and baling costs are presented in Fig. 3. A significant portion of the total cost was due to feeding biomass to the machine in all unit operations except the small baler, which had its own loader.

The type of chippers, such as drum or disc, did not significantly change the biomass chipping cost. However, a previous study mentioned that disc chippers are more fuel efficient but less productive than drum chippers when

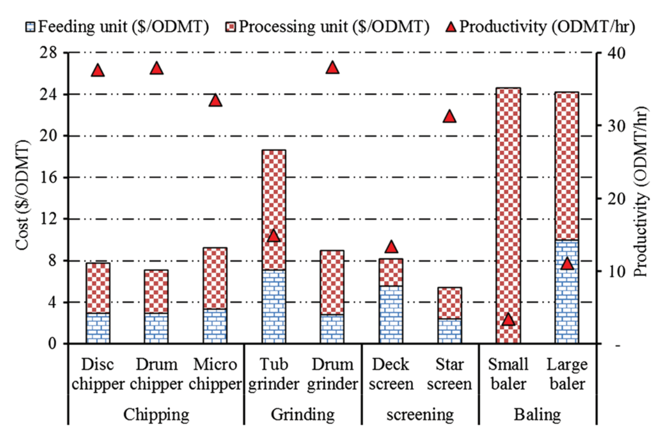


Figure 3. Cost and productivity of comminution, baling and screening phases for generating high quality feedstock.
* Values decreased and increased by 20% of average, opposite to other inputs. (SMH: sheduled machine hour; PMH: performed machine hour; D: depreciation; ODMT: oven dry metric ton).

used for lower quality forest residues.[49] Similar results on chipping cost had been reported in past studies for whole trees[32,33] and processed biomass trees.[43] The micro-woodchip production cost was about 25% more than usual woodchips, mainly due to the productivity reduction and increased fuel consumption required to produce the smaller chips.[66,67] Micro-woodchips are better in quality (uniform in size) than woodchips.[13,43]

The grinding cost using a tub-grinder was about twice that of a drum or horizontal grinder due to very low productivity in the former (15 ODMT h^{-1}[44]) compared with the latter (38 ODMT h^{-1}[43]). However, studies have reported both tub grinders and horizontal grinders having similar productivity.[68] Hence, assuming similar productivity of both tub grinder and horizontal grinder, the cost of grinding slash or low-quality biomass in each would be similar and also similar to the cost of chipping biomass.

Baling forest residues, e.g., slash piles was found to be an expensive option comparing to comminution. The estimated total baling costs by both small and large balers were almost the same, at about $24.00/ODMT, although the larger baler was about three times as productive as the small baler. The large baler uses a separate feeding unit compared to the self-feeding unit inbuilt into the small baler. The actual cost of only baling using the large baler was about half that of the small baler. But, the additional cost of a feeding unit increased the overall cost of baling forest residues in the case of the large baler. This provides an opportunity to improve forest residue baler designs for cost reduction.

Baling of forest residues is a new technology and thus it can be assumed that, with this technology's advancement, the productivity of balers will increase and prices will decrease. For example, baling cost (i.e., large rectangular bales) of agricultural biomass such as cotton stalk was about $13.32/ODMT,[39] which is about 50% lower than producing similar size rectangular bales from forest residues. The baler used for baling agricultural residues, as mentioned in Sahoo and Mani,[39] was about half of the purchase price of a baler to bale forest residues considered in this study. With the improvement in technology and commercial production of forest balers in the future, the cost of baling forest residues will be much lower than the estimated cost presented here. The cost of baling slash piles using small and large balers was about three times that of grinding using drum grinders. The higher baling cost was due to substantially lower machine productivity (Fig. 3). However, there may be cost advantages to transporting and handling bales compared with ground hog fuel due to the higher bulk density of bales. The cost-benefit of transporting bales compared to hog fuel is covered in further detail in the next section.

Screening comminuted biomass may be necessary to provide uniform-size materials for making solid biofuels and bioproducts.[13] Figure 3 also presents the cost of screening comminuted biomass, if it is required for chips and ground materials. The cost of screening using a star screener was about 36% lower than the cost using a deck screener. Considering the additional cost of screening, the supply of uniform screened chips was more than the cost of supplying unscreened micro woodchips.

