ECONOMIC ANALYSIS OF FOREST RESIDUES LOGISTICS OPTIONS TO PRODUCE QUALITY FEEDSTOCKS

Waste to Wisdom: Subtask 4.1.1

Prepared By:
Kamalakanta Sahoo[*1,3], E.M. (Ted) Bilek[1], Richard Bergman[1],
Anil Raj Kizha[2], and Sudhagar Mani[3]

[1] Forest Products Laboratory, United States Forest Service, Madison, WI 53726, USA
[2] School of Forest Resources, University of Maine, Orono, ME 04469, USA
[3] College of Engineering, University of Georgia, Athens, GA 30602, USA

Corresponding author: Kamalakanta Sahoo; E-Mail: ksahoo@fs.fed.us;
Tel.: +1-: 608-231-9272; Fax: +1-608-231-9508

May 2018

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297.

This Page Blank

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 cost, such as biomass sorting and treetops processing (BSTP), micro-chipping, and screening, 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 residues logistics operational costs and analyze the economics of delivering feedstocks to near-woods Biomass Conversion Technology (BCT) sites or to faraway-located power plants in the form of chips, hog-fuel, and bales. The results show that the cost of BSTP can vary between $30 and $82/Oven Dry Metric Ton (ODMT) 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 (< 220-km away) was more economic than transporting bales from landings and grinding at the plant. 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 from lower cost of handling and storage, which can be studied in the future.

Keywords: Bioenergy, forest residues, logistics, baling, comminution, and economic analysis

This Page Blank

Economic analysis of forest residues logistics options to produce quality feedstocks

Kamalakanta Sahoo[*1,3], E.M. (Ted) Bilek[1], Richard Bergman[1], Anil Raj Kizha[2], and Sudhagar Mani[3]

[1]Forest Products Laboratory, United States Forest Service, Madison, WI 53726, USA.
[2]School of Forest Resources, University of Maine, Orono, ME 04469, USA
[3]College of Engineering, University of Georgia, Athens, GA 30602, USA

* Author to whom correspondence should be addressed; E-Mail: ksahoo@fs.fed.us; Tel.: +1-: 608-231-9272; Fax: +1-608-231-9508.

Introduction

The majority of world leaders have agreed to displace fossil fuels with renewables to mitigate climate change[1]. The U.S. has mandated [Energy Independence and Security Act (EISA), 2007] the production of about 60 billion liters of advanced biofuel from cellulosic biomass [2]. In addition to liquid biofuel, biomass such as woodchips and pellets from woody biomass can play a major role in producing renewable electricity to achieve the Renewable Portfolio Standard (RPS) policy mandate of different states in the U.S.[3, 4]. Moreover, biomass can be used to produce various industrial chemicals and displace fossil resources[5, 6]. The U.S. can sustainably produce more than 1 billion[1] dry Mg of biomass with about 36% of total biomass in 2040 coming from forest residues and woody energy crops[2]. Currently, large demand for solid biofuels such as pellets from woody materials comes from European countries to displace fossil resources for generating heat and power. For example, about 4.7×10^6 tonnes of wood pellets were exported from the U.S. to European countries in 2017[7, 8]. Torrefied biomass (having higher energy density) is also getting attention from power plant industries due to the potential for logistics cost reductions compared with white pellets[9]. At present, the commercial production and use of biochar is small but growing fast[10], and this niche market is expected to expand in the future due to the utilization of biochar in the agricultural sector as a soil quality enhancer. Hence, considering EISA and RPS mandates, steady growth in overseas exports, growing use of pellets, briquettes, torrefied pellets/briquettes and biochar, the future U.S. demand for forest biomass is evident. Finally, the use of forest residues in bioenergy and bioproduct industries will create new jobs and improve the overall rural economy[11].

In the U.S., especially the west, a common practice for managing forest residues generated from harvesting timber is to pile residues and burn them. This facilitates replanting, and reduces fuel loading, forest fire risks, and problems related to insects and rodents. Piling and burning of forest residues incurs cost (e.g., $700 –

[1] In this paper, the term “billion” refers to 10^9.

$2000/ha)[12, 13], increases air pollution[14], and often increases wildfire risk. Open pile burning is restricted to a small time window in any year and regulatory agencies require substantial resources to provide permitting, reviewing, monitoring, and responding to complaints from smoke due to pile burning[14]. These difficulties notwithstanding, often the quality of the treated stands is so poor that they are not usually suitable for replanting[14, 15].

Forest residue collection can incur an additional expense to the logging operation but a significant cost reduction can be achieved in site preparation for replanting trees in the harvested area[12, 16]. Traditional practices adopted for harvesting forest residues produce biomass having a large amount of 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 extraction, and collection phases. But feedstocks that are both high quality and low-cost are essential for the consistent production of biofuel or bioproducts[17] and the overall economic feasibility of the downstream industries[18].

Both the U.S. Department of Agriculture (USDA) and the U.S. Department of Energy (DOE) are firmly committed to increasing the role of biomass as a clean and renewable energy source and to recognize the positive carbon impacts in bioconversion systems. The agencies jointly created and fund the Biomass Research and Development Initiative (BRDI) as an interagency program to support the development of a biomass-based industry in the U.S. for environmental protection and energy production.

This study was part of a larger project referred to as Waste-to-Wisdom (WTW: http://wastetowisdom.com/), a BRDI grant led by Humboldt State University. 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[12]. Kizha and Han[12] demonstrated an alternative residue handling method during harvesting in which sawlogs and biomass trees are sorted into separate piles. The top portions of trees (treetops, 15 cm diameters to tip of the main stem) were cut from the sawlogs and rather than going to waste, were delimbed to produce high-quality biomass feedstock. Also, biomass sorting during logging operations helped to reduce contamination and improve the forest residues collection efficiency.

Although, such biomass sorting and treetops processing (BSTP) improved the biomass quality, there was an increase in the sawlogs' total harvesting cost resulting from additional treetops' processing and sorting[12]. Foresters and landowners who are interested in these techniques will be interested to see the cost-benefit analysis of the BSTP on sawlog and biomass production, and also on 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. This can be done either at the landing, at a near-wood BCT site or at a plant (i.e., large biorefinery or power plant consuming biomass). Comminution at the landing can help to increase the biomass bulk density and reduce the transportation cost from the landing to 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. 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[19].

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[19-21]. 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[19]. Hog-fuel is a suitable feedstock to power biomass boilers for heat or in power plants [22]. However, hog-fuel has low bulk density and it may incur high transportation cost[23].

Baling slash piles is another option to increase bulk density compared to hog-fuel to reduce overall transportation cost. Bales can then be ground at the plant location to produce hog-fuel[24, 25]. A comparative study of bales and hog-fuel supply logistics can provide an insight into making a decision to adopt the most economical pathway among 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, and transport[26, 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,[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[22]. 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 a single-pass or integrated (sawlogs + biomass) harvesting, Harrill and Han[30] illustrated the production cost of woodchips (at landing site) was about $30.00/ODMT in spite of 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[16].

Most of the economic analyses of biomass have been related to the woodchips delivery from forest thinning operations [31], second-pass harvesting of forest residues[28], and single-pass or integrated harvesting of forest residues along with sawlog harvesting[16]. Comparative and holistic analyses of different forest residues supply chain configurations are scarce and limited[26]. 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[12]. The advantages of the baling slash piles were presented by Dooley et al.[24, 25]. 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 figure 1. Forest residues (remain 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 harvested have assumed that no sorting had been done[28, 32]. Sorting merchantable (i.e., conifers) and non-merchantable trees (i.e. hardwood and small diameter conifers) at the landing is a proposed new practice to produce high-quality feedstock (i.e., stem wood) and forest residues slash (small branches, leaves, and unprocessed stems)[12, 33].

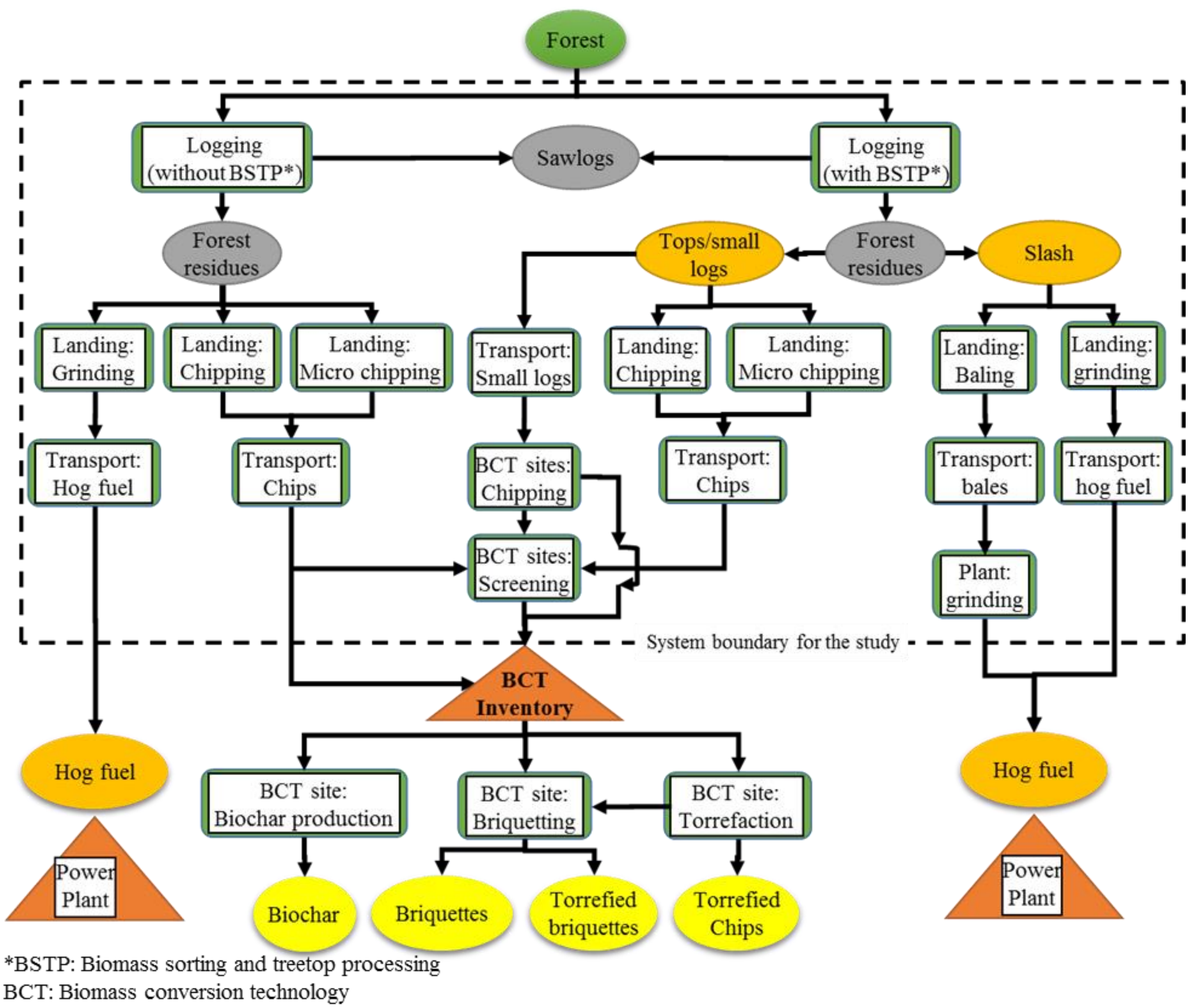


Figure 1: Forest residues supply logistics pathways – Forest residues to solid fuels and biochar

