Wildfire fuel-reduction biomass for remote energy: Small-scale combined heat and power feasibility and strategic implications for British Columbia's bioeconomy

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HIGHLIGHTS

- Selected fuel-reduction biomass can serve as feedstock for small bioenergy systems.
- One-year natural drying significantly reduced biomass moisture and fine particle content.
- Supply chain costs ranged from $175 to $426 per oven-dry tonne across evaluated scenarios.
- For short distance biomass recovery, chipping at the delivery site resulted in lower overall costs than roadside chipping.

ARTICLE INFO

ABSTRACT

Wildfire fuel-reduction treatments in British Columbia (BC) generate large volumes of underutilized biomass. This study assesses the technical suitability and supply chain economics of using biomass from thinning and surface fuel reduction for small-scale combined heat and power (CHP) systems. Biomass availability, including non-delimbed and delimbed energy wood, residues, and surface woody debris, was evaluated in a 12-ha forest stand in the interior of BC, Canada. Woodchip quality was analyzed for particle size distribution, ash content, moisture content, and bulk density. Supply chain costs were estimated for multiple recovery methods, machinery scales, and chipping locations, considering specific treatment options. Results showed that one year of natural air drying enabled non-delimbed and delimbed energy wood to meet CHP system requirements for particle size and ash content, whereas residues and woody debris required targeted post-processing. Supply chain costs ranged from $175-426 per oven-dry tonne, driven primarily by transportation distance and treatment intensity. These findings demonstrate that fuel-reduction biomass can support small-scale CHP system operations when feedstock is locally sourced and of sufficient quality. Integrating energy production with higher-value product streams may provide a practical approach to cost-effective biomass utilization while contributing to wildfire risk mitigation, local energy security, and the regional bioeconomy. This study offers a transferable framework for evaluating operational feasibility and supply chain design in other fire-prone regions.

1. Introduction

Thinning and surface fuel reduction are recognized as effective wildfire mitigation strategies across western North America (Hessburg et al., 2025). In British Columbia (BC), Canada, their effectiveness has been evaluated and recognized from regulatory and governance perspectives (LMFRS, 2020; FPB, 2010), and these measures have been incorporated into local and provincial wildfire risk management guidance (BCWS & MOF, 2024; Day et al., 2010). Implemented primarily with heavy equipment, these treatments reduce hazard potential across parts of western North America (Huggett et al., 2008), with empirical evidence demonstrating reductions in wildfire intensity and severity (Brodie et al., 2024). Low-quality biomass is an established feedstock for combustion-based heat-only and combined heat and power (CHP) bioenergy systems, as demonstrated in mechanized harvesting systems

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(Röser et al., 2011b), national forest energy practice (Routa et al., 2013), and forest fuel supply chain literature (Wolfsmayr and Rauch, 2014), but in BC, limited demand and low market values mean recovered biomass rarely offsets high treatment costs, especially in remote, difficult-to-access areas. Even with support from programs such as the FireSmart Community Funding and Supports initiative (BCWS, 2025a), treatment residues are rarely recovered and are usually burned as slash piles, as reflected in provincial policy guidance (BCFLNRORD, 2020) and operational studies (Spencer and Röser, 2017). This practice leads to the loss of recoverable biomass (Nance, 2023) and produces a considerable amount of greenhouse gas emissions (BCECS, 2024). Fuel treatment progress in the wildland–urban interface, where human settlements adjoin flammable vegetation, has been slow. Many remote Indigenous communities are located in these high-risk areas (Johnston and Flannigan, 2018), a vulnerability repeatedly highlighted by wildfire history and seasonal summaries (BCWS, 2025b; BCWS & MOF, 2024) as well as governance reviews documenting persistent gaps in mitigation implementation (FPB, 2010, 2015), making the lack of implementation particularly pressing.

The underutilization of treatment residues underscores both a missed opportunity for emissions reduction and a need to strengthen resource recovery. Recognizing their biomass value could partially offset treatment costs through additional bioenergy value, encouraging wider implementation of wildfire mitigation strategies. At the same time, wildfires and pest outbreaks have reduced harvestable timber volumes (BCFLNRORD, 2018; BCFOR, 2024, 2025), increasing vulnerability of regional fiber supply. In this context, residues from fuel treatments represent an available fiber source that can enhance the supply resilience to natural disturbances without relying on conventional harvesting allocations (Forest and Range Practices Act, 2002). Moreover, diverting residues from slash burning as low-carbon feedstock can substitute for fossil fuels and contribute to BC's climate and bioeconomy goals (BC, 2021). Since the energy crisis in the 1970s, forest biomass has regained attention globally as an independent and renewable energy source (Lunnan et al., 2008). In the European Union (EU), forest biomass, including roundwood, logging residues, industrial by-products, and post-consumer recovered wood, constitutes a major share of renewable energy consumption, accounting for 61.8% in 2016 (Camia et al., 2021; Popp et al., 2021). This extensive utilization is largely driven by district heating and CHP systems, which play a central role in EU heat decarbonization (Connolly et al., 2014) and serve as key end-user sectors for forest biomass, particularly in Nordic countries (Röser, 2012). These European experiences demonstrate the viability of integrating recovered forest biomass into local energy systems.

Unlocking this potential in BC requires a practical understanding of how residues can be efficiently recovered and delivered. Scenario-based supply chain cost analyses of energy wood procurement from early thinning commonly vary in recovery methods, with non-delimbed and delimbed energy wood recovery representing the most frequently studied options (e.g., Ahtikoski et al., 2021; Kärhä, 2011; Karttunen et al., 2016; Laitila et al., 2010; Schweier et al., 2018; Spinelli et al., 2014). Scenario parameters vary across studies and include stand structure and harvested stem volume (Ahtikoski et al., 2021; Kärhä, 2011; Laitila et al., 2010; Karttunen et al., 2016), the level of mechanisation in small-scale or access-limited thinning operations (Schweier et al., 2018; Spinelli et al., 2014), and transportation distance (Karttunen et al., 2016). While these studies provide insights into cost performance associated with the two recovery methods, logistical decisions constitute an additional determinant of overall efficiency and cost-effectiveness of the supply chain (Wolfsmayr and Rauch, 2014). Prior studies further demonstrate how recovery costs respond to the choice of biomass drying and chipping location, including forest roadside, centralized terminals, and bioenergy facilities (Ranta and Rinne, 2006; Röser et al., 2011b).

Previous studies on energy wood procurement have quantified cost components and logistics tradeoffs for merchantable residues under the condition of stable feedstock, but they do not capture operational challenges associated with wildfire fuel treatment residues in small-scale CHP systems in BC. In the remote communities, which represent key target areas for fuel treatment, gasification-based small-scale CHP systems are more suitable than medium- or large-scale CHP technologies because their small, distributed configuration can match limited heat and power demand and locally available biomass supplies. Such systems typically achieve electrical efficiencies of 23–30% and thermal efficiencies of 47–55%, however, their performance is highly sensitive to both feedstock quality and locally constrained logistics (Schilling et al., 2025a). Reliable operation requires feedstock with low ash content, low moisture, and uniform particle size. These requirements are more difficult to meet with fuel treatment residues, which tends to be heterogeneous and contaminated with soil and bark. This sensitivity is particularly relevant for smaller-scale CHP systems, which operate with narrower thermal and mechanical tolerance, limited fuel blending capacity and higher maintenance cost per unit of energy output, making them less able to absorb variability in feedstock quality (Marinescu, 2013; Moskalik and Gendek, 2019; Röser, 2012; Schilling et al., 2017). Inadequate quality lowers conversion efficiency and increases maintenance frequency, ultimately raising operating costs. Particle-size inconsistency disrupts gasification stability. High moisture increases drying energy demand, depresses reactor temperatures, and reduces syngas quality. Moreover, elevated ash levels from contaminants contribute to slagging (Schilling et al., 2025a). These sensitivities necessitate strict control of feedstock quality.

Despite a growing interest in small-scale CHP systems, few studies have assessed the feasibility of utilizing fuel treatment residues in BC through an integrated analysis of biomass quality and supply chain costs. Most biomass procurement studies originate from Nordic and Central European contexts, where harvesting performance is strongly conditioned by species composition (Chakroun et al., 2016), terrain slope (Cadei et al., 2020), and operator practices (Kärhä et al., 2004). Due to different stand structures, steeper terrain (Mologni et al., 2018), and limited operational experience associated with fuel treatment in the region, the cost results are often difficult to transfer directly. In addition, land tenure constraints and lower competitive energy prices in BC (BC Hydro, 2025; FortisBC, 2025) further compress economic margins and introduce uncertainty in supply chain feasibility. The absence of a mature energy-wood market also places greater responsibility for feedstock quality control at the local supply chain level rather than at dedicated fuel terminals, and the demanding fuel specifications of small-scale CHP systems introduce an additional layer of technical uncertainty when relying on fuel treatment residues. Schilling et al.

(2025a, 2025b) evaluated a biomass gasification CHP system in a remote Indigenous community in BC, with attention to sustainability and operational considerations. While informative, these studies did not investigate the relationship between biomass quality attributes and the cost dynamics of supply chain costs, which remains largely under-examined in the current literature.

This study addresses that gap by evaluating the technical suitability of fuel-reduction biomass and the associated supply chain costs. The biomass sources assessed include non-delimbed and delimbed energy wood, harvesting residues, and surface woody debris. For each source, various supply chain configurations are evaluated, and costs are estimated based on local rates for felling, transportation, and chipping. Both conventional and small-scale machinery are considered, with different chipping locations evaluated. The novelty of the study lies in integrating wildfire fuel-reduction biomass, small-scale CHP system requirements, and regional-specific operational cost data into a unified supply chain

assessment. In addition, biomass supply chain costs were converted into equivalent energy costs under consistent assumptions of fuel heating value and the CHP system efficiency to support economic comparison with other local energy options. The objective is to identify cost-effective supply chain options under BC conditions and to establish a transferable framework for other fire-prone regions.

2. Methodology

Biomass load was estimated through field sampling and calculation, biomass quality through field sampling and laboratory analysis, and supply chain costs through theoretical estimation. Stand-level load under different fuel treatment options was first used to estimate potential availability, which was then refined using quality results to determine the useable fraction for the small-scale CHP system. These useable load estimates subsequently informed the supply chain cost

Fig. 1. Zoning map of the Alex Fraser Research Forest (AFRF) property showing the 27 designated sampling plots.

analysis. While methodologically distinct, these steps were implemented sequentially under consistent assumptions to enable integrated interpretation.

