Industrial Crops & Products 237 (2025) 122145

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Availability and procurement cost analysis of fresh Norway spruce (*Picea abies*) logging residue chips and needles from regeneration fellings to biorefining in Finland

Juha Laitila [a,*], Paula Jylhä [b], Hanna Brännström [b], Tapio Ranta [c], Antti Asikainen [a]

[a] Natural Resources Institute Finland, Yliopistokatu 6, Joensuu FI-80101, Finland
[b] Natural Resources Institute Finland, Teknologiakatu 7, Kokkola FI-67100, Finland
[c] Lappeenranta-Lahti University of Technology LUT, Yliopistokatu 34, Lappeenranta FI-53850, Finland

ARTICLE INFO

Keywords:
Crown biomass
Pre-feasibility study
Needles
Cost curve
Screening
Techno-economical potential
Cascading use

ABSTRACT

Logging residues of Norway spruce *(Picea abies)*, especially needles with a high extractives content, show potential as a raw material for biorefineries. The present study aimed to assess the availability and procurement costs of fresh Norway spruce logging residue chips and needles for five hypothetical sites in different parts of Finland through a region-level system analysis. The raw material potential and sourcing costs were calculated for an area within a 100-km transport distance along the existing road network from the five hypothetical delivery points. The yield and cost calculations were based on stand data from three major forest industry companies. The procurement cost simulations included harvesting, chipping, chip transportation, and screening of the chips at the delivery point. Both accumulation and procurement costs were calculated per dry tonne. The highest marginal procurement costs of logging residue chips were within the range of 98.8–100.5 € per dry tonne, when their technical harvesting potential varied between 47,000 and 198,000 dry tonnes per year among the five delivery points. Compared to logging residue chips, the procurement cost for the needles was 11.1–16.6 € per dry tonne higher when the recovery rate of needles by screening was assumed to be 50 % of the total which was 15,000–63,000 dry tonnes per year. Procurement costs were very sensitive to the recovery rate of the needles, which affects both the screening cost and the accumulation of needle feedstock.

1. Introduction

1.1. Logging residue chips as a fuel

The proportion of renewables in energy generation has significantly increased in Finland in the 21st century, as forest chips have replaced fossil fuels such as coal, oil, natural gas, and peat (Ranta et al., 2007, 2017). In 2023, 11 million solid cubic meters (m^3) of forest chips were used for energy generation. Of this, 6.6 million m^3 came from small-diameter trees from thinnings, and 3.0 million m^3 from logging residues harvested from regeneration fellings (Official Statistics of Finland, 2024). Additionally, plants used chips from large-diameter stemwood, mostly decayed or dried-out, amounting to 1.1 million m^3, and stumps totalling 0.3 million m^3. Logging residues, consisting of unmerchantable stemwood, branches, and foliage, are recovered after regeneration fellings mainly from stands dominated by Norway spruce (*Picea abies*) (Hakkila, 2004).

The recovery of logging residues is integrated with the harvesting of industrial roundwood through an adapted logging technique, in which tops and branches are piled along the strip road instead of being accumulated in front of the harvester (Laitila et al., 2019). Piling also decreases contamination of the logging residues and promotes their drying. On the other hand, piling residues decreases soil bearing capacity, and branches and tops do not provide a protective layer against soil rutting and compaction (Nurmi, 2007). Needles are estimated to constitute 26–32 % of the biomass of Norway spruce logging residues (Hakkila, 1991). Fresh needles are rich in alkali metals and chlorine, which cause agglomeration of bed sand and corrosion in boilers and heat exchangers at the heat and power plant (Nurmi, 2007). To promote drying and needle shedding, the piles are usually seasoned on site during the spring and early summer (Lindblad et al., 2018). Besides enhancing fuel quality, leaving needles on site is helps maintain soil fertility

* Corresponding author.
E-mail address: juha.laitila@luke.fi (J. Laitila).

https://doi.org/10.1016/j.indcrop.2025.122145
Received 20 February 2025; Received in revised form 15 October 2025; Accepted 16 October 2025
Available online 17 October 2025

(Nilsson et al., 2018; Kons et al., 2022). Needles also contribute to the soil carbon stock (Muukkonen and Lehtonen, 2004).