This study analyzed the economics of forest residue extraction after removing the sawlogs from the stands. Two biomass streams are generated: (i) processed biomass and treetops, and (ii) slash. The pathways of delivering processed and sorted treetops/biomass logs to the plant considered here were (i) chipping (option 1.1) or microchipping (option 1.3) at the landing and delivering comminuted biomass to the plant in chip vans, and (ii) transport treetops/ biomass trees in log trucks and chipping (option 1.2) or microchipping (option 1.4) at the plant site. Slash piles were either ground at the landing site into hog-fuel and transported in chip vans to plant (option 2.1) or baled at the landing, transported in flatbed trailers, and ground into hog-fuel at the plant site (option 2.2). 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 specifications of the machine used 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 referred as forest residues. The quality attributes such as moisture content, ash content, contamination, and uniformity of size have substantial effects on the BCT manufacturing processes, the overall quality of the product, and its market price. Leaves and needles have a higher ash content compared with stemwood. Therefore, 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) that can be used as quality feedstocks for further processing.

However, processing treetops and forest residues sorting can have an impact on the overall productivity of merchantable wood for sawlogs and/or pulpwood[12, 16]. The sorting intensity may be directly related to the productivity loss[12]. Further, 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 production productivity. The productivity loss due to sorting and treetops processing increases the sawlog production cost. This cost increase can be attributed to 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 sawlogs production. A detailed description of the cost estimation for sorting and treetops processing is described in the section “estimating cost of processing treetops” below.

Forest residues comminution and baling

The comminution process (i.e. breaking down the biomass into small, relatively uniform-sized pieces) is one of the most critical phases of the bioenergy supply chain due to its high energy requirement and low overall process efficiency[34], both of which translate to higher cost. Grinding (using a horizontal or tub grinder) and chipping (using a drum or disc chipper) are the two primary methods of comminuting forest residues[18]. Forest residues comminution can be performed in conjunction with a logging operation using a chipper/grinder (single pass or integrated harvesting) or by leaving the residues at the landing for drying to reduce moisture content and later returning to the harvest unit to extract and comminute residues (two pass harvesting). Grinders and chippers can be fed biomass with either onboard loading equipment or off-board/off-road track type loaders. Onboard loading equipment has limited reach for collecting biomass. However, off-board/off-road track type loading equipment can collect the biomass from surrounding areas with a relatively larger reach.

Grinders are the most appropriate machines to comminute slash into hog-fuel. Tub-grinders are very efficient in terms of processing biomass, but they cannot be used to process whole tree or large branches without breaking them into smaller parts[35]. Grinder productivity can vary with feedstock species type, size of comminuted output material, and size of input material[18, 19]. Grinders have the ability to process contaminated forest biomass more efficiently than chippers, but grinders produce a lower quality product in terms of particle size[36]. While the maintenance and repair cost of chipping residues can increase exponentially with soil contamination, this has a lesser impact on grinders than chippers[35].

Quality of the comminuted materials especially the size is very important for torrefaction and other biofuel production processes compared to hog-fuel used for power generation[17]. Chippers are more appropriate if higher-quality feedstock is required. Disc chippers can be preferred over drum chippers due to the former's low specific energy requirements. But drum chippers can have higher productivity than similar-sized disc chippers[37, 38].

However, chippers still produce larger and relatively wide range of sizes of comminuted materials, which can have a significant impact on the quality of materials produced using torrefaction[17]. This is one of the major reasons that wood pellet manufacturers and advanced liquid biofuel producers are interested in micro-woodchips[39-41]. Micro-woodchips also have several advantages in pulp and paper manufacturing in terms of lower system energy requirements, faster processing, fewer processing steps, and smaller processing equipment sizes[40]. Similar advantages may be expected in biofuels production. Micro-chippers can produce smaller length chips (i.e., 6 to 19 mm) than chips (i.e., 32 mm) produced by conventional chippers. A micro-chipper should be used to comminute relatively cleaner biomass, such as processed treetops or stems, in order to produce quality micro-woodchips, maintain the equipment performance, reduce maintenance cost, and extend the equipment's economic life.

In this study, a chipper or micro-chipper was used to comminute processed biomass (non-merchantable trees and treetops). Slash generated from the logging operations was comminuted using a grinder[39] or baled using a forest residues baler[25] and delivered to a bioenergy plant for grinding into hog-fuel. The detailed descriptions of forest residues baling process and equipment performance were mentioned in Dooley et al.[24]

Screening of woodchips

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[42, 43]. Moreover, fine particles under 3 mm represent health and fire hazards. Woodchip size is affected by a number of parameters, including the type of chipper, tree species, moisture content, and type of forest biomass. Hence getting a uniform woodchip size may be challenging or impractical[43]. However, the inclusion of screening after comminution can help to produce the desired woodchip size and produce better-quality products by removing fines and contaminants from the feedstock[44].

The major technologies used for screening woodchips or ground wood/hog-fuel are star screens and trammel screens. Usually, screeners are fed with comminuted wood materials using a front-end loader[45], or a screener can be integrated with a grinder or chipper[44, 46]. An integrated screening operation in a wood comminution system must balance the operational productivity of each piece of equipment to optimize overall system productivity or to minimize overall system cost. This study assumes that a screening operation was independent of comminution and executed at the BCT site. A front-end loader was used to supply the comminuted wood materials to the screener.

Estimating cost of processing treetops

During conventional timber harvest, sawlogs are produced by delimbing the felled main stem up to a top diameter of 15 cm or so, depending on log specifications set by the sawmill. However, delimbing operations can be extended to tip of the main stem and delimbed tops sorted in separate piles from sawlog piles[12]. The small diameter delimbed trunk portion (from 15 cm diameter towards the tip of the crown) of the tree/main stem, known as a processed treetop. This study has estimated the cost of BSTP and the actual cost of treetop processing and sorting as calculated in equations *A* and *B* respectively.

$$C_{BSTP} = \left(C_{SL,w/\,BSTP} - C_{SL,w/o\,BSTP}\right) * Y_{SL} \quad \ldots \quad (A)$$

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

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[12] 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[12]. 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 [12]. Only 15%-25% of the increase in the sawlog production cost came from sorting biomass trees and 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.

Because a treetop makes up only a small portion of a tree's mass, 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[33]. 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[47]. Eckardt[35] 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[35]. In this study the fraction of total tree biomass as forest residues (f_{FR}) was 25%; the fraction of only treetops in the total forest residues (f_{TT}) was 30%, and density of treetops (ρ_{SL})[48] was 0.510 ODMT/m^3.

Estimating machine cost using rate models

Unit operation cost estimates can be calculated by either machine rate or discounted cash flow methods[49-52]. 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, machine rate models produce cost estimates that are close to those derived from discounted cash flow methods using the same limited information[50].

The cost of each operational component can be broadly segregated into fixed/ownership costs, operating costs, and labor costs. Fixed costs 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) compose labor cost. Annual machine usage (scheduled machine hours, or 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. 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 as either as dollars per PMH or dollars per ODMT (eqn. r0) considering biomass productivity ($Pr_{i,m}$, ODMT/hr) of the unit operation. Hourly machine cost (C_i, \$/PMH) includes fixed ($F_{i,m}$, \$/PMH) and variable cost ($V_{i,m}$, \$/PMH) (eqn. r1). 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. r2). SMH_m and U_m are scheduled machine hours (SMH) in a year and the machine utilization rate expressed as a percentage ranging from 0%-100%, respectively. ACC_m is (eqn. r3) 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})[50]. The capital recovery factor (CRF_m) for each piece of equipment (m) was estimated (eqn. r4) considering the interest rate (r_{int}) and the equipment's economic life (T). Equations r5 and r6 shows estimation 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.

$$C_i(\$/ODMT) = \frac{C_i(\$/PMH)}{Pr_{i,m}} \quad \ldots\ldots\ldots (r0)$$

$$C_i = \sum_{m=1}^{M} F_{i,m} + V_{i,m} \quad \forall m = 1\ to\ M \ldots\ldots (r1)$$

$$F_{i,m} = \frac{ACC_m + I\&T_m + S\&L_m}{SMH_m * U_m} \ldots\ldots (r2)$$

$$ACC_m = CRF_m * \left(PP_m - \frac{SV_m}{(1 + r_{int})^T}\right) \ldots\ldots (r3)$$

$$CRF_m = \frac{r_{int} * (1 + r_{int})^T}{(1 + r_{int})^T - 1} \ldots\ldots (r4)$$

$$I\&T_m = AYI_m * r_{ins\&tax} \ldots\ldots (r5)$$

$$AYI_m = \frac{PP_m * (1 - SV_m) * (T + 1)}{2 * T} + SV_m \ldots\ldots (r6)$$

Each component of the variable (related to machine) cost and labor cost was estimated using equations r7 to r12. 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. r7).