Decision makers should be interested in knowing the most sensitive input parameters impacting a machine's unit operational cost. It remains challenging to decide the best option for size reduction of processed biomass due to uncertainties in the assumptions related to economic inputs, machine performance, and biomass characteristics. The literature reviewed in this study provided a wide range of data related to machine fuel use, productivity, and input assumptions. Figure 4 illustrates the increase / decrease in the unit operating cost with respect to ±20% variations in the most sensitive input parameters (parameters with < 2% variation in the output were not presented here). Machine productivity and utilization are the most sensitive input parameters. A ±20% change in machine productivity can decrease / increase the cost of chipping, grinding, and baling by 17% and 25%, 18% and 25%, and 13%, and 20% respectively. In all cases, the penalty (i.e. percentage increase in unit cost) due to a decrease in productivity was more than the benefits (i.e., the percentage decrease in unit cost) following a comparable increase in productivity. A similar pattern was observed for other input parameters such as machine utilization, SMH, and economic life of the machine. Fuel cost and machine purchase price also have significant impacts on the unit's total cost but are beyond the operator's direct control. The estimated cost presented in Fig. 3 can be reduced further by the efficient use of machines such as increasing productivity and utilization. Sorting of treetops and biomass tree can help in improving the productivity of the feeding unit, which feeds biomass into chippers or grinders. This needs to be studied further. Moreover, low contamination biomass produced through sorting will incur lower expenses for repair and maintenance of chippers or microchippers, which ultimately reduces the unit operation cost in forest residue harvesting.

Each operation, such as chipping, grinding, or baling, used two separate units, i.e., a feeding unit and a processing unit with specific individual biomass handling capacity. The overall operation's biomass processing capacity

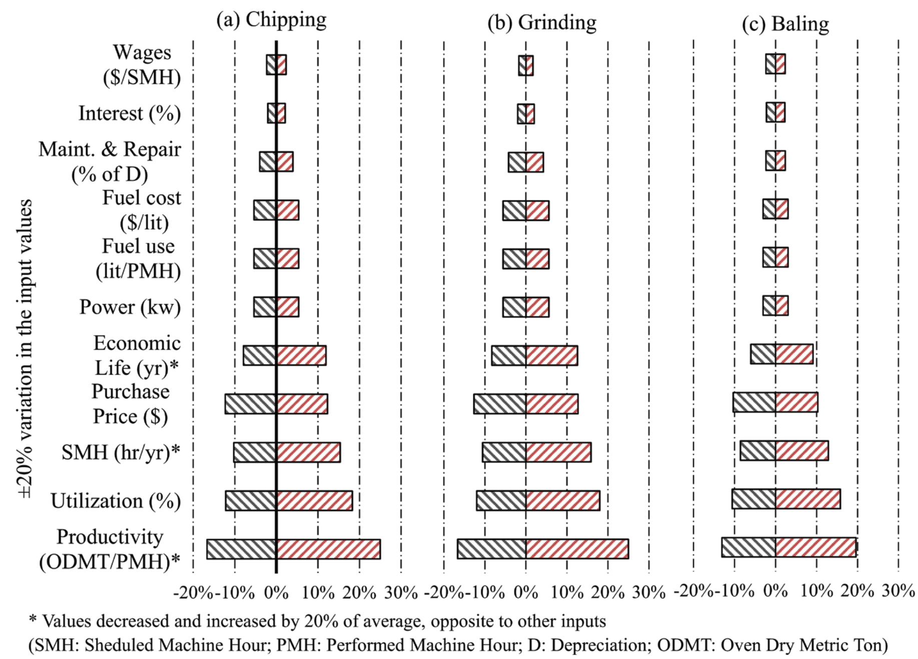


Figure 4. Impacts of various input parameters and variability (±20%) on the costs of (a) chipping logs/treetops, (b) grinding, and (c) baling slash.

will be determined by the processing unit with the lowest biomass handling capacity. Similarly, if a series of operations is considered in a biomass processing system, the bottleneck operation (i.e., the one having lowest throughput) dictates the throughput / productivity of the entire system. Matching of the machine capacities – in terms of biomass handling and subsequent utilization of each machine's output – is therefore critical in a real-life practical application and can influence the actual operating cost of each unit operation and the overall system cost.

A simulation modeling approach such as a discrete-event simulation model is able to accommodate the variations in the individual machine productivities in a unit operation or a series of operations[7,69] and may represent the next development for in-forest biomass logistics to estimate costs accurately, with higher confidence levels.