2.1. Study site

The study was conducted at the University of British Columbia's Alex Fraser Research Forest (AFRF) in Williams Lake, BC (52.17° N, 122.07° W; Fig. 1). It lies within the Interior Douglas-fir biogeoclimatic ecosystem zone, characterized by a dry, warm interior climate dominated by interior Douglas-fir (*Pseudotsuga menziesii var. glauca*) (BCFLNRO, 2016). The site encompasses 22.3 ha and it is located within the wildland-urban interface of timber supply area 29 (BCWS, 2023), where forested land and human development overlap, resulting in elevated wildfire risk. Consequently, the 12-ha forest is designated for wildfire fuel-reduction treatment. The AFRF property includes several facilities including an administrative office, an accommodation facility, a storage shed, and livestock barns. Together these facilities generate only modest energy demand. The site was selected for the installation of a CHP unit as part of a pilot initiative. The CHP system was not installed to meet critical local energy needs but to demonstrate technical feasibility and evaluate the potential applicability of small-scale bioenergy systems in remote communities across BC.

2.2. Available biomass load estimation

Biomass load data were sampled during two field campaigns (December 2023 and April 2024), using a systematic sampling design with a density of two plots per hectare. A total of 27 sampling plots were distributed across the 12.2-ha forested area (Fig. 1). Standing trees were sampled using variable-radius plots (prism, basal area factor BAF) = 4 m^2/ha) for diameter at breast height (DBH, i.e., diameter at 1.3 m above ground level) over 12.5 cm and fixed-area plots (radius = 3.99 m) for DBH 5–12.5 cm. Recorded tree attributes included species, DBH (cm), height (m), live or dead status, and qualitative remarks such as disease, pest, or defects. Woody debris was sampled using the line-intersect method (Wagner, 1968) along a slope-corrected 30-m transect centered at each plot and oriented along a random azimuth. All woody debris intersecting the transect with diameter ≥5 cm and decomposition class 1–3 (Maser et al., 1979) was recorded by species and diameter. These criteria represent relatively large, solid, and structurally intact pieces that fall within the grapple extraction limits of common machinery and are considered optimal for feedstock.

Three potential treatment options were assessed for biomass availability and composition (Table 1). The wildfire risk reduction prescription recommended a residual stand density of 200 stems/ha (LMFRS, 2020), while local expert guidance suggested that retaining 500 stems/ha may reduce windthrow risk. In addition, conserving deciduous species may help regulate stand temperature. However, at a target residual density of 200 stems/ha, full retention of these species would substantially increase the proportion within the remaining stand. Given their lower economic potential and the resulting preference for early-stage removal, such retention is less feasible than under the 500

Table 1
Overview of the three fuel treatment options, defined by target residual stand density, and the proportion of deciduous tree removal. RSD200: residual stand density (RSD) of 200 stems/ha with 100% deciduous removal; RSD500: residual stand density of 500 stems/ha with 100% deciduous removal; RSD500HW: residual stand density of 500 stems/ha with 0% deciduous removal (i.e., all hardwood (HW) species were retained).

Treatment options label	Residual stand density (stems/ha)	Deciduous removal
RSD200	200	100%
RSD500	500	100%
RSD500HW	500	0%

stems/ha scenarios. Accordingly, three fuel treatment objectives were defined: two scenarios with a residual density of 500 stems/ha, involving either full removal or full retention of deciduous species, and one scenario with a residual density of 200 stems/ha with full retention of deciduous species.

Biomass calculations were performed at the plot level for both standing trees and woody debris, considering the presence of the following species: interior Douglas-fir (*Pseudotsuga menziesii var. glauca*), lodgepole pine (*Pinus contorta*), hybrid spruce (*Picea engelmannii × glauca*), and deciduous species, primarily trembling aspen (*Populus tremuloides*). For standing trees, individual tree biomass was estimated with a 30-cm stump height subtracted from total height (BCMoF, 2009). Stem volumes were calculated using the Whole Stem Cubic Metre Volume Equations from the *Forest Handbook for British Columbia* (Marshall and LeMay 2005) and Kozak's taper equation (1988), and converted to oven-dry tonnes (ODT) using species-specific wood densities (FPL, 2010; NW, 2024). The corresponding residual biomass components, including bark, branches, and foliage, were estimated using Canadian biomass equations for BC forest species (Ung et al., 2008). For woody debris, biomass per unit area (ODT/ha) was calculated using equations from Wagner (1982), with transect lengths adjusted for slope according to Brown (1974). Plot level values were summed and averaged to project stand-level biomass availability. Final results were expressed in oven-dry tonnes per hectare (ODT/ha), disaggregated by component, and scaled to the mapped forested area through the Sample Data Compilation Process (BCMoF, 2009). To simulate the fuel treatments, smaller-diameter trees were prioritized for removal to meet the objectives, and the amount of woody debris was kept consistent across all options.

2.3. Biomass sampling for quality assessment

At the study site, several options were identified in accordance with availability estimation targets for utilizing fuel-reduction biomass as feedstock for the CHP system. Biomass can be recovered and used either in a green state or left onsite to air-dry for one year before use. Recovery methods included non-delimbed whole trees (stems, bark, tops, branches, and foliage), delimbed trees (stems, bark, and tops), or residues (consisting of only tops, branches, and foliage). In addition, surface woody debris can be collected and chipped. Woodchips derived from these different sources were expected to exhibit different quality attributes in ash content, moisture content, particle size distribution, and bulk density. In total, seven biomass source options were sampled (Table 2).

Woody debris was assumed to have air-dried for over one year before sampling. Green delimbed energy wood (Dlm$_{grn}$), green non-delimbed energy wood (Ndlm$_{grn}$), and green residues (Res$_{grn}$) constituted the green biomass group and were sampled within one week of extraction. One-year-dried delimbed energy wood (Dlm$_{dry}$), one-year-dried non-delimbed energy wood (Ndlm$_{dry}$), and one-year-dried residues (Res$_{dry}$)

Table 2
Biomass source options.

Biomass source label	Drying state	Recovery method	Included components
Ndlm$_{grn}$	Green	Non-delimbed	Whole tree (stems, bark, tops, branches, foliage)
Dlm$_{grn}$	Green	Delimbed	Stems, bark, tops
Res$_{grn}$	Green	Residues	Tops, branches, foliage
Ndlm$_{dry}$	One-year air-dried	Non-delimbed	Whole tree but complete foliage loss during air-drying
Dlm$_{dry}$	One-year air-dried	Delimbed	Stems, bark, tops
Res$_{dry}$	One-year air-dried	Residues	Tops, branches, foliage (with partial loss during air-drying)
Woody debris	One-year air-dried	Woody debris	Naturally fallen deadwood on the forest floor

formed the one-year-dried biomass group.

Given the limited volume of woodchips available from the one-year-dried biomass sources (i.e., sources $Ndlm_{dry}$, Dlm_{dry}, and Res_{dry}), the total sampling volume for each biomass source was standardized to 1000 L to maintain consistency. The number of sample replicates, sample sizes, and the sequential analysis procedures were designed in accordance with ISO standards (CEN, 2011; ISO, 2015a, 2015b, 2016, 2017, 2022). Each biomass source provided a standardized 1000 L lot, which was divided into five 200 L sub-lots. Subsamples were then extracted with sample sizes for each analysis: 50 L for bulk density, 10 L for moisture content, 10 L for particle size distribution, and 1 g for ash content. The procedure flow (Fig. 2) was deliberately structured to allow multiple analyses on the same sample without cross-interference and, whenever possible, with preceding steps supporting subsequent ones. For instance, moisture content was measured before size distribution because its calculation required both wet and oven-dry weights. The resulting oven-dried wood chips were then used for size distribution, where dry material was preferred for greater precision (ISO, 2016). All sampling and subsampling procedures were conducted in strict accordance with the prescribed standards (CEN, 2011; ISO, 2017).

2.4. Combined heat and power system

The installed CHP system is a Volter 40 model (40 kW electrical and 100 kW thermal) operating in continuous mode. It employs a downdraft gasifier coupled with an internal combustion engine, where woodchips are converted into producer gas in the reactor, followed by gas cooling, filtering, and combustion for power and heat generation (Volter Oy, 2018). It is intended for distributed off-grid applications in remote communities, and has been shown to deliver relatively low cost and high energy efficiency (Schilling et al., 2017).

The system is designed to use clean, uniform woodchips, with an ideal moisture content under 15% (maximum 18%). Fuel specifications require chips smaller than 63 mm, with 80% between 8 and 30 mm and less than 1% fine particles (<3.15 mm). Acceptable ash content is 1–2%

(Volter Oy, 2018).

2.5. Quality assessment

The quality assessment was structured to evaluate physical quality attributes of woodchips that determine the suitability of biomass for small-scale gasification-based CHP systems. Specifically, the assessment considered bulk density, moisture content, particle-size distribution, and ash content.

Bulk density was measured on an "as received" basis in accordance with ISO 17828:2015 (2015a). The measurement involved using a container of known volume, into which the woodchips were filled and weighed, and the bulk density was calculated using Equation [1].

$$Bulk\ Density_{as\ received} = \frac{Mass_{woodchips}}{Volume_{container}} \qquad [1]$$

Moisture content was determined in accordance with ISO 18134-1:2015 (2015b) by oven-drying the samples at 105 °C for 24 h, followed by calculation of the moisture percentage by dividing the weight loss by the initial wet weight, as shown in Equation [2].

$$Moisture\ Content = \frac{Mass_{wet} - Mass_{dry}}{Mass_{wet}} \times 100\% \qquad [2]$$

where $Mass_{wet}$ denotes the mass of wet woodchip in g, $Mass_{dry}$ denotes the mass of dry woodchip.