Various input factors affect fuel consumption in comminution equipment including biomass type, moisture content, size of products, and knife sharpness[18, 34]. Wide variations in the specific fuel usage were reported in the literature, i.e., 0.09 and 0.20 liter/kW-h based on the type of machine and factors related to machine load[30, 32, 54, 55]. If fuel consumption records were not available, an empirical equation (eqn. r8) 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].

$$V_m = Fu_m + O\&L_m + R\&M_m + L\&B_m \ldots\ldots (r7)$$

$$Fu_m = sf_m * hp_m * lf_m \ldots\ldots (r8)$$

The consumption of oil and lubricants depends on many factors similar to fuel consumption. Bilek[50] 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, often a certain percentage of the fuel cost is considered as oil and lubricant cost ($O\&L_m$, \$/PMH) (eqn. r9). 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. r10) as fixed percentage (RMF_m) of annual straight-line depreciation cost (D_m)[57]. Equations r11 and r12 represent the estimation of labor cost ($L\&B_m$) and productive machine hours (PMH_m) respectively. $L\&B_m$ was estimated considering 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.

$$O\&L_m = OLf_m * Fu_m \quad \ldots \quad (r9)$$

$$R\&M_m = RMF_m * \frac{D_m}{PMH_m} \quad \ldots \quad (r10)$$

$$L\&B_m = \frac{LRPE_m * W_m * (1 + WB_m)}{SMH_m * U_m} \quad \ldots \quad (r11)$$

$$PMH_m = SMH_m * U_m \quad \ldots \quad (r12)$$

Table 1: Machine rates 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 ($/SMH)[a]	17.73	17.73	12.24	25.51
Labor fringe benefits[a] (% of labor)	35.00	46.00	33.00	59.00
Fuel use (l/SMH)	Table 2	0.12	0.09	0.26
Lube and oil (% of fuel cost)	38.50	38.5	36.80	43.70
Machine use (SMH/yr)	2,160	2,160	2,000	2,300
Fuel cost ($/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 2012-2017
[c]data from previous studies 11, 30-32, 35, 49, 55, 57-60

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

	Power (kW)	Purchase price ($)	Salvage Value (% of PP)	Economic life (Yrs)	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]12; [b]39; [c]31; [d]58; [e]61; [f]62, 63; [g]24, 25

Estimating biomass transportation cost

Usually, truck/trailers are the available options for transporting forest biomass[64, 65]. 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[66]. 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)[47]. A significant portion of daily working hours for a truck in the short distance hauling can be spent on biomass loading and unloading[62]. Moreover, biomass trucks on the forest roads travel at very low speeds[27]. Annual operational miles for forest industry trucks hauling short distances[67] are significantly less than for long-distance hauling trucks[68]. Hence, biomass transport cost was estimated on an hourly basis and 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. t1). The PMH on a day (PMH_d) and annual (PMH_{Yr}) basis were estimated considering t2 and t3 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 mins/log trailer (for treetops and biomass logs)[12], 56 mins/chip van (chips, microchips, and hog-fuel)[63, 69] and 88/72 mins (for small/large bales)[62]. A truck can only make a specific number of trips ($N_{Trip/day}$, eqn. t4) 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 t5 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_{ulo}), and travel speed of an empty truck (V_{ulo}). There are many cost components such as tire cost, oil change, 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. t6.

$$Tc^b = \frac{\sum_a (AFC^b_a + AVC^b_a)}{PMH_{Yr}} \quad \forall\ a = [1\ (tractor), 2\ (trailer)];\ b \in B(\log trailer, chip\ van, flatbed) \ldots\ldots\ldots (t1)$$

$$PMH_{Yr} = WD_{Yr} * PMH_d \ldots\ldots (t2)$$

$$PMH_d = t^b_{trip} * N_{\frac{trips}{day}} \ldots\ldots (t3)$$

$$N_{Trip/day} = Int\left(\frac{SMH_d * U^b}{t^b_{trip}}\right) \ldots\ldots (t4)$$

$$t^b_{trip} = t^b_{lo} + \frac{D_{av}}{V_{lo}} + t^b_{ulo} + \frac{D_{av}}{V_{ulo}} \ldots\ldots (t5)$$

$$D_{Yr} = WD_{Yr} * PMH_d * \frac{V_{lo} + V_{ulo}}{2} \ldots\ldots (t6)$$

Fixed cost and variable cost were estimated as described in eqns. t7 and t12 respectively. Fixed cost (AFC^b_a) included annualized capital charge (${AFC_{Cap}}^b_a$), insurance (${AFC_{Ins}}^b_a$), license (${AFC_{lic}}^b_a$), and miscellaneous (${AFC_{Mis}}^b_a$) costs (eqn. t7). The truck and trailer life can be specified in terms of lifecycle mileage (${D_{life}}^b_a$) or lifecycle years (${T_{life}}^b_a$). The lifecycle years (T^b_a) for tractors/trailers was 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. 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 as 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^b_a) was estimated (eqn. t8), which was then used to estimate the capital recovery (CRF), salvage value (SV^b_a) and annual average capital investment (${AYI_{Inv}}^b_a$). Equation 9 was used to estimate annual capital charge (${AFC_{Cap}}^b_a$) considering purchase price (PP^b_a), salvage value, lifecycle year, and annual discounted rate (r_{int}). Annual insurance cost (${AFC_{Ins}}^b_a$, eqn. t10) was assumed as a specified percentage/fraction (Ins_{frac}) of the ${AYI_{Inv}}^b_a$ (estimated using eqn. t11). Miscellaneous fixed costs

($AFC_{Mis}{}_a^b$) such as license fee, utilities, parking, etc. are included during estimation of transport cost (mentioned in table 3).

$$AFC_a^b = AFC_{Cap}{}_a^b + AFC_{Ins}{}_a^b + AFC_{lic}{}_a^b + AFC_{Mis}{}_a^b \qquad (t7)$$

$$T_a^b = Min\left(\frac{D_{life}{}_a^b}{D_{Yr}}, T_{life}{}_a^b\right) \qquad (t8)$$

$$AFC_{Cap}{}_a^b = \frac{r_{int} * (1 + r_{int})^{T_a^b}}{(1 + r_{int})^{T_a^b} - 1} * \left(PP_a^b - \frac{SV_a^b}{(1 + r_{int})^{T_a^b}}\right) \qquad (t9)$$

$$AFC_{Ins}{}_a^b = Ins_{frac} * AYI_{Inv}{}_a^b \qquad (t10)$$

$$AYI_{Inv}{}_a^b = \frac{(PP_a^b - SV_a^b) * (T_a^b + 1)}{2 * T_a^b} + SV_a^b \qquad (t11)$$

Annual variable costs (AVC_a^b, eqn. t12) 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. t13 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[67]. The annual oil cost ($AVC_{Oil}{}_a^b$) was estimated by multiplying number oil changes ($Max\left(\frac{D_{Yr}}{Dist_{oil}}, \frac{365}{OCI_{oil}}\right)$) by the price per engine oil change (PP_{Oil}) as mentioned in eqn. t14. Tire life is normally expressed in transport distance, i.e. 65,000-80,000 km. Old tires can be replaced with new or retreaded tires for both trailer and tractor, except for the steering tires, which must be new. But retreaded tires have about 20% less life at a 50% lower price compared with new tires.[70]. Annual costs of tractor tires ($AVC_{Tire_1}{}_a^b$), and trailer tires ($AVC_{Tire_2}{}_a^b$) were estimated as shown in eqn. t15, and t16 respectively. Equations t17 to t21 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 ($/km) (eqn. t22). Additional costs ($AVC_{Adm}{}_a^b$) required to manage accounting, scheduling, dispatching of trucks were assumed as an administration cost (C_{adm}) for a truck (eqn. t23). Wage costs (CL_{Driver}) to truck drivers constitute a significant portion of total transport cost[62, 70]. The annual labor cost ($AVC_{Labor}{}_a^b$) was estimated (eqn. t24) 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.

$$AVC_a^b = AVC_{Fuel}{}_a^b + AVC_{Oil}{}_a^b + AVC_{Tire}{}_a^b + AVC_{L\&M}{}_a^b + AVC_{Adm}{}_a^b + AVC_{Labor}{}_a^b \qquad (t12)$$

$$AVC_{Fuel}{}_a^b = \frac{D_{Yr}}{\frac{1}{mi_{lo} + mi_{ulo}}} * P_{fuel} \qquad (t13)$$

$$AVC_{Oil}{}_{a}^{b} = PP_{Oil} * Max\left(\frac{\mathrm{D}_{Yr}}{Dist_{oil}}, \frac{365}{OCI_{oil}}\right) \ldots\ldots \text{(t14)}$$

$$AVC_{Tire}{}_{1}^{b} = \left(N_{Tire}{}_{1,Str}^{b} + N_{Tire}{}_{1,Dri,new}^{b}\right) * PP_{Tire,new} + N_{Tire}{}_{1,Dri,Retread}^{b} * PP_{Tire,Retread} \ldots\ldots \text{(t15)}$$

$$AVC_{Tire}{}_{2}^{b} = N_{Tire}{}_{2,Tra,New}^{b} * PP_{Tire,New} + N_{Tire}{}_{2,Tra,Retread}^{b} * PP_{Tire,Retread} \ldots\ldots \text{(t16)}$$

$$N_{Tire}{}_{1,Str,new}^{b} = N_{StrTire} * \frac{\mathrm{D}_{Yr}}{TiLi_{Str,New}} \ldots\ldots \text{(t17)}$$

$$N_{Tire}{}_{1,Dri,new}^{b} = \left(N_{DriTire} * \frac{\mathrm{D}_{Yr}}{TiLi_{Dri,new}}\right) * Pct_{New} \ldots\ldots \text{(t18)}$$

$$N_{Tire}{}_{1,Dri,Retread}^{b} = \left(N_{DriTire} * \frac{\mathrm{D}_{Yr}}{TiLi_{Dri,Retread}}\right) * (1 - Pct_{New}) \ldots\ldots \text{(t19)}$$

$$N_{Tire}{}_{2,Tra,New}^{b} = \left(N_{TraTire} * \frac{\mathrm{D}_{Yr}}{TiLi_{Tra,New}}\right) * Pct_{New} \ldots\ldots \text{(t20)}$$

$$N_{Tire}{}_{2,Tra,Retread}^{b} = \left(N_{TraTire} * \frac{\mathrm{D}_{Yr}}{TiLi_{Tra,Retread}}\right) * (1 - Pct_{New}) \ldots\ldots \text{(t21)}$$

$$AVC_{L\&M}{}_{a}^{b} = L\&M_{a}^{b} * \mathrm{D}_{Yr} \ldots\ldots \text{(t22)}$$

$$AVC_{Adm}{}_{a}^{b} = \mathrm{PMH}_{Yr} * \mathrm{C}_{adm} \ldots\ldots \text{(t23)}$$

$$AVC_{Labor}{}_{a}^{b} = \mathrm{SMH}_{d} * \mathrm{WD}_{Yr} * CL_{Driver} * (1 + FB_{Driver}) \ldots\ldots \text{(t24)}$$