Feedstock's transportation costs

Figure 5 shows the estimated cost of transporting treetops / processed biomass logs, woodchips, micro-woodchips, hog fuel (ground biomass), and bales from landing sites to BCT (including loading and unloading). The forest biomass transport cost varied from $11 to $22/ODMT depending on its form.

The cost contribution from trailers to total transport cost was smaller (7–14%) than the cost from either tractor (40–45%) or labor (46–50%). Similar to other studies, the

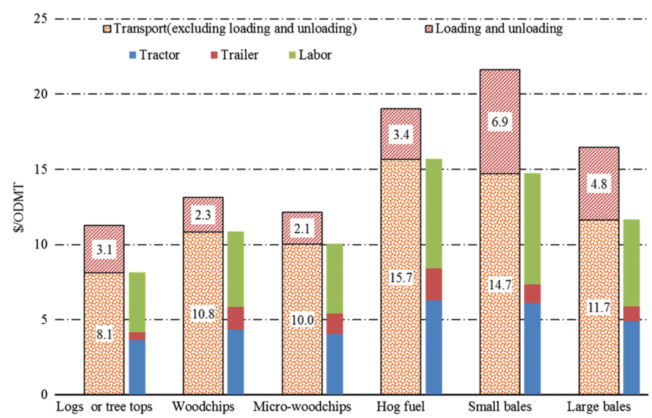


Figure 5. Transportation cost of forest residues in logs, chips, microchips, hog fuel, and bales (in $/ODMT). * Wage values decreased and increased by 20% of average, opposite to other inputs. (ODMT: oven dry metric ton).

hourly transport costs (not including loading and unloading) varied between $56 and $60, depending on the type of trailer (not shown here).[42,61] Loading and unloading of bales contributes about 29–32% of total transportation cost depending on the feedstock type. Other researchers reported similar costs for loading comminuted biomass to trucks.[19] The cost of loading / unloading forest residues bales to / from flatbed trailers was similar to agricultural residue bales.[39] The labor (driver's wage) cost was about 50% of total transportation cost (not including loading-unloading) compared to 35–40% as mentioned in literature for commercial long-distance hauling.[42,61] Those studies assumed lower hourly labor costs and benefits compared to this study.

Another difference between forest residue transport and typical long-haul commercial trucking is the annual mileage, which is typically much lower for a truck hauling forest residues than the annual mileage assumed in long-haul commercial trucking studies (e.g. Mason *et al.*[61]). Lower annual mileage also reduces other variable costs components such as replaced tires, repair, and maintenance, etc. The annual travel distance estimated for trucks transporting forest residues in this study was about 50% of the annual travel distance by a log truck.[61]

The size of the tractors was same for each type of trailer including log trucks, chip vans, and flatbeds. The variabilities in the trailer costs are wide but their impacts on total transportation cost will be minimal as the contribution of the trailers was only a small part of the total transportation cost.

Treetops/processed stems had the lowest transport cost among the feedstocks evaluated in this study. Chip transport cost was about 44% less than hog fuel transport cost due to the higher bulk density of woodchips (200 ODMT m^{-3}) compared to hog fuel (137 ODMT m^{-3}).[13] Large bale transport cost was also less than hog fuel due to the higher bulk density of bales (200 ODMT m^{-3}) and the lower cost for flatbed trailers compared with moving-bed woodchip vans. Considering feedstock's transport cost, slash generated during logging should be transported in flatbed trailers (as large bales) to power plants in place of transporting in vans (as hog fuel) if both bales and hog fuel have the same production cost at the landing.

The transport distances between landing and near-woods BCT sites were very low[70] (32 km was assumed in this study). The total cost of delivering bales – making bales ($24.2/ODMT) and transporting them – to a power plant was $40.60/ODMT compared to $28.00 as hog fuel (grinding ($9/ODMT) plus transport). Moreover, there will be an additional cost incurred for grinding bales into hog fuel at the plant before using the biomass to produce energy. But with an increase in the transport distance (higher cost), the cost-benefit of transporting the higher