Particle size distribution was determined in accordance with ISO 17827-1:2016 (2016) using an oscillating round-hole chip-size classifier (Retsch AS 400 control horizontal sieve shaker) equipped with sieves of 3.15 mm, 8 mm, 16 mm, 31.5 mm, and 45 mm. The proportion of woodchips within each size class was calculated using Equation [3].

$$Size\ Distribution_{s\in S} = \frac{Mass_s}{Mass_{total}} \times 100\% \qquad [3]$$

where size distribution$_s$ is the percentage of dry woodchip mass ($Mass_s$) that is within the *size interval s,* with $S = \{\leq$3.15 mm, 3.15–8 mm, 8–16
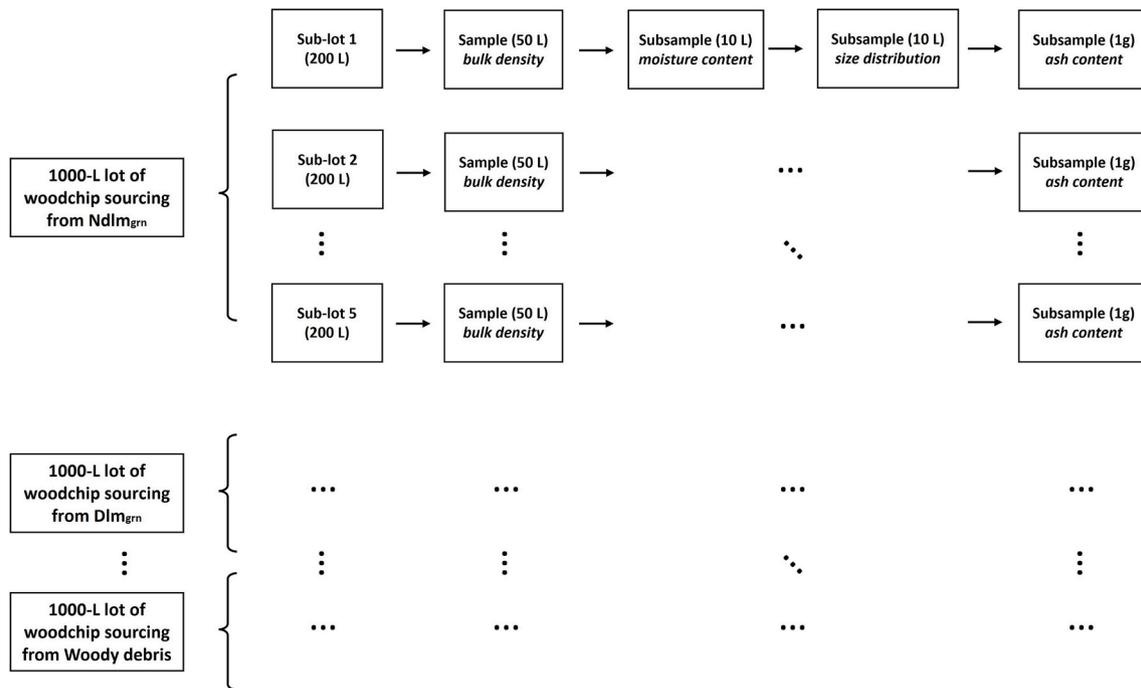
Fig. 2. Schematic diagram of the sequential analysis procedures for biomass quality assessment, including the required sample sizes for each quality attribute. Ellipses (three dots, " …") denote sampling procedures processed in the same way as the other sub-lots or biomass sources. Specifically, for each of the seven biomass sources ($Ndlm_{grn}$, Dlm_{grn}, Res_{grn}, $Ndlm_{dry}$, Dlm_{dry}, Res_{dry}, Woody debris), five sub-lots were sampled. Each sub-lot followed the same sampling sequence, namely bulk density, moisture content, particle size distribution, and ash content.

mm, 16–31.5 mm, 31.5–45 mm, >45 mm}. $Mass_{total}$ denotes the mass of total dry woodchip.

Ash content was analyzed in accordance with ISO 18122:2022 (2022). Samples were milled using a cutting mill (Retsch SM 100) to a nominal top size of 1 mm. Approximately 1 g of each sample was placed in a furnace and incinerated at 550 °C for a minimum of 2 h. Ash content was calculated using Equation [4].

$$Ash\ Content = \frac{Mass_{ash}}{Mass_{woodchips}} \times 100\% \qquad [4]$$

Furthermore, two-sample t-tests (assuming unequal variances) were performed to assess significant differences in moisture content and fine particle distribution between one-year-dried and green biomass sources.

2.6. Biomass supply chain cost analysis

Costs were analyzed for the 12.2 ha treatment area across the biomass supply chain, from stand-level operations to delivery at the CHP facility, including felling, primary transportation, chipping, and secondary transportation. Multiple supply chain configurations were developed based on technical feasibility and operational compatibility across recovery methods, and categorized as either conventional or small-scale systems based on the machinery size used for felling and primary transportation (Table 3). To assess the influence of chipping location on overall cost, each configuration was duplicated to represent two operational scenarios: storage-site chipping and roadside chipping (Fig. 3). Skidding/forwarding trails were laid out following provincial guidance (BCFLNRORD, 2021) and professional judgment, based on two criteria: 5-m-wide trails and 15-m-wide thinning corridors, and large turning-angles for fully loaded machines. Due to wildlife-fencing constraints, minimizing travel distance was not prioritized, but the layouts were considered operationally appropriate. This resulted in a total of 12 configurations for non-delimbed and 6 for delimbed energy wood recovery. The purpose of this duplication was to evaluate cost dynamics related to variations in skidding/forwarding trail distances and the additional use of tractors for woodchip transport. The cost analysis for chipping and secondary transportation was based on a Junkkari HJ 252 chipper and a PALMS 3.67 crane, both PTO-powered by separate farm tractors, and a pickup truck with a five-tonne towing capacity pulling a bin trailer. The transportation from the storage site to the CHP unit was assumed cost-trivial, with biomass conveyed internally by a screw system. In addition, biomass recovery from fuel treatments was assumed to occur as a one-time operation. Although temporal gaps may exist between individual recovery stages, harvesting activities were considered to be carried out consecutively within a single operational cycle.

Productivity values for felling and primary transportation were compiled from an extensive literature review on small-diameter tree harvesting in fuel-reduction treatments and first thinning, and were based on input parameters such as average stem size, DBH, green density, and extraction distance (Tables A-1 and A-2). Extraction distances were estimated from the skidding/forwarding trail layout by manually enumerating round-trip collection routes and calculating average distances, assuming an even spatial distribution of recovered biomass (Fig. 3). Chipping productivity was estimated based on the operator's experience. The productivities were assumed to be 8 m^3 per scheduled machine hour (m^3/SMH) for non-delimbed energy wood chipping and 12 m^3/SMH for delimbed wood chipping, falling within the specification range (Junkkari Oy, 2024). Secondary transportation productivity was calculated by dividing the total delivered woodchips by the corresponding time consumed. Moisture content measurements were applied to the woodchips to estimate the number of payloads required under a transportation capacity of five tonnes per trip, assuming no volumetric constraint. For each payload, round-trip travel (approximately 286 m) and unloading were each assigned a fixed time of 0.17 SMH (10 min), while loading time was determined by chipping performance at the specified transportation capacity.

Hourly operating rates were selected to be current and locally relevant to BC (Table A-3) and adjusted to reflect regional market conditions. For machines not commonly used in the province and lacking direct cost data, rates were estimated using comparable base machines or attachments. All hourly rates were considered all-inclusive, covering ownership, operation, and labor costs.

Both productivity and hourly operating rates were standardized to SMH. If productivity figures were originally reported as delay-free productive machine hours (PMH$_0$) or productive machine hours with delays up to 15 min (PMH$_{15}$), they were converted to SMH using Equations (5) and (6) (Cadei et al., 2020; Holzleitner et al., 2018; Spinelli and Visser, 2008; Stampfer, 1999).

$$Productivity\ (SMH) = Productivity\ (PMH_{15}) / 0.711 \qquad [5]$$

$$Productivity\ (PMH_{15}) = Productivity\ (PMH_0) / 1.3 \qquad [6]$$

where *Productivity (SMH)* denotes the productivity at scheduled machine hours, productivity (PMH$_{15}$) denotes the productivity at productive machine hours with delays up to 15 min, and productivity (PMH$_0$) denotes the productivity at delay-free productive machine hours.

Unit cost refers to the cost associated with delivering one unit of biomass from the 12.2 ha treatment area to the CHP system. For each supply chain configuration in Table 3, costs were calculated for different fuel treatment options (RSD200, RSD500, RSD500HW) using Equations (7) and (8).

Table 3
Supply chain configurations.

| Supply chain label	Recovery method	Felling	Primary transportation	Chipping location	Secondary transportation
N-FBc-SKc-C	Non-delimbed	Conventional Feller-Buncher	Conventional Grapple Skidder	Storage site	-
N-FBc-SKc-C-T	Non-delimbed	Conventional Feller-Buncher	Conventional Grapple Skidder	Roadside	Woodchip Truck
N-FBs-FWt-C	Non-delimbed	Small-scaled Feller-Buncher	Farm Tractor Pulled Forwarding Trailer	Storage site	-
N-FBs-FWt-C-T	Non-delimbed	Small-scaled Feller-Buncher	Farm Tractor Pulled Forwarding Trailer	Roadside	Woodchip Truck
N-MF-FWc-C	Non-delimbed	Motor-manual Felling	Conventional Forwarder	Storage site	-
N-MF-FWc-C-T	Non-delimbed	Motor-manual Felling	Conventional Forwarder	Roadside	Woodchip Truck
N-MF-FWt-C	Non-delimbed	Motor-manual Felling	Farm Tractor Pulled Forwarding Trailer	Storage site	-
N-MF-FWt-C-T	Non-delimbed	Motor-manual Felling	Farm Tractor Pulled Forwarding Trailer	Roadside	Woodchip Truck
N-HVc-FWc-C	Non-delimbed	Conventional Harvester	Conventional Forwarder	Storage site	-
N-HVc-FWc-C-T	Non-delimbed	Conventional Harvester	Conventional Forwarder	Roadside	Woodchip Truck
N-HVs-FWs-C	Non-delimbed	Small-scaled Harvester	Small-scaled Forwarder	Storage site	-
N-HVs-FWs-C-T	Non-delimbed	Small-scaled Harvester	Small-scaled Forwarder	Roadside	Woodchip Truck
D-HVc-FWc-C	Delimbed	Conventional Harvester	Conventional Forwarder	Storage site	-
D-HVc-FWc-C-T	Delimbed	Conventional Harvester	Conventional Forwarder	Roadside	Woodchip Truck
D-HVs-FWs-C	Delimbed	Small-scaled Harvester	Small-scaled Forwarder	Storage site	-
D-HVs-FWs-C-T	Delimbed	Small-scaled Harvester	Small-scaled Forwarder	Roadside	Woodchip Truck
D-HVs-FWt-C	Delimbed	Small-scaled Harvester	Farm Tractor Pulled Forwarding Trailer	Storage site	-
D-HVs-FWt-C-T	Delimbed	Small-scaled Harvester	Farm Tractor Pulled Forwarding Trailer	Roadside	Woodchip Truck
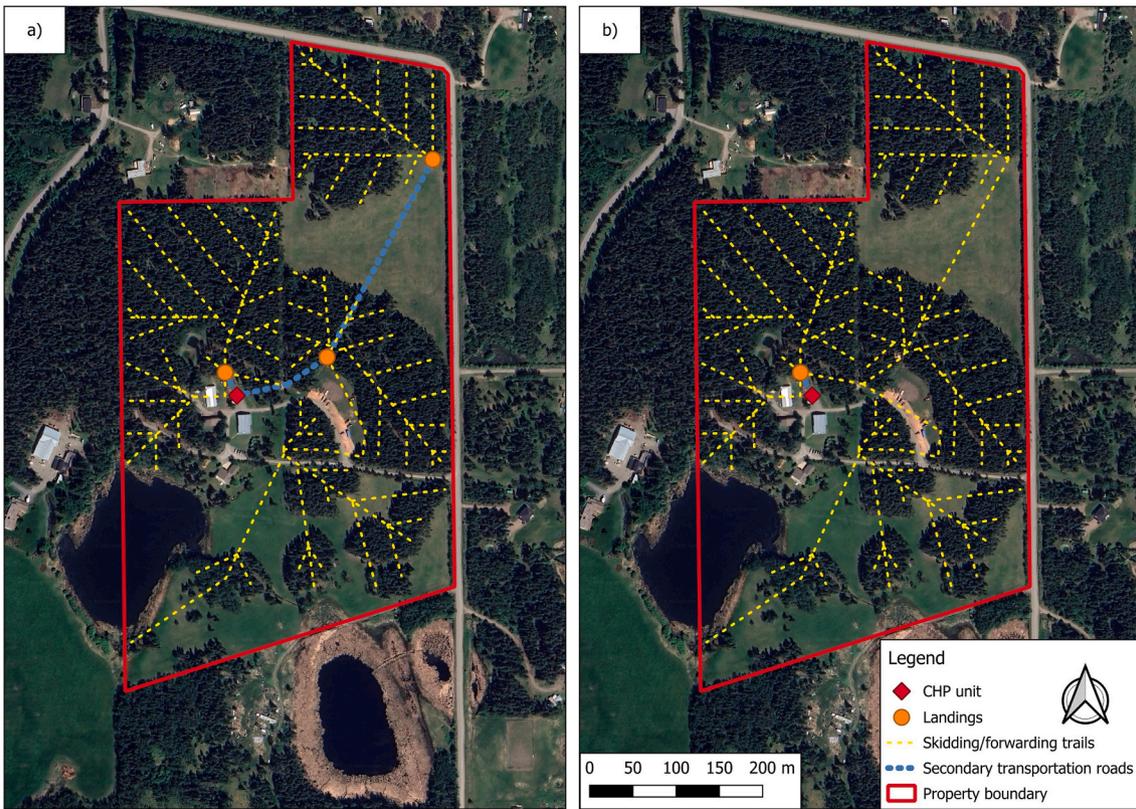
Fig. 3. (a) Layout of skidding/forwarding trails and secondary transportation roads for the roadside chipping scenarios; (b) Layout of skidding/forwarding trails and secondary transportation roads for the storage-site chipping scenarios.