Table 3: Assumptions and inputs for transport calculation of log trucks, chip vans, and flatbed truck 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 (hr/year)	
PMH_{d}	Productive machine hours in a day (hr/day)	
WD_{Yr}	Working days in a year (days/year)	
t_{trip}^{b}	Total time required for a truck to supply biomass to demand site and return back to the landing (hrs/trip)	
t_{lo}^{b}	Loading time of biomass to a trailer (hr/load)	t_{lo}^{1} =14 mins (assuming same as loading logs in log trucks)[12] t_{lo}^{2} = 1.83 mins per chip/hog-fuel bucket load (5 m^3)~ 37 mins [63]

		t_{lo}^{2} = 1 mins per bale (44 and 36 mins for small and large bales respectively for a truck)[62]
t_{ulo}^{b}	Unloading time of biomass to a trailer (hr/unload)	t_{ulo}^{1}= same as loading time t_{ulo}^{2}=Assumed 50% of unloading time (self-unloading trailer)[71] t_{ulo}^{3}= same as loading time
D_{av}	Average trip distance between supply and demand (km/hr)	Average distance between landing site and 5 BCT locations in this study
V_{lo}	Speed of the truck with biomass in trailer (km/hr)	32 km/hr[72], average speed from landing to BCT
V_{ulo}	Speed of the truck without biomass in trailer	Assumed same as loaded
$\mathrm{N}_{Trip/day}$	Number of trips a truck daily performed between supply (i.e. landing) and demand point (i.e., BCT).	Estimated using eqn. t5
U^{b}	Truck/tractor utilization (%)	Assumed 85%[39]
D_{Yr}	Average distance traveled by trucks in a year (km/year)	Calculated using eqn. t7
AFC_{a}^{b}	Total annual fixed cost ($/year)	Calculated using eqn. t8
${AFC_{Cap}}_{a}^{b}$	Capital cost ($/year)	Calculated using eqn. t9
${D_{life}}_{a}^{b}$	Life of truck or trailer in km (km)	${D_{life}}_{1}^{b}$= 1,207,008 km[68, 70] ${D_{life}}_{2}^{b}$= 2,414,016 km [70]
${T_{life}}_{a}^{b}$	Life of truck or trailer in years (yr)	${T_{life}}_{1}^{b}$= 10 years [62] ${T_{life}}_{2}^{b}$= 20 years [62]
T_{a}^{b}	Life of truck in terms of years (yr) used in the calculation	Estimated using eqn. t10
${AFC_{Ins}}_{a}^{b}$	Insurance cost ($/year)	Calculated using eqn. t11
Ins_{frac}	% of Av. annual investment (${AYI_{Inv}}_{a}^{b}$)	5.95% [67], or $4643 per year cost for an average annual capital investment of $78,000.
${AYI_{Inv}}_{a}^{b}$	Average yearly investment($/year)	Estimated using eqn. t12
${AFC_{lic}}_{a}^{b}$	License and registration cost ($/year)	$2,225/year,[67]
${AFC_{Mis}}_{a}^{b}$	Miscellaneous fixed cost ($/year)	$2,000/year,[67]. It includes union fee, citation, etc.
AVC_{a}^{b}	Annual variable cost ($/year)	Estimated using eqn. t13
${AVC_{Fuel}}_{a}^{b}$	Annual fuel cost ($/year)	Estimated using eqn. t14
P_{fuel}	Average fuel price ($/liter)	$0.75/liter, avg. US diesel price for last five years
mi_{lo} & mi_{ulo}	Mileage in loaded and unloaded trucks (km/liter)	2.17 km/liter[67]

$AVC_{Oil}{}_a^b$	Annual cost engine oil change ($/year)	Estimated using eqn. t15
$Dist_{oil}$	Average mileage for oil change (km)	16,000 km[67]
OCI_{oil}	Number of days between oil change (days)	4 weeks[67]
PP_{Oil}	Price of an engine oil change	$242.89/oil change @ 23 liter[67]
$AVC_{Tire}{}_a^b$	Annual tire cost ($/year) for truck or trailer	Estimated using eqn. t16 for truck Estimated using eqn. t17 for trailer Price of new tire ($PP_{Tire,new}$)= $465.78[67] Price of retreaded tire ($PP_{Tire,Retread}$)= $174.67[67]
$AVC_{Tire}{}_1^b$	Annual tire cost ($/year) for truck	Estimated using eqn. t16 for truck
$N_{Tire}{}_{1,Str}^b$	Number of steering tires replaced in a year from tractor	Estimated using equation eqn. t18 considering number of steering tires in trucks ($N_{StrTire}$=2)[67]and life of a steering tire ($TiLi_{Str}$), 40,000 km[70]. 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. t19 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. t20 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 $N_{TraTire}$=16, [67, 70]
$AVC_{L\&M}{}_a^b$	Annual cost of repair and maintenance ($/year)	Estimated using eqn. t21
LM_a^b	Lube and maintenance cost ($/km)	RM_a^b=0.041 $/km assuming ($2,880/year for lube, $1,200/year for hose and light, $600/year for brakes for an annual mileage of 114,588 km/year[67].
$AVC_{Adm}{}_a^b$	Annual cost of administration for a truck	Estimated using eqn. t22
C_{adm}	Cost of administration per truck per day ($/day/truck)	C_{adm}= $28/day/truck, Cost incur due to accounting, scheduling, dispatching and other activities to operate trucks[67]
$AVC_{Labor}{}_a^b$	Annual labor cost ($/year)	Estimated using eqn. t23
CL_{Driver}	Hourly cost of driver's wage	$20.81 (at March 2017) hourly median wage (Range = $13.50 – $29.70)[73]
FB_{Driver}	Fringe benefits (% of wage)	35% of wages[67, 73]

Results and discussion

Cost of treetops processing and sorting

The treetop consists of the sawlog top (15 cm diameter) upwards towards a small-diameter tip of 2.54 cm[17]. Processing treetops and sorting increased the overall sawlog production cost by \$1.40-\$3.94/m^3 based on the sorting intensity. Treetops 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 harvesting of timber in the stand[12]. 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 Figure 2. Treetops 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[12] and the estimated volume of treetops generated per unit volume of sawlog production. The estimated costs of processed treetops was \$24/m^3 or \$30/ODMT considering moderate sorting during logging operations. For intensive sorting, the processed treetops cost was \$64/m^3 or \$82/ODMT. The treetops cost produced through only moderate sorting was similar to cost of processed biomass (\$27.5/ODMT[12]) trees. However, treetops produced through intensive sorting was about thrice than the processed biomass trees (\$29.5/ODMT) as presented in Kizha and Han[12].

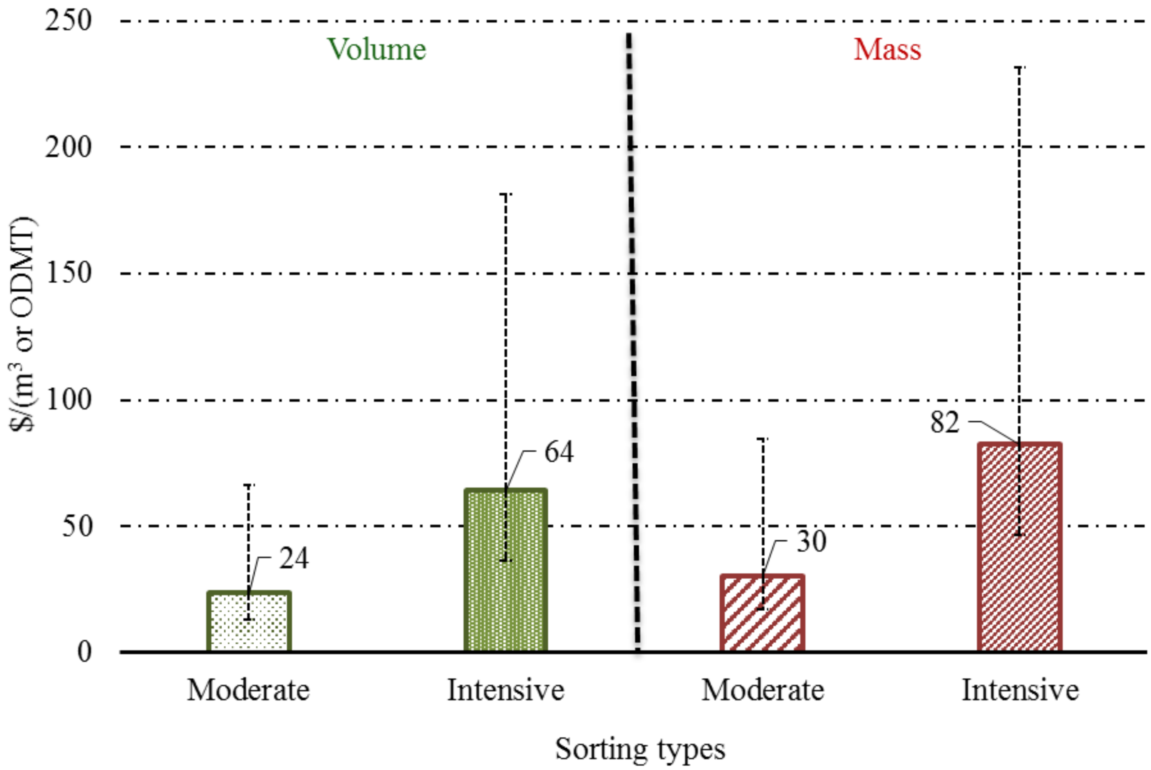


Figure 2: Estimated cost of treetops processing and sorting (error bars: standard error of mean)

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[74]. The cost of sorting and treetop processing was estimated (equation A) 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 owners may 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[12, 13]. 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 in addition to that, it may 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.