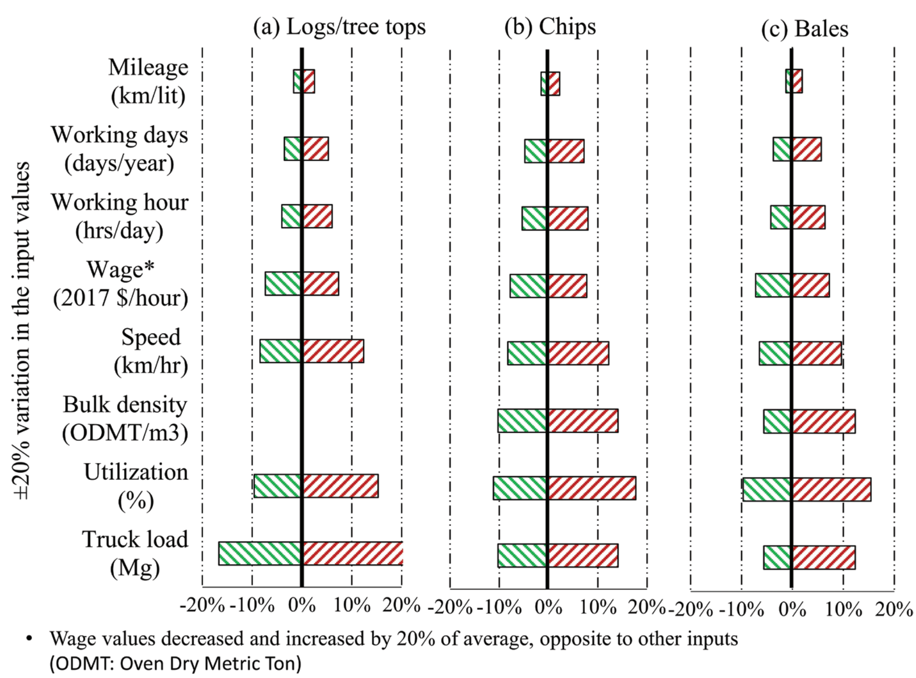


Figure 6. Impacts of various input parameters and variability (± 20%) on total transportation cost (loading / unloading excluded) for (a) treetops/logs, (b) chips, and (c) large bales. * Excluding the cost of biomass harvesting. Opt 1.1: Chipped at landing + chip truck; Opt 1.2: Transport in log truck + chipping at the plant; Opt 1.3: Micro-chipped at landing + chip truck; Opt 1.4: Transport in log truck + micro-chipped at the plant; Opt 2.1: Slash grounded at landing + chip truck; Opt 2.2: baling slash + flatbed trailer + grinding at the plant.

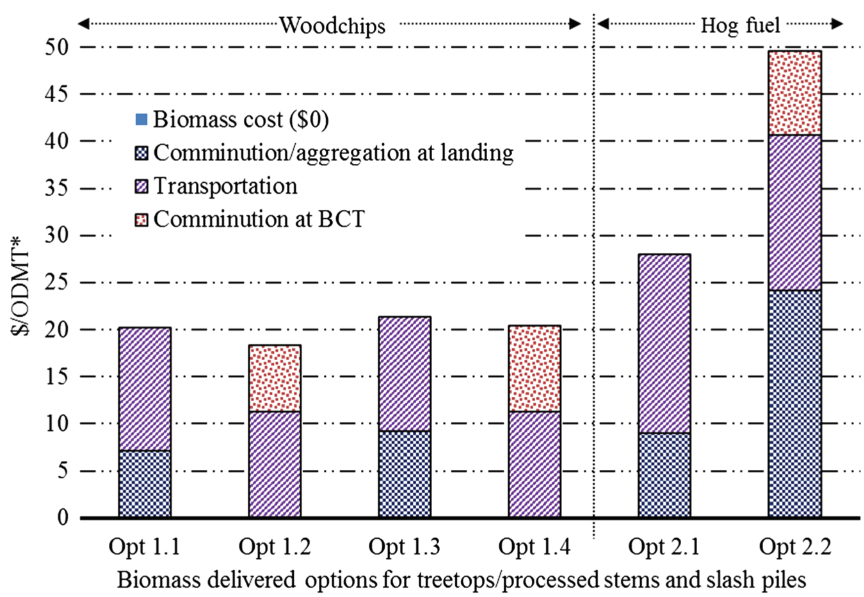
density bales will improve and at a certain minimum distance it may be economical to deliver the denser bales rather than less-dense hog fuel, even considering the additional grinding cost of bales at the plant. The detailed breakeven analysis is presented in the later section of this paper (Fig. 8).