$$T_{i.j.k(m)} = \frac{Biomass\ Processed_{i.j.k}}{Productivity_{k(m)}} \qquad [7]$$

$$Supply\ Chain\ Unit\ Cost_{i,j} = \sum_{k \in K} \frac{Machine\ Operating\ Rate_{k(m)} \times T_{i.j.k(m)}}{Biomass\ Delivered_{i.j}} \qquad [8]$$

where $T_{i.j.k}$ is the SMH required for *Machine m* to process biomass at *Stage k*, with *K = {Felling, Primary Transportation, Chipping, or Secondary Transportation}*, under *Supply Chain Configuration i* (Table 3) and *Fuel Treatment Option j* (RSD200, RSD500, or RSD500HW); *Machine Operating Rate_m* is the hourly cost rate for *Machine m* (Table A-3); *Supply Chain Unit Cost_{i,j}* is the supply chain cost per unit of biomass delivered to the CHP

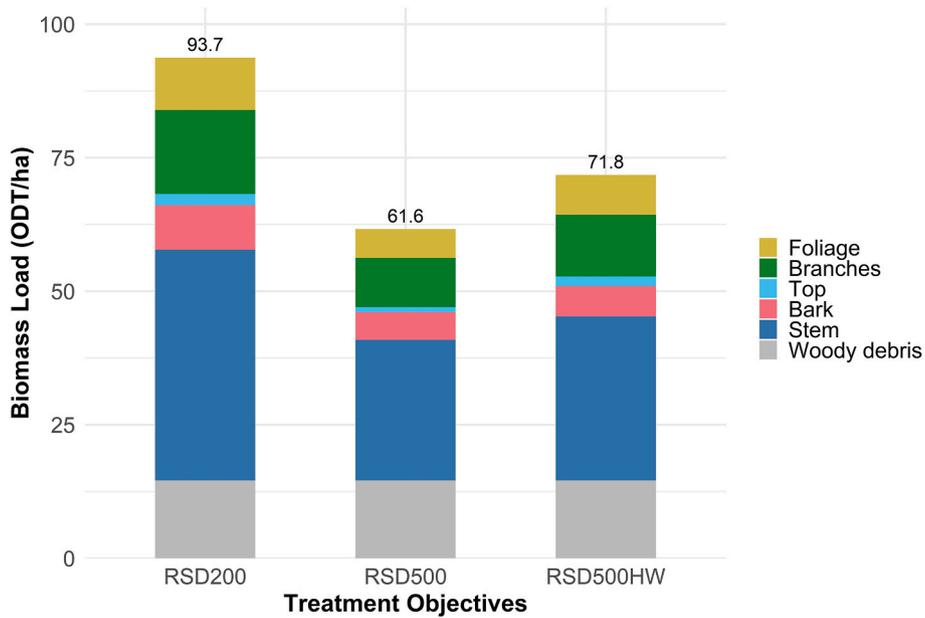**Fig. 4.** Biomass availability by component and sources (foliage, branches, top, bark, stem, and woody debris) across three treatment options, reported in oven-dry tonnes per hectare (ODT/ha). RSD200: residual stand density of 200 stems/ha with 100% deciduous removal. RSD500: residual stand density of 500 stems/ha with 100% deciduous removal. RSD500HW: residual stand density of 500 stems/ha with 0% deciduous removal.

system ($/ODT). *Biomass Processed*$_{i,j,k}$ is the amount of biomass processed at *Stage k* which may differ from *Biomass Delivered*$_{i,j}$ to the CHP system due to, for example, storage and handling losses.

3. Results

3.1. Biomass load

Biomass loads for the three treatment options are presented in Fig. 4, with corresponding detailed values provided in Table A-4. The results are disaggregated into biomass contributions from multiple tree components as well as woody debris. Woody debris remained consistent across the three treatments. Biomass availability was the highest under the treatment that retained 200 stems/ha (RSD200), reaching 93.7 ODT/ha, compared to 61.6 ODT/ha under RSD500. Biomass load under RSD500HW (hardwood retained) was intermediate (71.8 ODT/ha) and higher than RSD500. This is because to achieve the same treatment objective of 500 stems/ha through thinning from below, retaining hardwoods required additional removal of an equivalent number of interior Douglas-fir trees, which had larger individual tree volumes.

3.2. Feedstock quality

Among the green biomass sources, Dlm$_{grn}$ produced the lowest proportion of fine particles, followed by Ndlm$_{grn}$, while Res$_{grn}$ generated the highest (Fig. 5, with detailed values available in Table A-5). Because the proportions of fine and medium-sized particles are inversely related, the ranking for medium-sized particles showed the opposite trend (Dlm$_{grn}$ > Ndlm$_{grn}$ > Res$_{grn}$). In the one-year-dried samples, however, the ranking shifted (Ndlm$_{dry}$ > Dlm$_{dry}$ > Res$_{dry}$ for medians). This likely reflects the role of foliage, because leaves and small twigs were fragmented into small particles through chipping. As foliage was lost during air-drying, the generation of fine particles decreased and the proportion of medium-sized particles increased (Table 2). This interpretation is supported by statistical comparisons of fine particle distribution (t-tests in Table A-6): Dlm$_{dry}$ and Ndlm$_{dry}$ (not significantly different), Dlm$_{grn}$ and Dlm$_{dry}$ (not significantly different), Ndlm$_{grn}$ and Ndlm$_{dry}$ (significantly lower after air-drying), and Res$_{grn}$ and Res$_{dry}$ (significantly lower after air-drying). In contrast, woodchips from woody debris showed slightly more fine particles than Ndlm$_{dry}$ despite the absence of foliage, likely resulting from chipping of decomposed material.

Only woodchips from Dlm$_{grn}$, Dlm$_{dry}$, and Ndlm$_{dry}$ demonstrated overall particle size distributions that aligned reasonably well with the quality thresholds, with IQR falling largely within acceptable limits. The median proportions of fine particles ($\leq$3.15 mm) for these three sources were 0.63%, 0.73%, and 0.77%, respectively, while the corresponding medians for the 8–31.5 mm fraction were 84.02%, 79.73%, and 85.38%.

All biomass sources met the ash content requirement, ranging from 0.25% to 1.90%, with higher values observed in samples containing foliage. In general, ash content varied in accordance with fine particle proportion, except in woody debris, which had fine proportions similar to Ndlm$_{grn}$ and Res$_{dry}$ but lower ash content. This difference arises because, in addition to soil contaminants, fine particles in woody debris were mainly wood dust, whereas foliage had larger concentrations of micronutrients, leading to higher ash content.

None of the woodchip samples had moisture content below the 18% threshold. As expected, the green biomass samples exhibited higher moisture levels, with medians between 34.60% and 42.02%, while one-year-dried samples had significantly lower moisture content, with medians between 20.97% and 28.45% (Table A-7). Biomass air-dried more efficiently when foliage and branches were present. After one year of air drying, moisture content decreased by 15% in Ndlm and 20% in Res, compared with only 6% in Dlm.

Bulk density varied in accordance with the proportion of fine particles. A higher share of fine particles fills void spaces and raises bulk density. Moisture content also has a strong effect. Woodchips with

higher moisture levels contain more mass per unit volume, which raises bulk density on an as-received basis. This extra mass does not add to useable biomass yield and lowers conversion efficiency. Bulk density is not a requirement for the CHP system, but it is important for supply chain analysis and comparison.

3.3. Supply chain cost

Ndlm$_{dry}$ and Dlm$_{dry}$ emerged as the most suitable feedstock, with particle size and ash content consistently within acceptable limits. Supply chain costs were therefore calculated based on the availability of these two feedstocks. Their corresponding availability were 69.38 and 53.65 ODT/ha under RSD200, 41.67 and 32.46 under RSD500, and 49.76 and 38.20 under RSD500HW (Tables 2 and A-4, Fig. 5).