Biomass comminution, screening, and baling

The estimated comminution, screening, and baling costs are presented in figure 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.

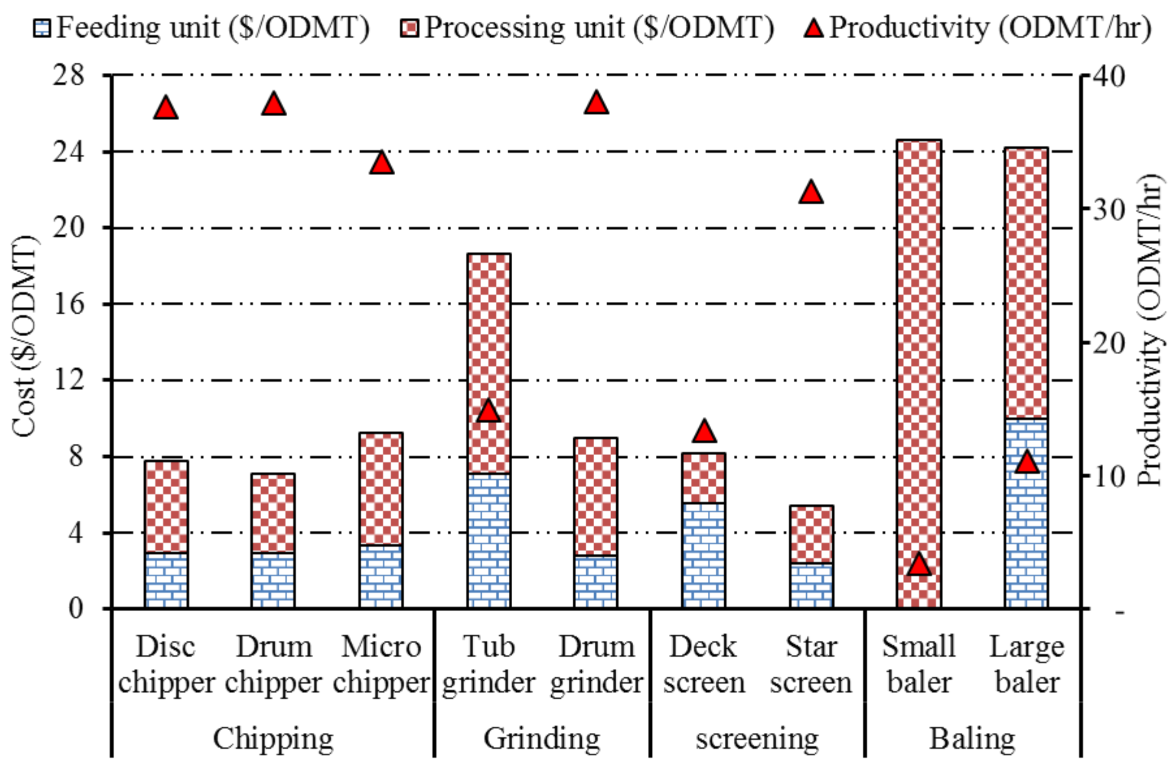


Figure 3: Comminution, baling and screening of logging residues

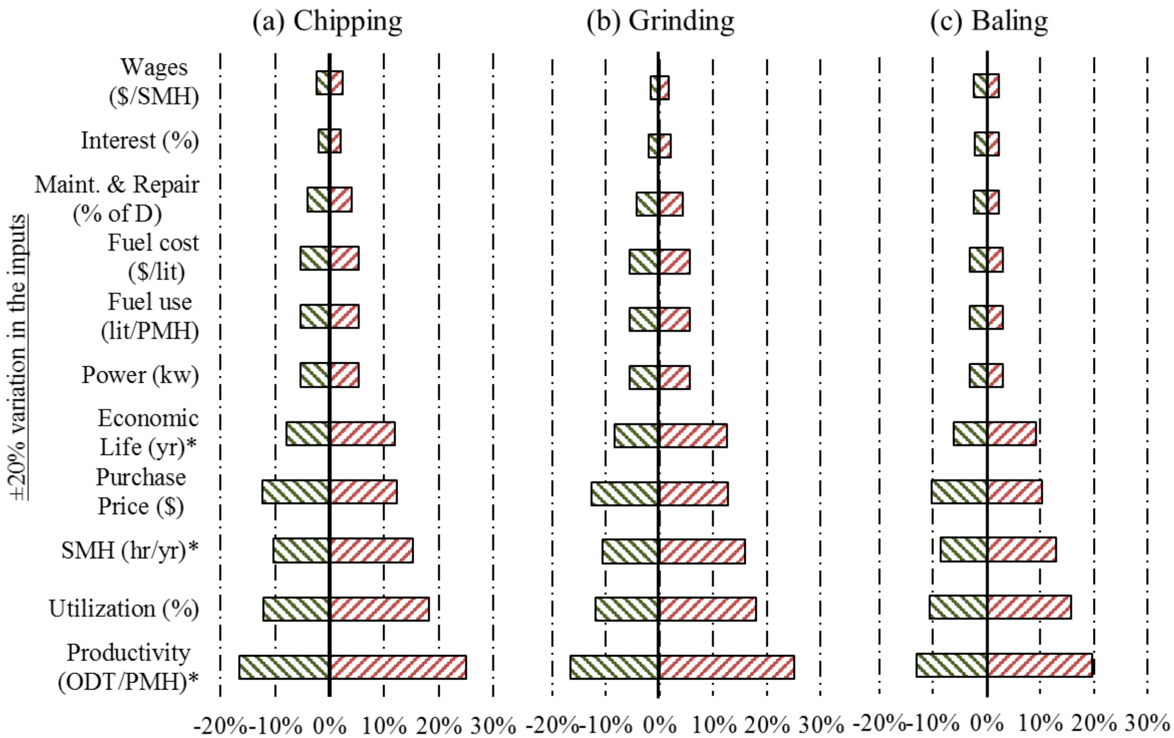
The type of chippers such as drum or disc did not significantly change the biomass chipping cost. However, a previous study mentioned that disc chippers are more fuel efficient but less productive than drum chippers when used for lower quality forest residues[38]. Similar results on chipping cost had been reported in the past studies for whole trees[31, 32] and processed biomass trees[39]. 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[40, 75]. Micro-woodchips are better in quality (uniform in size) than woodchips[17, 39].

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/hr[58]) compared with later (38 ODMT/hr[39]). However, studies have reported both tub-grinders and horizontal grinders having similar productivities[76]. 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 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 self-feeding unit inbuilt into the small-baler. The actual cost of only baling using the large-baler was about half than small-baler. But, the additional cost of a feeding unit increased the overall cost of baling forest residues in case of the large-baler. This provides an opportunity to improve forest residues 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[62] 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 [62] 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, 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 thrice that of grinding using drum grinders. The higher baling cost was due substantially lower machine productivity (figure 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[17]. 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.



* Values decreased and increased by 20% of average, opposite to other inputs

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

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 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 the 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 benefits (i.e., percentage decrease in unit cost) following a comparable increase in productivity. A similar pattern was observed for others inputs 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 figure 3 can be reduced further by efficient use of machines such as increase productivity, utilization, etc. Sorting of treetops and biomass tree can help in improving the feeding unit's productivity that feeds biomass into chippers or grinders, which needs to be studied further. Moreover, low contamination biomass produced through sorting will incur lower expenses on repair and maintenance of chippers or microchipper which ultimately reduce the unit operation cost in forest residue harvesting.

Each operation such as chipping, grinding, or baling used two separate units, i.e., feeding unit and a processing unit with specific individual biomass handling capacity. Among the two units, the lowest biomass handling capacity will dictate the overall biomass processing capacity of a unit operation. Similarly, if a series of operations are considered in a biomass processing system, the bottleneck operation (i.e., having lowest throughput) dictate the throughput/productivity of the entire system. Therefore, matching of the machine capacities – in terms of biomass handling and subsequent utilization of each machine's output – is very critical in a real-life practical application and can influence the actual operating cost of each unit operation and overall system cost.

A simulation modeling approach such as discrete-event simulation model is able to accommodate the variations in the individual machine productivities in a unit operation or a series of operations[69, 77] and may represent the next development in-forest biomass logistics to accurately estimate costs with higher levels of confidence.

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 was varied from \$11 to \$22/ODMT depending on its form.