The transportation cost estimations are based on several assumptions and input parameters (Table 3). The transportation cost model that was developed was simulated with ±20% variations in the input parameters to estimate the variations in the transport cost for different feedstocks. Figure 6 presents the most sensitive input parameters impacting the biomass transportation cost. Truck-loading capacity is one of the most sensitive input parameters in log trucks, as weight, rather than volume is the limiting factor in how much a truck can carry. Truck utilization, bulk density (except logs), and truck speed are other sensitive parameters that impact transport cost.

Feedstock's supply logistics options to BCTs and power plants

Figure 7 presents the comparative results for the estimated cost of delivering woodchips (option 1.1–1.4) and hog fuel (option 2.1 and 2.2) at a plant assuming a 32 km distance between the plant and the biomass source. The delivered cost of treetops and biomass in the form of woodchips varied from \$18–\$22/ODMT not including the biomass cost (i.e., collection and processing costs). Delivering processed treetops/biomass in log trucks to a plant and chipping at the plant site (option 1.2) was the lowest cost (excluding biomass cost) among all options studied here. This was due to the lower cost of transporting logs compared to chips. However, differences in the delivered comminuted biomass cost between options 1.1/1.3 and 1.2/1.4 will increase with an increase in transport distance between landing and plant. If biomass collection and processing cost is considered at the landing, the delivered cost of woodchips will be around \$51.00-\$53.00/ODMT considering costs of producing biomass (\$27.50/ODMT[11]) and star screening (\$5.50/ODMT) respectively. Harrill and Han[30] estimated the cost of delivering biomass as chips was \$33.00/ODMT for a hauling distance of 15.8 km. The lower woodchip delivered costs estimated in that study[30] can be attributed to the lower cost of producing biomass (\$15.00/ODMT) and transportation (\$6.00/ODMT) compared to the estimated costs in this study.

Screening is used to provide uniform-sized woody feedstocks to a plant, which may be critical to maintain the



*Excluded the cost of biomass harvesting. Opt 1.1: Chipped at landing + chip truck; Opt 1.2: Transport in log truck + chipping at the plant; Opt 1.3: Micro-chipped at landing + chip truck; Opt 1.4: Transport in log truck + micro-chipped at the plant; Opt 2.1: Slash grounded at landing + chip truck; Opt 2.2: baling slash + flatbed trailer + grinding at the plant

Figure 7. Different options studied for the biomass delivery and the related cost in \$/ODMT (oven dry metric ton).

quality of the products produced from those feedstocks. Uniform-sized feedstocks are especially important for torrefied products, where it is difficult to obtain uniform torrefaction with different-sized chips. Micro-woodchips may not require screening as the process produces more uniform-size feedstocks and may avoid additional screening costs. Hence, it may be economical to deliver micro-woodchips ($49/ODMT, without screening) to the plant compared with woodchips ($51/ODMT, with screening).

Machine utilization assumptions have a large impact on the estimated comminution operations costs Utilization assumptions can also result in a wide range of variability in operations cost estimates. Machine utilization in chipping can be as low as 41% if sufficient biomass is not available at the landing to feed the comminution equipment and there can be a mismatch in capacities between dependent machines.[30,65] Frequent moving of comminution equipment between sites can also hamper the utilization and overall system productivity. For large-capacity plants, it may be more cost-effective to chip processed treetops at the plant site if a high-capacity chipper or microchipper can be more fully utilized at the plant site than at the landing or at a BCT.

Hog fuel is different from woodchips or micro woodchips. Hog fuel requires grinding, not chipping, and is used for lower quality biomass, typically with higher bark and ash content. Assuming a 32 km transport distance between plant and landing sites, the cost of delivering hog fuel directly to the plant in chip vans (option 2.1) was 77% less than the cost of baling then grinding (option 2.2). Baling was about 50% of total cost of delivering hog fuel in option 2.2. The additional cost of slash baling overshadows the lower cost of transporting bales compared with hog fuel. However, for long-distance transport, baling, then grinding at the plant (option 2.2) may be more economical than transporting ground biomass (option 2.1). The analysis is shown in Fig. 8.