After drying, the logging residues are forwarded and stored in windrows at roadside until transport to heat and power plants (Nilsson et al., 2015). A majority (78 % in 2020) of harvested logging residues are chipped at roadside landings (Strandström, 2021). Comminution of logging residues at an early stage is justified, as chipping increases the bulk density in transportation (Eriksson et al., 2013, Björheden 2008). Besides improving transport efficiency, increased payloads also have a positive impact on CO2 emissions, manpower requirements, and road traffic (Ranta and Rinne, 2006; Routa et al., 2013; Eriksson et al., 2014). A common logistic system consists of a mobile chipper and two to three trucks with trailers (Väätäinen et al., 2021).

The particle size of logging residue chips intended for energy use in Finland typically ranges from 8 to 63 mm. These chips also contain fine particles, such as bark or needles either detached from branches or still attached to them (Alakangas et al., 2016), as not all needles fall to the ground at the harvesting or roadside storage site despite seasoning (Nurmi, 1999a, 1999b). The fresh needles of Norway spruce are dark green, and the dry mass is approximately 0.4 g (Nurmi, 1999a). In terms of form, the Norway spruce needles are narrow, sharp-pointed and typically 1–2 cm long.

1.2. Cascade use potential of logging residues

The Finnish Forest Bioeconomy Science Panel recommended increasing the value added of the forest industry by improving the efficiency of raw material use according to the cascading principle (Österberg et al., 2024). Currently, logging residues are considered one of the lowest-valued biomass sources in Finland, and methods for their industrial valorisation are under development (Tienaho et al., 2024). In particular, fresh needles contain high amounts of valuable extractives, which are potential constituents pharmaceutical products, cosmetic components, platform and specialty chemicals, and nutritional supplements (Klavins et al., 2023; Wawro et al., 2023; Tienaho et al., 2024).

Current logging residue chip procurement systems must be adjusted to supply raw material with desired properties for novel biorefining processes (Dessbesell et al., 2017; Tienaho et al., 2024). Separating needles from the other components of logging residues will improve the quality of the remaining fuel fraction (Tienaho et al., 2024). To prevent the losses of valuable chemical compounds from needles, urgent delivery and pre-treatment of logging residue chips are required, but synchronising supply logistics with the raw material needs of a biorefinery remains a significant challenge (Klavins et al., 2023; Tienaho et al., 2024).

For decision-making, reliable information on raw material availability and supply costs is required for planning investments and determining the location of a biorefinery (Johnson et al., 2012). In brief, the availability of raw materials, the cost of procurement logistics, and the cost-efficiency of the biorefining process determine the overall feasibility of converting forest biomass into various added-value products (Kurian et al., 2013).

1.3. The aim of the study

So far, little is known about the procurement of fresh Norway spruce logging residues or their fractions for biorefining. This study aimed to determine the accumulation and procurement costs of fresh Norway spruce logging residue chips and needles for five hypothetical sites in Finland by means of a region-level system analysis. The results of the present case study can be used e.g. to estimate the economic feasibility of needles and fresh logging residue chips as raw materials for various biorefinery products, as well as to estimate the value of biorefinery residues in energy production after needle separation or extraction of valuable compounds.

2. Material and methods

2.1. Approximation of the technical harvesting potential of Norway spruce logging residues and needles

The technical harvesting potential and supply costs of fresh Norway spruce logging residue chips and needles per dry tonne were assessed within a 100-kilometer transport distance along the road network from delivery points in Jyväskylä (62.237° N 25.816° E), Joensuu (62.596° N 29.844° E), Kajaani (64.231° N 27.704° E), Kouvola (60.909° N 26.657° E) and Vaasa (63.092° N 21.559° E). All of the selected delivery points have a combined heat and power (CHP) plant that use forest chips. These regions also host a variety of mechanical and chemical forestry industries. Yield calculations for logging residues were based on regeneration felling stand data from year 2000 (Table 1), provided by three major forest industry companies, assuming no competing use for the logging residues. These data, used earlier by Asikainen et al. (2001) and Ranta (2002, 2005), were still considered valid for the procurement cost calculations, since no major changes have occurred either in harvesting volumes or the stand structure. The forest industry's felling volume of spruce roundwood in Finland was 24.3 million m^3 in 2001 and 24.5 million m^3 in 2024, while the average annual felling volume for the entire 2000s was 23.0 million m^3 (standard deviation 2.7 million m^3). In addition, there were no significant changes in the relative proportions of the main spruce assortments during the reference period: the share of sawlogs in the total spruce felling volume remained at 60 %, and that of pulpwood at 40 %. (Official Statistics of Finland, 2025).