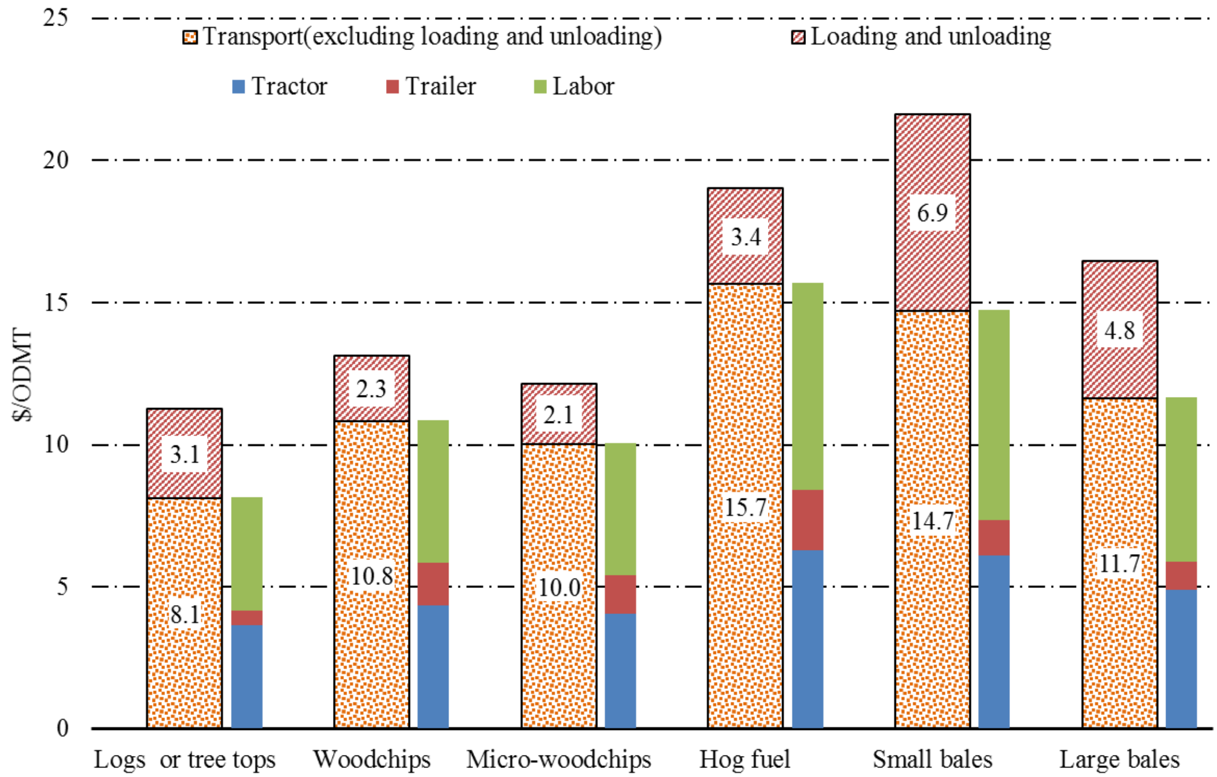


Figure 5: Transportation cost of forest residues in logs, chips, microchips, hog-fuel, and bales (in $/ODMT)

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 hourly transport costs (not including loading and unloading) varied between $56 and $60, depending on the type of trailer (not shown here)[67, 68]. Loading and unloading of bales contribute about 29%-32% of total transportation cost depending on the feedstock type. Other researchers reported similar costs of loading comminuted biomass to trucks[22]. The cost of loading/unloading forest residues bales to/from flatbed trailers was similar to agricultural residues bales[62]. 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[67, 68]. Those authors assumed lower hourly labor costs and benefits compared to this study.

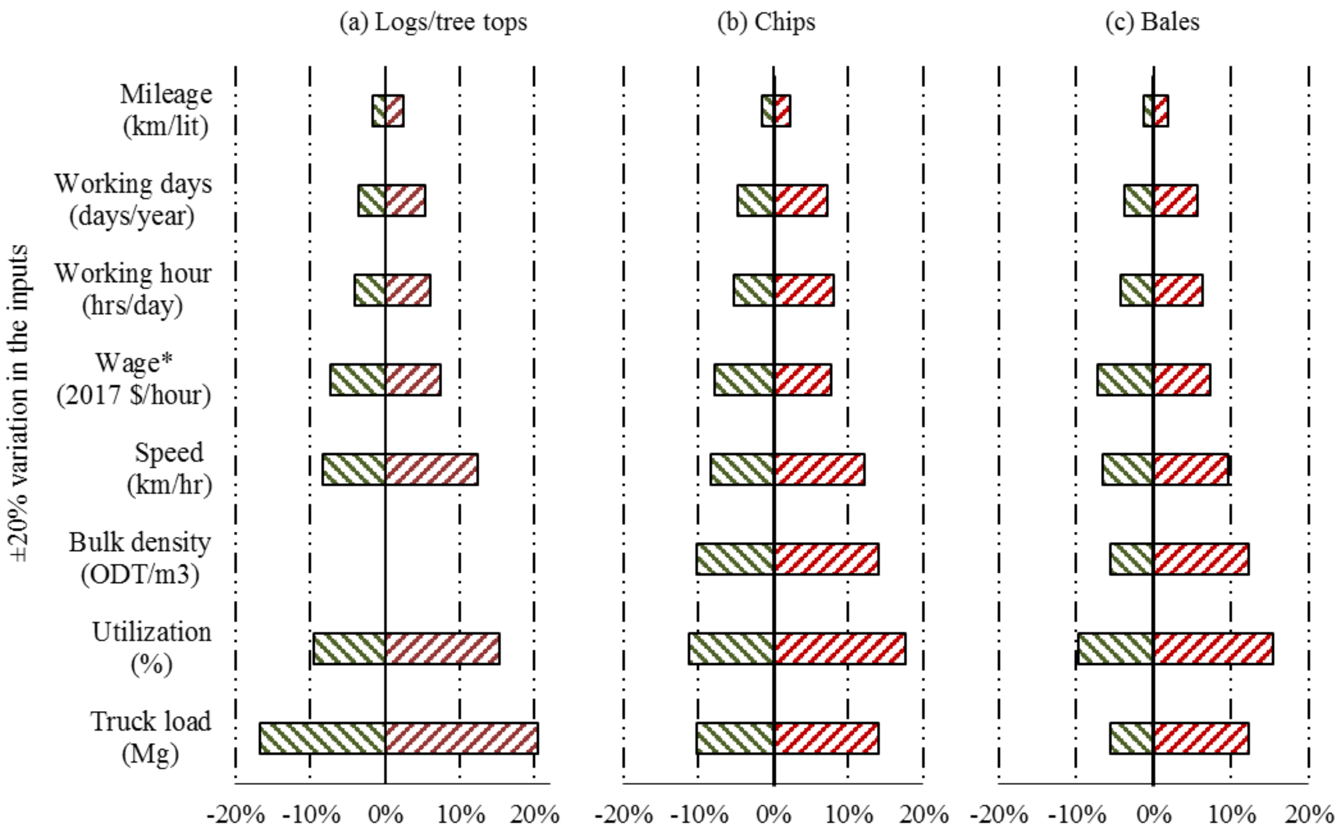
Another difference between forest residue transport and typical long-haul commercial trucking is the annual mileage. A truck hauling forest residues is typically much lower than the annual mileage assumed in long-haul commercial trucking studies (e.g. Mason et al.[67]). Lower annual mileage also reduces 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 40%-50% of annual travel distance by a logging truck.

The size of the tractors was same for each type of trailer including log truck, chip van, and flatbed. The variabilities in the trailer costs are wide but these cost 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)[17]. 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 distance between landing and BCT sites were very low[78] (assumed 32 km 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) + 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-density bales will improve and at a certain minimum distance, it may be economical to deliver the denser bales 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 (figure 8).

The transportation cost estimations of are based on several assumptions and input parameters (Table 3). The developed transportation cost model was simulated with a ±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.



* Wage values decreased and increased by 20% of average, opposite to other inputs

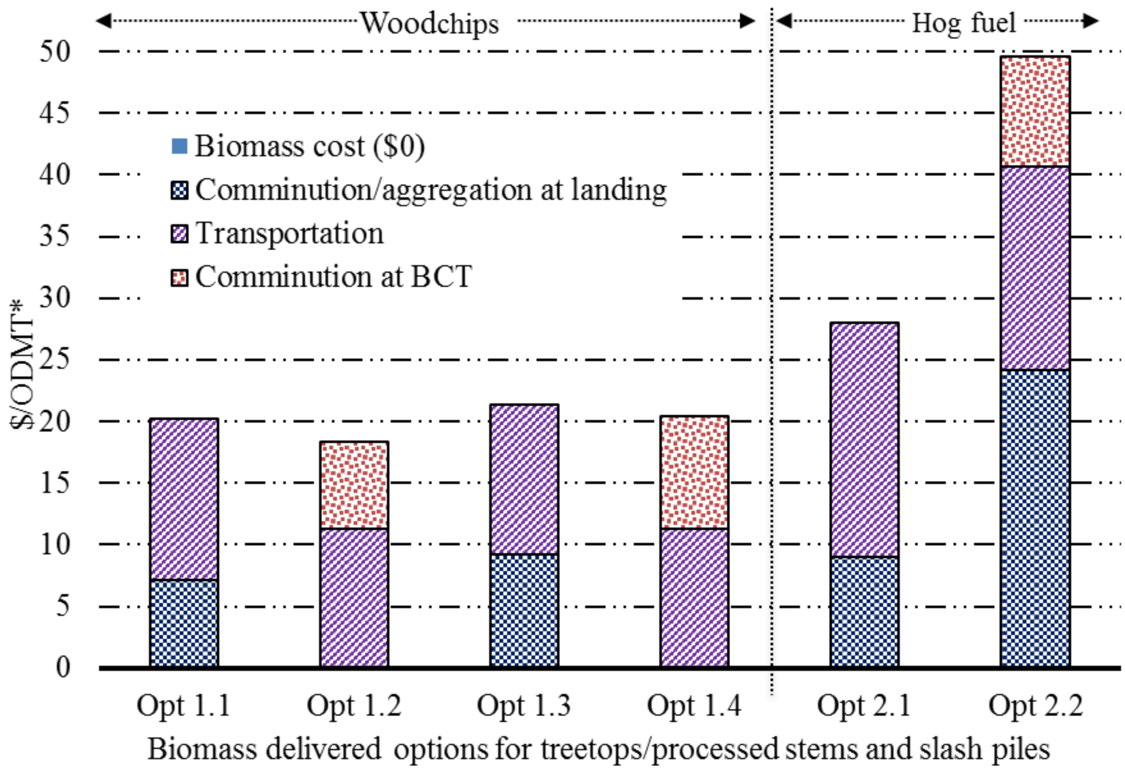
Figure 6: Sensitivity analysis of input parameters variability (± 20%) on total transportation cost (loading/unloading excluded) for (a) treetops/logs, (b) chips and (c) large bales.

Feedstock's supply logistics options to BCTs and power plants

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. 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

Figure 7 presents a comparative results on the estimated cost of delivering woodchips (option 1.1 to 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[12]) 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 estimated costs in this study.



* 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: Biomass delivery cost of processed treetops/biomass and slash in comminuted form at the plant

Screening is used to provide uniform sized woody feedstocks to a plant, which may be critical to maintain the quality of the products produced from those feedstocks. Uniform feedstocks are especially important for torrefied products, where it is difficult to get uniform torrefaction through 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 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]. 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 than 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 baling of slash overshadows the lower cost of transporting bales compared to 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 figure 8.