The overall supply chain unit cost ranged from $175/ODT (N-FBc-SKc-C, RSD200) to $426/ODT (N-MF-FWt-C-T, RSD500) (Fig. 6, with detailed values available in Table A-8). Supply chain configurations with roadside chipping and secondary transportation (suffix -C-T) were more expensive than their storage-site chipping counterparts (suffix -C). While roadside chipping lowered primary transport (yellow bars) through shorter extraction distances, the added cost of secondary transport (purple bars) offset this benefit, resulting in $74-97/ODT higher costs. Non-delimed material (prefix N-) chipped at $126 per ODT, and delimbed energy wood (prefix D-) at $113 per ODT (green bars). Primary transportation (yellow bars) dominated the cost differences among supply chain configurations. Forwarding non-delimbed wood was more expensive than delimbed wood due to limited load per cycle. Configurations with conventional machines (-SKc-, -FWc-) were more efficient despite higher hourly cost, and they performed better when paired with mechanized felling (-FBc-, -FBs-, -HVc- or -HVs-) than motor-manual felling (-MF-). When trees were felled without delimbing, skidders (-SKc-) outperformed forwarders (-FWc- and -FWs-) of the same scale because their shorter loading time provided an advantage at short extraction distances.

Felling (blue bars) contributed the least to overall supply chain unit costs and varied little across different supply chain configurations. They were generally lower with small-scale harvesters, highlighting the cost-efficiency in fuel-reduction treatments. Unit costs of felling in delimbed recovery were generally higher, due to the additional time required for delimbing and the reduced biomass yield from branch and foliage removal. Under the same supply chain configuration, unit costs of felling decreased with higher treatment intensity because productivity improved with larger tree volume. This effect was less evident in the N-HVs configuration because the average piece size, which is the key parameter used to estimate productivity, showed very little variation across the treatment objectives. In contrast, despite similar productivity variation in D-HVs-, lower recovery rates significantly amplified unit cost differences.

4. Discussion

4.1. Fuel-reduction Biomass's suitability for CHP systems

Fine particle distribution in green biomass sources followed foliage content, consistent with earlier studies showing that leaves and twigs fragment into fine particles during chipping (Nati et al., 2010; Spinelli et al., 2011). After one year of natural drying, foliage loss reduced small fragments and increased the share of medium-sized particles in non-delimbed wood, confirming the role of foliage in particle generation (Nurmi, 1999). In contrast, residues retained some foliage, likely due to reduced exposure inside the piles, while woody debris produced excess fine particles because decomposition weakened wood structure. These findings confirm that both foliage content and drying conditions strongly influence chip size quality. Medium-sized particles are the most desirable fraction for combustion. Their inverse relationship with fine particles explains much of the observed variation among sources.
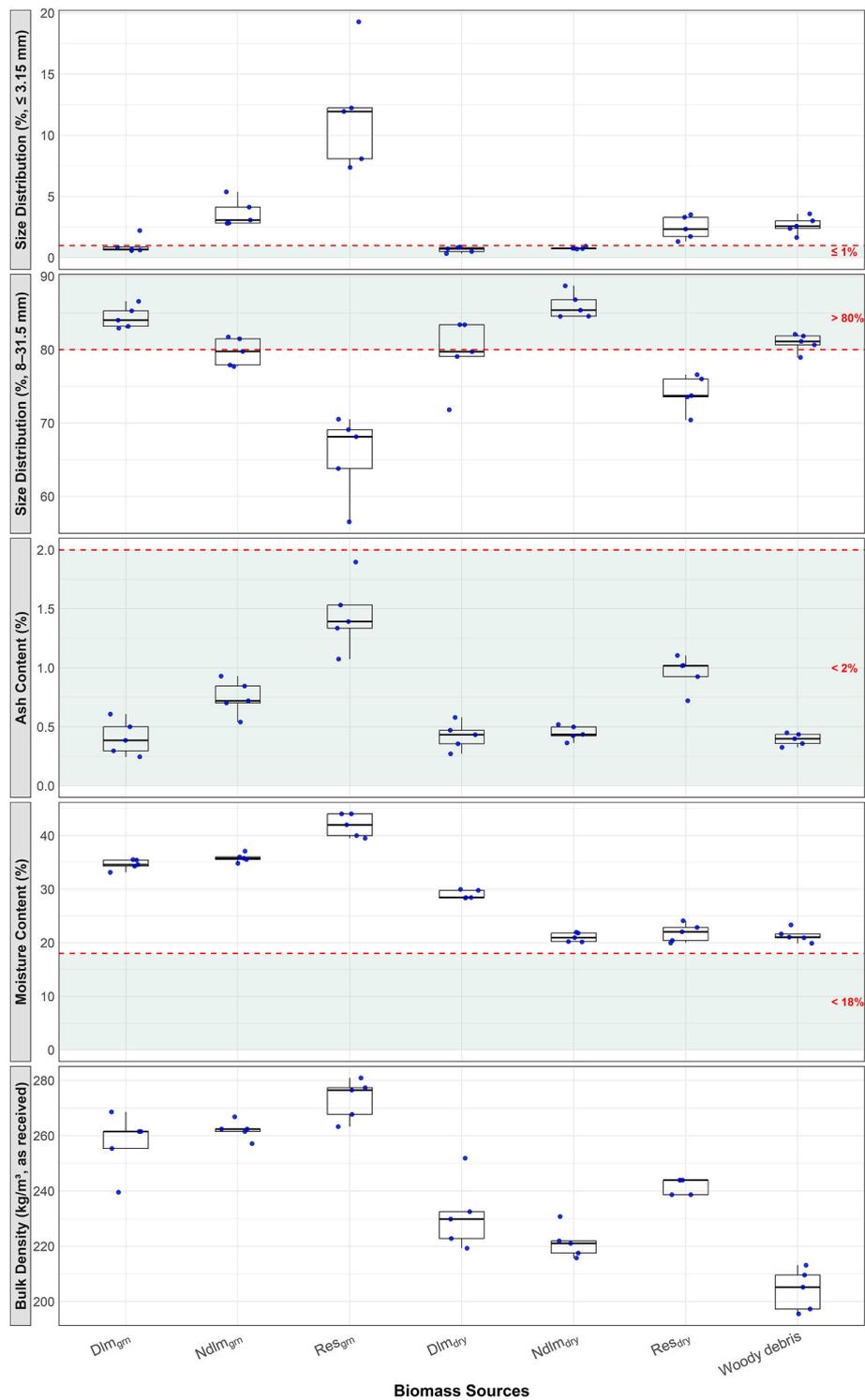
Fig. 5. Box-and-jitter plots showing key quality attributes of woodchips from seven biomass sources evaluated for small-scale combined heat and power (CHP) applications. Each subplot represents a different attribute: size distribution (%) by class, ash content (%), moisture content (%), and bulk density (kg/m³, as received). Biomass sources include green and one-year-dried material from different harvesting and processing strategies. Red dashed lines indicate quality thresholds: ≤1% for fine particles (≤3.15 mm), >80% for medium-sized particles (8–31.5 mm), <2% for ash content, and <18% for moisture content. Boxes show interquartile ranges (IQR), whiskers extend to 1.5 × IQR, and dots represent individual replicates. Biomass sources are as follows: green delimbed energy wood (Dlm$_{grn}$); green non-delimbed energy wood (Ndlm$_{grn}$); green residues (Res$_{grn}$); one-year-dried delimbed energy wood (Dlm$_{dry}$); one-year-dried non-delimbed energy wood (Ndlm$_{dry}$); one-year-dried residues (Res$_{dry}$); and woody debris. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
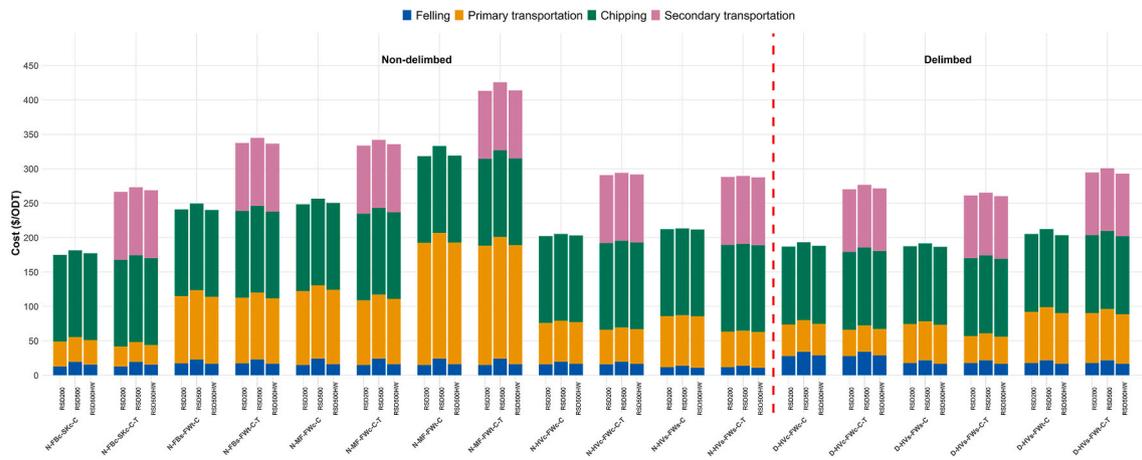
Fig. 6. Supply chain unit cost ($ per oven-dry tonne) across 18 biomass supply chains under six treatment scenarios, comparing storage-site chipping and roadside chipping. Cost components include chipping, felling, primary transportation, and secondary transportation. All supply chains use the Junkkari HJ 252 chipper for chipping, and a pickup truck with a five-tonne towing capacity for secondary transportation, where applicable. Treatment options and supply chain configurations are outlined in Tables 1 and 3

Importantly, no particles exceeded 63 mm, confirming compliance with the CHP system's size requirements.

Ash content showed the same general pattern as fine particle distribution: higher in foliage-rich or residue material and lower in delimbed energy wood. This outcome is consistent with previous studies reporting that residues have elevated ash due to higher micronutrient levels and greater risk of soil contamination (Kuptz and Hartmann, 2015). All sources nonetheless remained within the <2% ash limit, showing that fuel-reduction biomass does not pose a risk for excessive ash production.

Moisture content was substantially reduced by one year of air drying but remained above the <18% requirement. The reductions observed (6-20%) are in line with earlier studies on roadside drying for 4–12 months (Kuptz and Hartmann, 2015; Pettersson and Nordfjell, 2007; Röser et al., 2011a). However, none of the samples reached equilibrium moisture content (12–15%; FPL, 2010), as one year is generally insufficient (Kuptz et al., 2019). Delimbed energy wood, in particular, retained higher moisture due to denser stacking that restricted airflow (Eliasson et al., 2020; Röser et al., 2011a; Wetzel et al., 2017). Woody debris, despite assuming it had been exposed for over a year, had moisture levels similar to one-year-dried material, indicating that storage design and pile configuration influence final moisture content more than storage duration. These results highlight the need for drying optimization or supplementary measures, such as pile geometry adjustment, covered storage, or a short period of additional kiln-drying, to consistently meet CHP system fuel requirements.