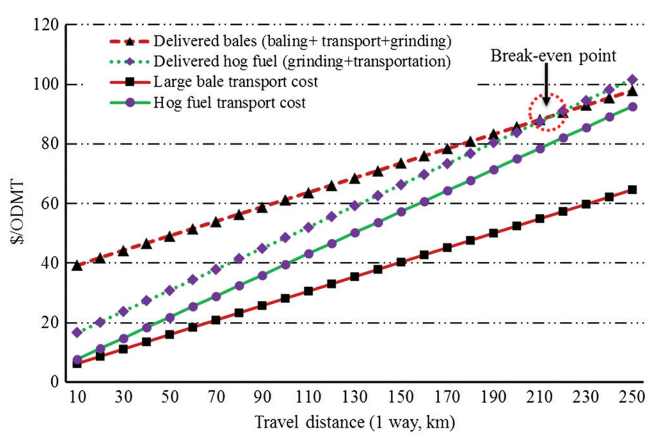


Figure 8. Variations of biomass delivered cost and transport cost with travel distance for hog fuel and bales (ODMT: oven dry metric ton).

The break-even transport distance between plant and the landing should be at least 220 km to realize the cost benefits of transporting bales (option 2.2) rather than ground wood (option 2.1). The technology of baling forest residues is new and under development. As the technology develops, it is expected that the cost of baling equipment will decline, and its performance will significantly improve, which would further reduce this breakeven distance.

Conclusions

For biofuel and bioproduct manufacturing plants to be competitive they will seek to adopt the most economical biomass supply logistic options. This study has provided an improved understanding of the impact on the cost of delivered biomass by sorting and processing of treetops / biomass to produce quality feedstock through multiple supply logistics options, in addition to the impact of a densification technology such as baling, on forest-residue supply logistics. The cost of processing treetops was determined considering the increased cost of sawlog production due to treetop processing and sorting (moderate and intensive) compared to no sorting. A suite of machine-rates models was developed for estimating the cost of chipping and micro-chipping of processed treetops / biomass, and grinding and baling of low-quality forest residues such as slash. A comprehensive transport cost model was developed to estimate the transport cost of treetops / biomass, comminuted biomass, and bales. The delivery cost of each form of biomass at the plant site was estimated and compared to identify the lowest cost option to deliver processed treetops/biomass as chips and slash as hog fuel.

About 70–90% of the total cost increase in sawlog production by moderate or intensive sorting was due to treetops processing. The estimated cost of treetop processing and sorting varied from on average $30 ($17–$85)/ODMT for moderate sorting and $82 ($46–$232)/ODMT for intensive sorting. The increase in the sawlog production cost due to BSTP was estimated to be about $564–$1822/ha of timberlands based on sawlog and forest residue yield in the Pacific Northwest USA.[65] However, forest owners can avoid residues piling and burning (reported cost $700–$2100/ha[5,11]) by adopting BSTP forest-residues management practice. In addition to the direct cost savings, other subjective benefits such as mitigation of forest fire risks, air pollution, and pest outbreaks are also mentioned in the literature.

The estimated micro-chipping cost was higher than the chipping but the former might help in reducing screening cost due to the production of uniform-sized feedstock compared with later. The cost of grinding low-quality forest residues such as slash piles was much lower than baling. However, baling produced higher density material than grinding. For shorter transport distance between forest and plant, the lowest cost option to deliver woodchips/ micro-woodchips was to transport processed treetops / biomass logs in log trucks and use a chipper at the plant site (option 1.1 or 1.3, Fig. 8). It is also economical to grind slash at the landing and transport hog fuel in chip trucks to energy plants located near to the forest (option 2.1, Fig. 8). However, for power plants located at longer distances (i.e., > 220 km) from the forest, slash should be baled and transported in flatbed-trailers (option 2.2, Fig. 8) to obtain the lower unit transportation cost of large bales.

The results illustrated here provided a comparative analysis of different pathways for delivering forest residues to a plant. The developed suite of cost models can be used as a tool for making quantifiable decisions related to forest biomass supply logistics by the bioenergy and bioproducts industry. This study only focused on the inbound logistics of bioenergy or bioproduct production units using forest residues. A holistic view on using forest residues can be achieved by integrating the economic analysis of inbound logistics, product manufacturing (i.e., densified solid biofuels and biochar) and its outbound logistics. In the future, the proposed models can be further extended to product manufacturing and its delivery and can analyze the benefits of using high-quality biomass as processed treetops and biomass trees.

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