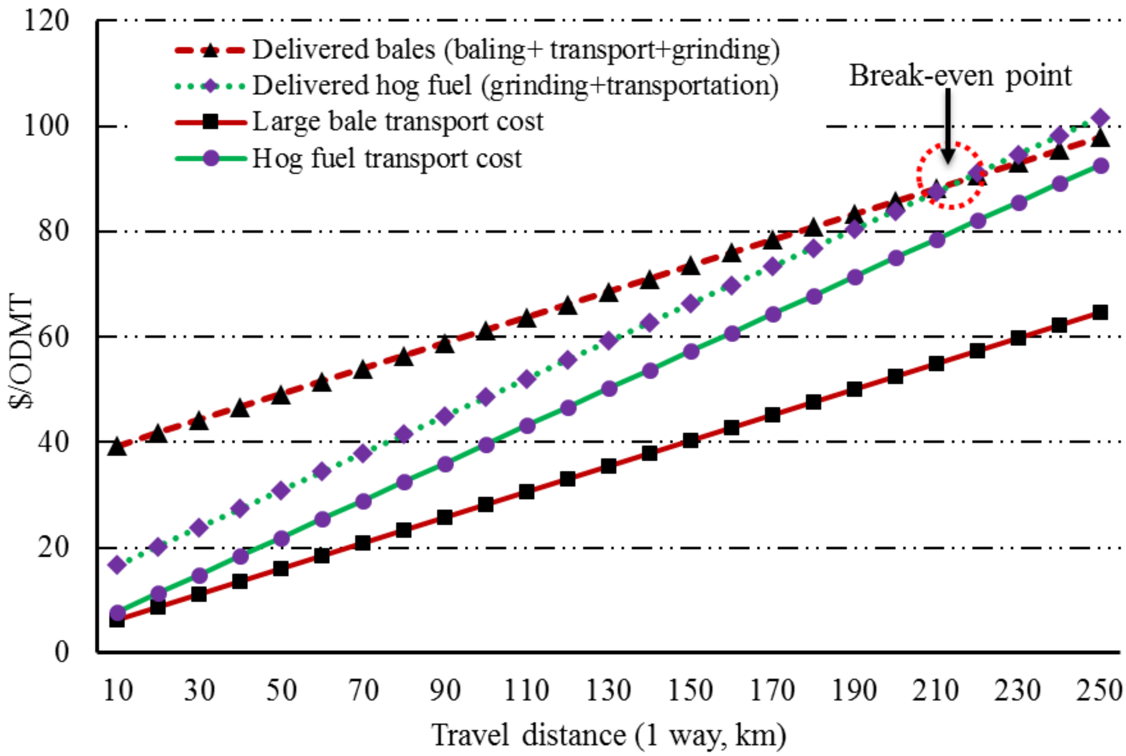


Figure 8: Variations of biomass delivered cost and transport cost with travel distance for hog-fuel and bales

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 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 biomass delivered cost of 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 residues supply logistics. The cost of processing treetops was determined considering the increased cost of sawlog production due to treetops 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. Sensitivity analysis of unit supply logistics operations was performed to identify critical input parameters to impact logistics cost.

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/hectare and $1,822/hectare of timberlands based on sawlog and forest residue yield in the Pacific Northwest U.S.[74]. However, forest owners can avoid residues piling and burning (reported cost $700-$2,100/hectare[12, 13]) by adopting BSTP forest residues management practice. In addition to the direct cost savings, other subjective benefits such mitigation of forest fire risks, air pollution, and pest outbreaks are also mentioned in the literature.

The cost model developed in this study can be used as a decision tool by forest owners to make credible decisions to adopt sorting and processing of treetops during logging operations. The estimated micro-chipping cost was higher than the chipping but former may help in saving screening cost due to the production of uniform-sized feedstock (micro-woodchips may not require screening) compared with later. 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 distances 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 1.1or 1.3, figure 8). It is also economical to grind slash at the landing and transport ground biomass (i.e., hog-fuel) in chip trucks to energy plants located near to the forest (option 2.1, figure 8). However, for power plants located longer distances (i.e., >220 km) from the forest, slash should be baled and transported in flatbed-trailers (option 2.2, figure 8) to get the lower unit transportation cost of large bales.

The results illustrated here provided a comparative analysis of different pathways of 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 delivery and to analyze the benefits of using high-quality biomass from processed treetops and biomass trees.

Acknowledgements

This material is based upon work supported by a grant from the U.S. Department of Energy under the Biomass Research and Development Initiative program: Award Number DE-EE0006297.

References

1. Natural Resources Defense Council, The Paris agreement on climate change. (2015). [Online]. Available at: https://assets.nrdc.org/sites/default/files/paris-agreement-climate-change-2017-ib.pdf?_ga =2.6041764 7.390110168.1524516422-343386622.1524516422 [April 15, 2018
2. U.S. Department of Energy, 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks, USDOE report no ORNL/TM-2016/160, lead by Langholtz MH, Stokes BJ, and Eaton LM. United States Department of Energy and Oak Ridge National Laboratory, Oak Ridge, TN, p. 448p (2016).
3. U.S. Department of Energy, U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry, USDOE report no ORNL/TM-2011/224, lead by Perlack RD and Stokes BJ. United States Department of Energy and Oak Ridge National Laboratory, Oak Ridge, TN, pp. 227 (2011).
4. Barbose G, U.S. Renewables Portfolio Standards: 2017 Annual Status Report. Lawrence Berkely National Laboratory (2017).
5. Aresta M, Dibenedetto A and Dumeignil F, Biorefinery : from biomass to chemicals and fuels. Walter de Gruyter, Berlin (2012).
6. Wegner T, Houtman C, Rudie A, Illman B, Ince P, Bilek E, et al., Prehydrolysis Pulping with Fermentation Coproducts. In: RSC Green Chemistry No. 18, Integrated Forest Biorefineries, Edited by Lew Christopher. The Royal Society of Chemistry 2013, Published by the Royal Society of Chemistry, www. rsc. org; 2013; pp. 134-150. 18: 134-150 (2013).

7. Dale VH, Kline KL, Parish ES, Cowie AL, Emory R, Malmsheimer RW, et al., Status and prospects for renewable energy using wood pellets from the southeastern United States. GCB Bioenergy 9(8): 1296-1305 (2017).
8. U.S. Energy Information Administration, Monthly Densified Biomass Fuel Report. Available at: https://www.eia.gov/biofuels/biomass/ [April 15, 2018]
9. Thrän D, Peetz D, Schaubach K, Backéus S, Benedetti L, Bruce L, et al., Global Wood Pellet Industry and Trade Study. IEA Bioenergy Task 40, Netherlands (2017).
10. Jirka S and Tomlinson T, State of the Biochar Industry-A Survey of Commercial Activity in the Biochar Field. International Biochar Initiative (2013).
11. Dodson E, Hayes S, Meek J and Keyes CR, Montana logging machine rates. International Journal of Forest Engineering 26(2): 85-95 (2015).
12. Kizha AR and Han H-S, Processing and sorting forest residues: Cost, productivity and managerial impacts. Biomass and Bioenergy 93: 97-106 (2016).
13. Berrill J-P and Han H-S, Carbon, Harvest Yields, and Residues from Restoration in a Mixed Forest on California's Coast Range. Forest Science 63(1): 128-135 (2017).
14. Springsteen B, Christofk T, Eubanks S, Mason T, Clavin C and Storey B, Emission Reductions from Woody Biomass Waste for Energy as an Alternative to Open Burning. Journal of the Air & Waste Management Association 61(1): 63-68 (2011).
15. Jones G, Loeffler D, Calkin D and Chung W, Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return. Biomass and Bioenergy 34(5): 737-746 (2010).
16. Jernigan P, Gallagher T, Aulakh J, Tufts R and McDonald T, Implementing residue chippers on harvesting operations in the southeastern US for biomass recovery. International Journal of Forest Engineering 24(2): 129-136 (2013).
17. Bisson JA and Han H-S, Quality of feedstock produced from sorted forest residues. American Journal of Biomass and Bioenergy 5(2): 81-97 (2016).
18. Sang-Kyun Han, Han-Sup Han and Bisson JA, Effects of Grate Size on Grinding Productivity, Fuel Consumption, and Particle Size Distribution. Forest Products Journal 65(5-6): 209-216 (2015).
19. Facello A, Cavallo E and Spinelli R, Chipping vs grinding, net energy requirements. In FORMEC, Dubrovnik (Cavtat), October 8–12 (2012).
20. Nati C, Eliasson L and Spinelli R, Effect of chipper type, biomass type and blade wear on productivity, fuel consumption and product quality. Croatian Journal of Forest Engineering 35(1): 1-7 (2014).
21. Spinelli R, Cavallo E, Facello A, Magagnotti N, Nati C and Paletto G, Performance and energy efficiency of alternative comminution principles: Chipping versus grinding. Scandinavian Journal of Forest Research 27(4): 393-400 (2012).

22. Anderson N, Chung W, Loeffler D and Jones JG, A Productivity and Cost Comparison of Two Systems for Producing Biomass Fuel from Roadside Forest Treatment Residues. Forest Products Journal 62(3): 222-233 (2012).

23. Pan F, Han H-S, Johnson LR and Elliot WJ, Net energy output from harvesting small-diameter trees using a mechanized system. Forest Products Journal 58(1/2): 25 (2008).

24. Dooley JH, J Lanning C and N Lanning D, Conceptual Specification of Forest Utility Balers for Wody Biomass. In 2016 ASABE Annual International Meeting, Paper Number: 162455264, Orlando, Florida July 17-20 (2016).

25. Dooley JH, J Lanning C and N Lanning D, Conceptual Specification of Forest Residues Balers using the Appreciative Design Method. In 2015 ASABE Annual International Meeting, Paper Number: 152189213, New Orleans, Louisiana July 26 – 29 (2015).