Localized supply chain design and operational practices exert greater influence on final feedstock quality compared with initial biomass properties. Although forest composition, sampling extent, treatment options and biogeoclimatic conditions introduce variation in initial properties, the mechanisms relevant to the CHP suitability remain consistent, including foliage-driven fine particle generation, ash increases from fines and contamination, and drying governed by material exposure. Overall, one-year natural drying under proper piling significantly improved woodchip quality by reducing fine particles, ash and moisture content, and was considered an intermediate step in the recovery operations without additional cost. Therefore, the technical feasibility of fuel-reduction biomass as feedstock for small-scale CHP systems across varying regional conditions largely depends on effective supply chain design and operational practices.

Delimbed and non-delimbed energy wood emerged as the most suitable feedstock, with particle size and ash content consistently within acceptable limits, enabling stable gasification conditions and low slagging risk, which in turn support reliable operation of the CHP system. Surface woody debris also demonstrated potential by meeting medium-size particle and ash requirements. Additionally, woodchips from residues exhibited favorable bulk density for efficient handling. Their fine particle content slightly exceeded the 1% threshold, indicating particle-size non-uniformity that can reduce gasification stability and CHP system availability. Nevertheless, targeted post-processing, such as screening (Kons, 2015; Kuptz et al., 2019), or blending with lower-fine material, could make them viable options, albeit with additional cost.

Therefore, fuel-reduction biomass can be made suitable for small-scale CHP systems. Targeted drying strategies and modest post-processing interventions can close the remaining quality gaps. From a supply chain perspective, starting with feedstocks that naturally meet most standards after a year of drying, particularly delimbed and non-delimbed energy wood, offers the most efficient pathway for utilizing fuel-reduction treatments in renewable energy production.

4.2. Key drivers of supply chain economics

Estimated supply chain costs ranged from $175 to $426 per ODT, with variation primarily driven by transportation distance. Among all factors, extraction distance is often the dominant driver of marginal supply costs. In this study, the CHP unit's close proximity to the treated stands (maximum hauling distance of 286 m) reduced the relevance of roadside chipping. At this scale, the short hauling distance meant that the added cost of secondary transportation outweighed the benefit of higher bulk density post-chipping. Prior work indicated that roadside chipping becomes cost-competitive when hauling distance increases in the order of tens of kilometers, particularly, for delimbed and non-delimbed energy wood, and even more so, for residues and woody debris due to reduced handling and improved transport efficiency (Bung, 2022). This suggests that transportation distance should be treated as the primary consideration when evaluating supply chain economics at other sites.

Another key factor was treatment intensity. Under the thinning-from-below strategy, higher treatment intensity (i.e., lower residual stand density) generally reduces per-unit felling costs. This is because higher intensity increases the average harvested stem volume, and machine productivity has been shown to rise with harvested stem volume (Chang et al., 2023; Chakroun et al., 2016; Laitila and Väätäinen, 2013; Petty and Kärhä, 2014). As intensity increases and harvested volume grows, mechanized harvesting becomes more favorable than manual felling, in agreement with previous studies (Schweier et al., 2018; Spinelli et al., 2014). However, this relationship mainly applies to thinning-from-below, where cost efficiency reflects larger harvested stem volumes at higher intensity. Under other thinning priorities, cost

outcomes depend on the specific stem volumes removed.

The small-scale harvester showed the lowest unit felling cost among the evaluated options in this study. This reflects its suitability for small-diameter tree harvesting in fuel-reduction operations (with average DBH of ~15 cm). However, these machines face limitations with larger tree sizes, steeper terrain, and higher extraction volumes, where larger mechanized systems may be more efficient (Chakroun et al., 2016; Laitila and Väätäinen, 2013). In this study, the current treatment area and intensity could only supply the CHP system for roughly 2–3 years. However, AFRF manages two additional forest units totaling approximately 9800 ha that also require fuel treatments, indicating that feedstock availability is not temporally constrained. Instead, long-term considerations relate to the spatial expansion of treated areas and the scale of operations, as increasing scale may erode the relative cost advantage of small harvesters.

Variability in machine performance introduces uncertainty into cost calculations. A ±30% variation in machine productivity was adopted, which translates into overlapping cost ranges among supply chain configurations (Table A-8), and no configuration consistently outperformed the others within the same chipping location across all conditions. Therefore, there is no universal optimal system for all remote communities. Although mixed deployments of small-scale and conventional systems can be considered in principle, the present analytical framework evaluates configurations independently and does not optimize hybrid solutions. Moreover, mixed deployments would entail additional coordination and equipment mobilization, with uncertain economic justification in small-scale fuel treatment contexts. Instead, effectiveness depends on aligning harvesting systems with local stand conditions, site-specific treatment objectives, and hauling distances.

Even with high-quality feedstocks from fuel-reduction treatments (i. e., one-year-dried delimbed or non-delimbed biomass), supply chain costs remain substantial. Establishing reliable operations also requires coordination among Indigenous groups, local governments, forest companies, and contractors. The proposed framework supports these considerations by explicitly integrating feedstock quality parameters and supply chain costs, enabling the identification of feedstocks with predictable quality (moisture content, particle size distribution, and ash content) to reduce operational risk and startup costs. Once a reliable baseline is established, the same framework can be used to evaluate incremental cost-reduction strategies, including gradual integration of low-quality materials such as tops, branches, and surface woody debris into the feedstock mix. This phased application demonstrates how the framework supports decision-making that balances technical feasibility, cost control, and long-term resource utilization.

4.3. Strategic role of fuel-reduction biomass in the bioeconomy

Establishing a small-scale CHP system in remote communities involves multiple categories of cost: (i) feedstock supply chain cost covering all steps from forest extraction to delivery at the CHP facility gate; (ii) CHP unit capital cost (CapEx) including the investment in boilers, engines, generators, and on-site handling systems; (iii) CHP system operations and maintenance (O&M) cost such as labor, maintenance, consumables, and administrative overhead; and (iv) Integration costs, which reflect the expense of connecting the CHP facility to electricity distribution networks and district heating pipelines.

This study focused on estimating the feedstock supply chain cost for the AFRF CHP system at \$175–426/ODT, equivalent to 4–10 ¢/kWh based on a lower heating value of 19.1 MJ/kg (dry basis) and an overall efficiency (electricity and heat) of approximately 81% (FAO, 2002; Padinger et al., 2019). While the economic feasibility of recovering energy wood from thinning has been demonstrated in prior studies (Ahtikoski et al., 2008, 2021), its applicability under BC conditions remains a context-specific and open question due to structural differences in stand structure, terrain condition, land tenure arrangements, and energy prices. Nevertheless, when treated strictly as a commodity

energy cost, the estimated supply chain costs remain competitively reasonable within the current BC energy price range of 5–14 ¢/kWh (BC Hydro, 2025; FortisBC, 2025). Once additional costs associated with full system operation are considered (27 ¢/kWh for CapEx and 6 ¢/kWh for O&M; Schilling et al., 2025b), the cost rises to 37–43 ¢/kWh. Furthermore, due to the predominance of steep terrain (Mologni et al., 2018) and Crown land tenure in BC (BC, 2025a), where mechanical productivity is reduced (Cadei et al., 2020) and stumpage fees remain applicable (BC, 2025b), unit supply chain costs in most remote communities are expected to be higher. Accordingly, extrapolating to these areas suggests higher energy cost, further diminishing the economic feasibility of deploying such systems on a stand-alone basis. Therefore, examining the utilization of fuel-reduction biomass through the lens of wildfire risk mitigation helps reveal its multiple economic, environmental, and social values, which is essential for assessing viability from an integrated perspective rather than based solely on stand-alone profitability. In BC, fuel accumulation without intervention frequently leads to severe wildfire events associated with substantial economic losses and long-term adverse impacts on ecosystems and community physical and mental health (Daniels et al., 2024; Hessburg et al., 2025). Targeted fuel treatments reduce economic, ecological, and social risks, and better support long-term sustainable forest management than clearcutting. Further, utilization of generated biomass for energy production also reduces open pile burning, alleviates wood-fiber shortages, enhances local energy security, and supports regional bioeconomy development. When these benefits are incorporated into an integrated assessment, they can substantially offset economic limitations at the CHP operational level, supporting the overall viability of the strategy.

While these integrated benefits strengthen the overarching rationale for utilizing fuel-reduction biomass, practical implementation ultimately depends on reliable feedstock supply. In operational terms, feedstock delivery costs rise modestly as the treatment scale expands outward from the facility and hauling distances increase. For context, Bung (2022) reported supply chain costs of 6–8 ¢/kWh for a district heating system in Haliburton, Ontario, Canada, while Schilling et al. (2025b) estimated supply chain costs of 15 ¢/kWh for the Kwadacha CHP system (BC, Canada; hauling distance of 5-10 km). These comparisons indicate the marginal cost of supplying an additional tonne of biomass remains relatively low, providing a useful proxy for potential economies of scale. In contrast, the high fixed costs of CHP unit investment weigh heavily on small systems, but diminish in relative importance as operation scales up, improving the overall cost per unit of energy.

The scope of such economies of scale, however, is inherently limited. Energy demand in remote communities is low, while the volumes of biomass released by wildfire fuel treatments often exceed that demand by orders of magnitude (Mansuy et al., 2025). As treatment areas expand outward, hauling distances quickly erode cost advantages. This mismatch means that energy use alone cannot mobilize the full volume of fuel-reduction biomass.

A more robust approach is to anchor supply chains in treatment operations but diversify their outputs. Energy production can absorb part of the flow, while higher-value streams such as engineered wood, biochemicals or textiles help distribute costs and reduce dependence on volatile energy markets. Diversification does not eliminate feedstock constraints, but it makes better use of the material that is available and cushions operations against swings in any single product market.

Trade and policy conditions also shape feasibility. Small-diameter biomass is disadvantaged in global markets by higher handling costs and lower product quality, making it sensitive to tariffs, subsidies, or phytosanitary rules. Building stronger domestic and regional markets therefore offers a more stable foundation than reliance on export demand.

Overall, these results suggest that fuel-reduction biomass can support CHP systems where treatment operations generate consistent feedstock within short hauling distances. Beyond this core niche, the

most sustainable path lies in integrated, regionally anchored value chains that couple energy use with material products. In this mode, bioenergy plays a role not as the sole outlet but as one part of a broader utilization strategy that links community energy security with landscape resilience.