26. Belbo H and Talbot B, Systems Analysis of Ten Supply Chains for Whole Tree Chips. Forests 5(9): 2084 (2014).

27. Kizha AR, Han H-S, Montgomery T and Hohl A, Biomass power plant feedstock procurement: Modeling transportation cost zones and the potential for competition. California Agriculture 69(3): 184-190 (2015).

28. Bisson JA, Han S-K and Han H-S, Evaluating the System Logistics of a Centralized Biomass Recovery Operation in Northern California. Forest Products Journal 66(1-2): 88-96 (2016).

29. Ghaffariyan MR, Brown M, Acuna M, Sessions J, Gallagher T, Kühmaier M, et al., An international review of the most productive and cost effective forest biomass recovery technologies and supply chains. Renewable and Sustainable Energy Reviews 74: 145-158 (2017).

30. Harrill H and Han H-S, Productivity and Cost of Integrated Harvesting of Wood Chips and Sawlogs in Stand Conversion Operations. International Journal of Forestry Research 2012: (2012).

31. Hanzelka NC, Bolding MC, Sullivan J and Barrett SM, Productivity and costs of utilizing small-diameter stems in a biomass-only harvest. International Journal of Forest Engineering 27(1): 43-52 (2016).

32. Whalley S, Klein SJW and Benjamin J, Economic analysis of woody biomass supply chain in Maine. Biomass and Bioenergy 96: 38-49 (2017).

33. Kizha AR and Han H-S, Cost and productivity for processing and sorting forest residues. In Council of Forest Engineering Annual Meeting, Lexington, KY, 2015.

34. Facello A, Cavallo E and Spinelli R In Some parameters that affect the wood chipping machines efficiency, Proceedings International Conference of Agricultural Engineering, Zurich, July 6-10 (2014).

35. Eckardt R, Forest harvesting systems for biomass production-Renewable biomass from the forests of Massachusetts. Innovative Natural Resource Solutions, Portland, ME (2007).

36. Laitila J and Routa J, Performance of a small and medium sized professional chippers and the impact of storage time on Scots pine (Pinus sylvestris) stem wood chips characteristics. SILVA FENNICA 49: (2015).

37. Facello A, Cavallo E and Spinelli R, Chipping machines: disc and drum energy requirements. Journal of Agricultural Engineering 44(2): (2013).

38. Spinelli R, Cavallo E, Eliasson L and Facello A, Comparing the efficiency of drum and disc chippers. Silva Fennica 47(2): 1-11 (2013).

39. Bisson JA. Evaluating Factors that Influence the Feedstock Quality of Comminuted Forest Residues, Master Thesis, Humboldt State University, CA (2016).

40. Thompson J and Sprinkle W, Production, cost and chip characteristics of in-woods microchipping. In Council on Forest Engineering Annual Meeting, Auburn, AL, July 8–10 (2013).

41. Hopkins C and Roise J, Microchiping Trials of Green versus Dry, Pine versus Hardwood: Measurement of Energy Efficiency and Productivity. In 35th Council on Forest Engineering Annual Meeting, New Bern, North Carolina (2012).

42. Nati C, Spinelli R and Fabbri P, Wood chips size distribution in relation to blade wear and screen use. Biomass and Bioenergy 34(5): 583-587 (2010).

43. Spinelli R, Ivorra L, Magagnotti N and Picchi G, Performance of a mobile mechanical screen to improve the commercial quality of wood chips for energy. Bioresource Technology 102(15): 7366-7370 (2011).

44. Dukes CC, Baker SA and Greene WD, In-wood grinding and screening of forest residues for biomass feedstock applications. Biomass and Bioenergy 54: 18-26 (2013).

45. Huber C, Kroisleitner H and Stampfer K, Performance of a Mobile Star Screen to Improve Woodchip Quality of Forest Residues. Forests 8(5): 171 (2017).

46. Laitila J and Yrjö N, Efficiency of integrated grinding and screening of stump wood for fuel at roadside landing with a low-speed double-shaft grinder and a star screen. Croatian Journal of Forest Engineering: Journal for Theory and Application of Forestry Engineering 36(1): 19-32 (2015).

47. Leinonen A, Harvesting Technology of Forest Residues for Fuel in the USA and Finland. VTT Research Notes 2229, Finland, 2004,132 p.

48. Forest Products Laboratory, Wood handbook - Wood as an engineering material. General Technical Report FPL-GTR-190, Forest Products Laboratory, Madison, Wisconsin, 2010, 508 p.

49. Miyata ES Determining fixed and operating costs of logging equipment, General Technical Report NC-55, North Central Forest Experiment Station, Forest Service, St. Paul, Minnesota. (1980).

50. Bilek T ChargeOut!: discounted cash flow compared with traditional machine-rate analysis, General Technical Report: FPL–GTR–178, United States Department of Agriculture, Forest Service, Forest Products Laboratory: Madison, WI, USA (2009).

51. Ackerman P, Belbo H, Eliasson L, de Jong A, Lazdins A and Lyons J, The COST model for calculation of forest operations costs. International Journal of Forest Engineering 25(1): 75-81 (2014).

52. Brinker RW, Miller D, Stokes BJ and Lanford BL Machine rates for selected forest harvesting machines, Circular 296, Alabama Agricultural Experiment Station, Auburn University, Alabama (1989).

53. Akay AE. Estimating machine rates and production for selected forest harvesting machines operating in the western United States and determining the most economical machine combinations under representative conditions in Turkey, Master Thesis, Oregon State University, Corvallis, Oregon (1998).

54. Oyier PO. Fuel consumption of timber harvesting systems in New Zealand. Master Thesis, University of Canterbury, New Zealand (2015).

55. Wu J, Wang J and McNeel J, Economic modeling of woody biomass utilization for bioenergy and its application in central Appalachia, USA. Canadian journal of forest research 41(1): 165-179 (2010).

56. Sessions J Cost control in logging and road construction, Forestry Paper: 99, Food and Agriculture Organization of the United Nations , Rome (1992).

57. Brinker RW, Miller D, Stokes BJ and Lanford BL, Machine rates for selected forest harvesting machines. Circular 296 (Revised), Alabama Agricultural Experiment Station, Auburn University, Alabama (2002).

58. Bolding MC, Kellogg LD and Davis CT, Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. Forest Products Journal 59(3): 35-46 (2009).

59. Benjamin JG, Seymour RS, Meacham E and Wilson J, Impact of whole-tree and cut-to-length harvesting on postharvest condition and logging costs for early commercial thinning in Maine. Northern Journal of Applied Forestry 30(4): 149-155 (2013).

60. Meek JP. Montana Logging Costs: Resources for Continued Industry Viability. Master Thesis, The University of Montana, Missoula, MT (2013).

61. Woo H and Han H-S, Performance of screening biomass feedstocks using star and deck screen machines. Applied Engineering in Agriculture 54(1): 35-42 (2018).

62. Sahoo K and Mani S, Engineering Economics of Cotton Stalk Supply Logistics Systems for Bioenergy Applications. Transactions of the ASABE 59(3): (2016).

63. Manzone M, Loader performance during woodchip loading. Biomass and Bioenergy 98: 80-84 (2017).

64. Baker S, Greene D, Harris T and Mei R Regional cost analysis and indices for conventional timber harvesting operations, Final Report to the Wood Supply Research Institute, Center for forest Business, University of Georgia & Wood Supply Research Institute, 2013, p. 39. Available at: http://wsri.org/resources/media/RegCostAnalFinalRpt.pdf [February 7 2018]

65. Leon BH and Benjamin JG, A survey of business attributes, harvest capacity and equipment infrastructure of logging businesses in the northern forest. The University of Maine, School of Forest Resources, Orono, ME (2012).

66. Hubbard W, Biles L, Mayfield C and Ashton S, Sustainable forestry for bioenergy and bio-based products: trainers curriculum notebook, Southern Forest Research Partnership, Athens, GA (2007).

67. Mason CL, Casavant KL, Lippke BR, Nguyen DK and Jessup E, The Washington log trucking industry: Costs and safety analysis. University of Washington and Washington State University (2008). Available at: https://www.ruraltech.org/pubs/reports/2008/log_trucks/log_truck_report.pdf [April 20 2018]

68. Torrey WF and Murray D, An Analysis of the Operational Costs of Trucking: 2016 Update, American Transportation Research Institute, Arlington, VA (2016).

69. Sahoo K. Sustainable design and simulation of multi-feedstock bioenergy supply chain, Doctoral Thesis, University of Georgia, Athens, Georgia (2017).

70. Han S-K and Murphy G, Trucking productivity and costing model for transportation of recovered wood waste in Oregon. Forest Products Journal 61(7): 552-560 (2011).

71. Janzé GFP, Biomass trucks and dumpers. Available at: http://www.advancedbiomass.com /2016/02/biomass-trucks-and-dumpers/[April 12 2018].

72. Han H-S, Oneil E, Bergman RD, Eastin IL and Johnson LR, Cradle-to-gate life cycle impacts of redwood forest resource harvesting in northern California. Journal of Cleaner Production 99: 217-229 (2015).

73. U.S. Bureau of Labor Statistics, Occupational Employment Statistics. Available at: https://data.bls.gov/oes/#/occGeo/One%20occupation%20for%20multiple%20geographical%20areas [April 10 2018].

74. Perez-Garcia J, Oneil E, Hansen T, Mason T, McCarter J, Rogers L, et al., Biomass calculator. Washington Department of Natural Resources (2017). Available at: http://wabiomass.cfr.washington.edu [April 05 2018].

75. Anderson N and Mitchell D, Forest Operations and Woody Biomass Logistics to Improve Efficiency, Value, and Sustainability. Bioenergy Research 9(2): 518-533 (2016).

76. Asikainen A and Pulkkinen P, Comminution of Logging Residues with Evolution 910R chipper, MOHA chipper truck, and Morbark 1200 tub grinder. Journal of Forest Engineering 9(1): 47-53 (1998).

77. Sahoo K and Mani S In GIS based discrete event modeling and simulation of biomass supply chain, Proceedings of the 2015 Winter Simulation Conference, IEEE Press: pp 967-978, (2015).

78. Berry M and Sessions J, The Economics of Biomass Logistics and Conversion Facility Mobility: An Oregon Case Study. . Applied Engineering in Agriculture 34(1): 57-72 (2018).