4.4. Limitations and future research

This study sought to ensure data reliability within the limits of available resources and provides valuable insights into the operational and techno-economic feasibility of utilizing fuel-reduction biomass for small-scale CHP applications in BC. In alignment with the objectives of an investigative assessment, this study was based on modeled and empirical estimates rather than continuous field monitoring. The biomass quality assessment was conducted under a single operational setup (motor-manual felling and tractor forwarding), which allowed control over key variables and a clear focus on intrinsic feedstock characteristics. While alternative extraction methods such as skidding may introduce additional ash content through soil contamination, previous studies (Cutshall et al., 2013) suggest that the effect is minor. Machine productivity data were derived from established studies representing specific harvesting contexts. Variations in stand structure, terrain, and operator performance (Cadei et al., 2020; Chakroun et al., 2016; Kärhä et al., 2004) may contribute to uncertainty, which was addressed through a ±30% productivity range to reflect realistic variability.

The analysis results are constrained by its regional focus and single-case design. Forest composition, treatment prescriptions, and market conditions in BC differ from those in other jurisdictions, limiting direct transferability of certain quantitative results. However, this regional specificity is also a key strength. It anchors the analysis in a real-world operational context and, as one of the first integrated assessments of fuel-reduction biomass utilization for small-scale CHP in BC, demonstrates the feasibility framework's applicability under practical conditions. While broader generalization should be approached cautiously, the methodological structure provides a foundation for replication and adaptation in other regions. Future research could adopt multi-scenario spatial analysis to identify transport distance thresholds affecting chipping location decisions. In addition, expanding sample sizes, incorporating more diverse forest types and operational setups, and integrating multi-year datasets, combined with mathematical programming approaches and sensitivity analysis, would support the evaluation of long-term fuel availability and system performance.

5. Conclusion

This study evaluates the viability of fuel-reduction biomass as a feedstock for small-scale CHP systems under BC-specific conditions. One year of natural drying significantly improved feedstock quality, ensuring that residue-derived biomass largely met particle size and ash content requirements. Further optimization, such as adjusting pile configurations or short-term kiln drying, could help achieve the target moisture content. Among all feedstocks, delimbed and non-delimbed energy wood showed the highest suitability, while residues and surface woody debris also exhibited potential with targeted post-processing, albeit at

additional costs.

From an economic standpoint, high-quality biomass feedstock can be supplied at a cost that is competitive under energy price conditions in BC, with transportation distance being the dominant cost driver. Higher treatment intensity and mechanized operations can reduce unit costs, though optimal configurations depend on site-specific conditions. While small-scale CHP systems may gain modest economies of scale with increasing biomass volumes, these advantages are constrained by low local energy demand and longer transport distances in remote communities. Integrating CHP system supply chains with higher-value product streams such as engineered wood, biochemicals, and textiles may offer a strategic pathway to distribute costs, enhance market resilience, and support long-term sustainable biomass utilization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendices.

Table A-1
Productivity reference table for felling.

Productivity (m³/SMH)	Non-delimbed			Delimbed			References
	RSD200	RSD500	RSD500HW	RSD200	RSD500	RSD500HW	
Motor-manual felling	8.17	5.17	7.46	-	-	-	Chang et al. (2023)
Conventional feller-buncher	37.70	25.85	31.09	-	-	-	Chang et al. (2023)
Small-scale feller buncher	19.48	15.15	20.02	-	-	-	Chakroun et al. (2016)
Conventional harvester	33.60[1]	27.96[1]	32.15[1]	24.89	20.71	23.81	Petty and Kärhä (2014)
Small-scale harvester	22.72	20.02	24.34	19.47	16.23	20.56	Laitila and Väätäinen (2013)

SMH: scheduled machine hours.

[1] A 35 % higher productivity was assumed when applying a harvester for non-delimbed energy wood recovery (Laitila and Väätäinen, 2013).

Table A-2
Productivity reference table for primary transportation.

Productivity (ODT/SMH)	Chipping location	Felling system	Non-delimbed			Delimbed			Reference
			RSD200	RSD500	RSD500HW	RSD200	RSD500	RSD500HW	
Conventional grapple skidder	Storage site	Mechanized	9.57	9.42	9.72	-	-	-	Chang et al. (2023)
	Roadside	Mechanized	11.97	11.78	12.15	-	-	-	
Conventional forwarder	Storage site	Manual	3.22[1]	3.22[1]	3.22[1]	-	-	-	Laitila et al. (2007)
		Mechanized	5.75[2]	5.75[2]	5.75[2]	6.61	6.61	6.61	
	Roadside	Manual	3.68[1]	3.68[1]	3.68[1]	-	-	-	
		Mechanized	6.90[2]	6.90[2]	6.90[2]	7.93	7.93	7.93	
Small-scale forwarder	Storage site	Mechanized	2.30[2]	2.30[2]	2.30[2]	2.65	2.65	2.65	Bavis (2024)
	Roadside	Mechanized	3.32[2]	3.32[2]	3.32[2]	3.82	3.82	3.82	
Farm tractor pulled forwarding trailer	Storage site	Manual	1.25[1]	1.20[1]	1.26[1]	-	-	-	Leszczyński et al. (2021)
		Mechanized	2.26[2]	2.18[2]	2.29[2]	2.60	2.50	2.63	
	Roadside	Manual	1.27[1]	1.24[1]	1.29[1]	-	-	-	
		Mechanized	2.32[2]	2.25[2]	2.34[2]	2.66	2.59	2.69	

[1] The productivity of primary transportation for hand-felled trees and ground woody debris was assumed to be 45% lower than for mechanically felled trees (Laitila et al., 2007).

[2] A 15% reduction in primary transportation productivity was assumed for non-delimbed energy wood extraction compared to delimbed energy wood (Heikkilä et al., 2006).

Table A-3
Hourly rate reference table.

	Machine	Hourly rate ($/SMH)	References
Conventional	Feller buncher	319.50	TimberTracks (2024)
	Motor-manual felling	80.00	Expert experiences
	Harvester	352.44	TimberTracks (2024)
	Grapple skidder	301.73	TimberTracks (2024)
	Forwarder	302.83	TimberTracks (2024)
Small-scale	Feller buncher	221.90	BCRB (2024)
	Harvester	175.00	Bavis (2024)
	Forwarder	150.00	Bavis (2024)
	Farm tractor pulled forwarding trailers	186.35	BCRB (2024); BCWS (2024)
Chipping and secondary transportation	Chipper and log feeder	192.50	BCRB (2024)
	Woodchip truck	133.51	BCWS (2024)

SMH: scheduled machine hours.

Table A-4
Look-up table of biomass load results.

Treatment options	Foliage (ODT/ha)	Branches (ODT/ha)	Top (ODT/ha)	Bark (ODT/ha)	Stem (ODT/ha)	Woody debris (ODT/ha)	Total (ODT/ha)
RSD200	9.79	15.72	2.1	8.33	43.22	14.56	93.73
RSD500	5.41	9.22	0.94	5.18	26.33	14.56	61.64
RSD500HW	7.45	11.56	1.78	5.7	30.72	14.56	71.77

Table A-5
Look-up table of woodchip quality results.

Biomass source	Replica	Ash content (%)	Moisture content (%)	Size distribution (%)						Bulk density (kg/m³)	
				≤3.15 mm	3.15-8 mm	8-16 mm	16-31.5 mm	31.5-45 mm	45-63 mm	received	on dry basis
Dlmgrn	1	0.50	35.43	0.63	1.86	26.14	59.14	10.22	2.01	261.57	168.88
Dlmgrn	2	0.61	33.15	0.59	2.20	19.60	63.34	12.54	1.74	255.41	170.75
Dlmgrn	3	0.25	35.52	0.69	1.91	26.23	60.36	10.01	0.81	261.57	168.65
Dlmgrn	4	0.30	34.31	2.23	4.04	31.12	52.90	8.48	1.24	268.62	176.44
Dlmgrn	5	0.39	34.60	0.88	2.67	28.77	54.43	11.65	1.61	239.56	156.67
Ndlmgrn	1	0.93	35.77	4.14	8.65	35.52	45.95	4.67	1.06	266.85	171.40
Ndlmgrn	2	0.72	37.10	3.08	7.61	30.83	48.95	6.94	2.59	257.17	161.75
Ndlmgrn	3	0.70	34.84	5.38	7.16	31.41	46.50	8.42	1.12	262.45	171.02
Ndlmgrn	4	0.85	36.04	2.83	6.04	31.99	49.74	7.61	1.79	261.57	167.31
Ndlmgrn	5	0.54	35.54	2.82	7.04	32.34	45.38	9.35	3.06	262.45	169.18
Resgrn	1	1.39	44.06	19.28	11.79	26.77	29.79	8.94	3.44	263.33	147.31
Resgrn	2	1.53	44.06	12.24	10.55	28.57	35.24	10.20	3.20	276.54	154.69
Resgrn	3	1.34	40.00	7.38	10.72	28.99	40.12	9.92	2.87	267.74	160.65
Resgrn	4	1.90	39.51	8.09	10.80	29.43	41.10	7.75	2.84	277.42	167.80
Resgrn	5	1.07	42.02	11.95	6.75	28.92	39.22	8.62	4.54	280.94	162.89
Dlmdry	1	0.36	28.45	0.89	2.42	20.65	58.42	13.04	4.58	222.82	159.42
Dlmdry	2	0.47	28.37	0.73	2.13	17.39	62.34	13.64	3.77	232.51	166.55
Dlmdry	3	0.58	28.44	0.51	2.01	23.50	59.92	10.21	3.86	251.88	180.25
Dlmdry	4	0.27	29.97	0.84	2.33	21.53	50.29	17.23	7.78	229.87	160.98
Dlmdry	5	0.43	29.79	0.34	1.64	22.32	61.08	12.09	2.53	219.30	153.98
Ndlmdry	1	0.44	20.16	0.78	2.54	26.39	58.14	6.79	5.35	230.75	184.23
Ndlmdry	2	0.36	20.22	0.75	2.40	28.44	56.12	9.13	3.16	221.06	176.37
Ndlmdry	3	0.50	21.81	0.77	2.20	32.76	54.05	5.84	4.37	215.78	168.73
Ndlmdry	4	0.52	21.96	0.94	2.38	28.62	60.08	7.27	0.70	221.94	173.20
Ndlmdry	5	0.42	20.97	0.71	2.40	29.33	56.05	9.45	2.06	217.54	171.93
Resdry	1	1.11	22.05	3.30	6.65	27.91	48.12	10.92	3.10	243.96	190.16
Resdry	2	1.02	19.97	3.53	6.58	28.10	45.64	11.52	4.63	238.68	191.01
Resdry	3	0.72	24.09	1.74	4.75	24.75	51.85	11.72	5.19	243.96	185.19
Resdry	4	0.93	20.43	2.35	6.61	29.00	44.58	11.99	5.48	238.68	189.92
Resdry	5	1.02	22.87	1.33	3.87	21.60	48.83	17.27	7.11	243.96	188.16
Woody debris	1	0.36	19.91	3.59	15.09	53.62	25.34	2.25	0.10	195.53	156.60
Woody debris	2	0.33	21.06	2.40	12.25	45.29	35.37	3.94	0.74	213.14	168.25
Woody debris	3	0.44	20.93	1.65	8.46	38.02	43.84	6.77	1.25	209.62	165.75
Woody debris	4	0.45	21.64	2.58	10.41	41.71	40.39	3.63	1.27	205.21	160.80
Woody debris	5	0.40	23.35	3.02	10.29	37.85	43.28	4.82	0.74	197.29	151.23

Table A-6
Summary statistics and two-sample *t*-test results (assuming unequal variances) comparing fine particle distribution (≤3.15 mm, %) between green and one-year-dried woodchips across three biomass types: delimbed energy wood, non-delimbed energy wood, and residues. For each biomass type and drying condition, mean, standard deviation, sample size (n = 5), degrees of freedom (df), t-statistic, two-tailed p-value, and critical t-value (α = 0.05) are reported.

Fine particle distribution (≤3.15 mm, %)	Dlm_{dry}	$Ndlm_{dry}$	Dlm_{grn}	Dlm_{dry}	$Ndlm_{grn}$	$Ndlm_{dry}$	Res_{grn}	Res_{dry}
Mean	0.66	0.79	1.00	0.66	3.65	0.79	2.45	0.79
Standard Deviation	0.23	0.09	0.69	0.23	1.11	0.09	0.95	0.09
Observation	5	5	5	5	5	5	5	5
df	5		5		4		4	
t Stat	1.18		1.04		5.76		16.28	
P(T ≤ t) two-tail	2.91E-1		3.46E-1		4.51E-3		1.81E-2	
t Critical two-tail	2.57		2.57		2.78		2.78	

Table A-7
Summary statistics and two-sample *t*-test results (assuming unequal variances) comparing moisture content (%) between green and one-year-dried woodchips across three biomass types: delimbed energy wood, non-delimbed energy wood, and residues. For each biomass type and drying condition, mean, standard deviation, sample size (n = 5), degrees of freedom (df), t-statistic, two-tailed p-value, and critical t-value (α = 0.05) are reported.

Moisture content (%)	Dlm_{grn}	Dlm_{dry}	$Ndlm_{grn}$	$Ndlm_{dry}$	Res_{grn}	Res_{dry}
Mean	34.60	29.00	35.86	21.02	41.93	21.88
Standard Deviation	0.97	0.80	0.82	0.85	2.16	1.71
Observation	5	5	5	5	5	5
df	8		8		8	
t Stat	9.97		27.97		16.28	
P(T ≤ t) two-tail	4.35E-6		1.44E-9		1.02E-7	
t Critical two-tail	1.86		1.86		1.86	

Table A-8
Look-up table of supply chain cost results.

Supply chain label	Scenario	Chipping location	Felling unit cost ($/ODT)	Primary transportation unit cost ($/ODT)	Chipping unit cost ($/ODT)	Secondary transportation unit cost ($/ODT)	Overall unit cost ($/ODT)	Minimum overall unit cost ($/ODT)	Maximum overall unit cost ($/ODT)
N-FBc-SKc-C	RSD200	Storage site	12.86	35.96	126.10		174.92	134.56	249.89
N-FBc-SKc-C	RSD500	Storage site	19.32	36.19	126.10		181.61	139.70	259.45
N-FBc-SKc-C	RSD500HW	Storage site	15.43	35.70	126.10		177.23	136.33	253.19
N-FBc-SKc-C-T	RSD200	Roadside	12.86	28.77	126.10	98.72	266.45	204.96	380.65
N-FBc-SKc-C-T	RSD500	Roadside	19.32	28.95	126.10	98.72	273.09	210.07	390.14
N-FBc-SKc-C-T	RSD500HW	Roadside	15.43	28.56	126.10	98.72	268.81	206.78	384.02
N-FBs-FWt-C	RSD200	Storage site	17.29	97.60	126.10		240.99	185.38	344.27
N-FBs-FWt-C	RSD500	Storage site	22.91	100.50	126.10		249.51	191.93	356.44
N-FBs-FWt-C	RSD500HW	Storage site	16.65	97.29	126.10		240.04	184.65	342.91
N-FBs-FWt-C-T	RSD200	Roadside	17.29	95.38	126.10	98.72	337.49	259.61	482.13
N-FBs-FWt-C-T	RSD500	Roadside	22.91	97.17	126.10	98.72	344.90	265.30	492.71
N-FBs-FWt-C-T	RSD500HW	Roadside	16.65	95.10	126.10	98.72	336.57	258.90	480.82
N-MF-FWc-C	RSD200	Storage site	14.86	107.37	126.10		248.33	191.02	354.76
N-MF-FWc-C	RSD500	Storage site	24.19	106.31	126.10		256.60	197.39	366.57
N-MF-FWc-C	RSD500HW	Storage site	16.10	108.17	126.10		250.38	192.60	357.68
N-MF-FWc-C-T	RSD200	Roadside	14.86	93.95	126.10	98.72	333.63	256.64	476.61
N-MF-FWc-C-T	RSD500	Roadside	24.19	93.02	126.10	98.72	342.03	263.10	488.62
N-MF-FWc-C-T	RSD500HW	Roadside	16.10	94.65	126.10	98.72	335.57	258.13	479.39
N-MF-FWt-C	RSD200	Storage site	14.86	177.45	126.10		318.42	244.94	454.88
N-MF-FWt-C	RSD500	Storage site	24.19	182.72	126.10		333.02	256.17	475.74
N-MF-FWt-C	RSD500HW	Storage site	16.10	176.89	126.10		319.09	245.45	455.84
N-MF-FWt-C-T	RSD200	Roadside	14.86	173.42	126.10	98.72	413.10	317.77	590.15
N-MF-FWt-C-T	RSD500	Roadside	24.19	176.67	126.10	98.72	425.68	327.45	608.12
N-MF-FWt-C-T	RSD500HW	Roadside	16.10	172.92	126.10	98.72	413.84	318.34	591.20
N-HVc-FWc-C	RSD200	Storage site	15.92	60.12	126.10		202.14	155.49	288.77
N-HVc-FWc-C	RSD500	Storage site	19.71	59.53	126.10		205.34	157.95	293.34
N-HVc-FWc-C	RSD500HW	Storage site	16.46	60.57	126.10		203.14	156.26	290.20
N-HVc-FWc-C-T	RSD200	Roadside	15.92	50.10	126.10	98.72	290.84	223.72	415.49
N-HVc-FWc-C-T	RSD500	Roadside	19.71	49.61	126.10	98.72	294.14	226.26	420.20

Table A-8 (*continued*)

Supply chain label	Scenario	Chipping location	Felling unit cost ($/ODT)	Primary transportation unit cost ($/ODT)	Chipping unit cost ($/ODT)	Secondary transportation unit cost ($/ODT)	Overall unit cost ($/ODT)	Minimum overall unit cost ($/ODT)	Maximum overall unit cost ($/ODT)
N-HVc-FWc-C-T	RSD500HW	Roadside	16.46	50.48	126.10	98.72	291.77	224.44	416.81
N-HVs-FWs-C	RSD200	Storage site	11.69	74.30	126.10		212.09	163.14	302.98
N-HVs-FWs-C	RSD500	Storage site	13.67	73.56	126.10		213.34	164.10	304.77
N-HVs-FWs-C	RSD500HW	Storage site	10.80	74.86	126.10		211.75	162.89	302.50
N-HVs-FWs-C-T	RSD200	Roadside	11.69	51.54	126.10	98.72	288.05	221.58	411.50
N-HVs-FWs-C-T	RSD500	Roadside	13.67	51.03	126.10	98.72	289.52	222.71	413.60
N-HVs-FWs-C-T	RSD500HW	Roadside	10.80	51.93	126.10	98.72	287.54	221.19	410.78
D-HVc-FWc-C	RSD200	Storage site	27.79	45.82	113.26		186.86	143.74	266.95
D-HVc-FWc-C	RSD500	Storage site	34.16	45.82	113.26		193.24	148.65	276.06
D-HVc-FWc-C	RSD500HW	Storage site	28.95	45.82	113.26		188.03	144.64	268.61
D-HVc-FWc-C-T	RSD200	Roadside	27.79	38.18	113.26	90.99	270.22	207.86	386.02
D-HVc-FWc-C-T	RSD500	Roadside	34.16	38.18	113.26	90.99	276.59	212.76	395.13
D-HVc-FWc-C-T	RSD500HW	Roadside	28.95	38.18	113.26	90.99	271.38	208.75	387.69
D-HVs-FWs-C	RSD200	Storage site	17.63	56.62	113.26		187.51	144.24	267.87
D-HVs-FWs-C	RSD500	Storage site	21.65	56.62	113.26		191.52	147.33	273.60
D-HVs-FWs-C	RSD500HW	Storage site	16.65	56.62	113.26		186.53	143.48	266.46
D-HVs-FWs-C-T	RSD200	Roadside	17.63	39.27	113.26	90.99	261.16	200.89	373.08
D-HVs-FWs-C-T	RSD500	Roadside	21.65	39.27	113.26	90.99	265.17	203.98	378.82
D-HVs-FWs-C-T	RSD500HW	Roadside	16.65	39.27	113.26	90.99	260.17	200.13	371.68
D-HVs-FWt-C	RSD200	Storage site	17.63	74.37	113.26		205.26	157.89	293.23
D-HVs-FWt-C	RSD500	Storage site	21.65	77.34	113.26		212.25	163.27	303.22
D-HVs-FWt-C	RSD500HW	Storage site	16.65	73.58	113.26		203.49	156.53	290.70
D-HVs-FWt-C-T	RSD200	Roadside	17.63	72.68	113.26	90.99	294.56	226.59	420.80
D-HVs-FWt-C-T	RSD500	Roadside	21.65	74.78	113.26	90.99	300.68	231.29	429.54
D-HVs-FWt-C-T	RSD500HW	Roadside	16.65	71.93	113.26	90.99	292.83	225.25	418.33

Data availability

Data will be made available on request.

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