The stand data (Table 1) described above included the location and stand parameters, such as harvested roundwood volume by tree species (m^3, solid above-bark), forwarding distance (m), and felling area (ha). The transport distances to the end use delivery points were calculated using a GIS application. Fig. 1 shows the locations and the procurement areas of each delivery point. The cutting method was adapted to the recovery of Norway spruce logging residues so that they were piled during timber processing, while slash from other tree species were accumulated on the strip roads to improve the soil bearing capacity.

The dry mass of fresh Norway spruce logging residues with needles was derived from the harvested roundwood volumes (Table 2). The estimates of biomass components were based on studies by Hakkila (1991), Asikainen et al. (2001) and Kiljunen (2002). Different biomass ratios were used for logging residues harvested from the southern and northern parts of Finland (Table 2, Fig. 1) due to the differences in the proportions of branch mass and unmerchantable top section (Asikainen et al., 2001). According to current forest management guidelines, 70 % of the volume of fresh Norway spruce logging residues was assumed to be recovered (Koistinen et al., 2019).

For stand selection and procurement cost calculations, the dry masses of the Norway spruce logging residues were converted into volumes (m^3) using the basic density 425 kg/m^3, based on the results by Hakkila (1978) (Table 2). In the stand selection for the raw material sourcing of the biorefineries, the following criteria were applied: the proportion of Norway spruce roundwood $\geq$ 50 % of the removal, logging residue volume $\geq$ 40 m^3 per stand, accumulation of logging residues $\geq$ 30 m^3/ha, and forwarding distance $\leq$ 300 m. Table 3 provides the basic stand estimates for the regeneration felling stands selected for raw material sourcing by the procurement areas.

2.2. Productivity and cost factors of the supply chain

The stages of the supply chain are illustrated in Fig. 2. The costs of various stages were first calculated per solid volume (€/m^3) and then converted to a dry mass basis (€ per dry tonne) using a basic density of 425 kg/m^3 (Hakkila, 1978). The organisation cost was assumed to be 3.9 €/m^3 (Table 4), which is equal to the average value for industrial roundwood procurement in Finland in 2023 (Strandström, 2024). The stumpage price of 7.7 €/m^3 (Table 4) for logging residues was based on

Table 1
Total harvesting volumes of industrial roundwood by tree species (solid m^3) and regeneration felling areas (ha) by procurement area, based on either the original regeneration felling stand data* or the sub-sample that meets the stand selection criteria for needle sourcing**.

	Jyväskylä	Joensuu	Kajaani	Kouvola	Vaasa
*Total area of regeneration felling stands, ha	15179	12623	7101	13488	7914
*Total harvesting volume of Norway spruce roundwood, m^3	2127016	1405433	685492	1599484	724694
*Total harvesting volume of Scots pine roundwood, m^3	704650	652133	360692	665186	421705
*Total harvesting volume of Silver and Downy birch roundwood, m^3	272123	288375	120446	211846	132090
*Average area of regeneration felling stands, ha	2.2	2.6	3.3	2.1	2.6
*Average forwarding distance, m	230	217	228	217	276
**Total area of stands selected for needle sourcing, ha	7389	5060	3078	5284	2372
**Total harvesting volume of Norway spruce roundwood from needle sourcing stands, m^3	1514077	971590	490720	1133621	355664
**Total harvesting volume of Scots pine roundwood from needle sourcing stands, m^3	292762	168582	95599	190635	88225
**Total harvesting volume of Silver and Downy birch roundwood from needle sourcing stands, m^3	100852	94450	55565	50484	43061
*Average area of stands selected for needle sourcing, ha	2.5	2.8	3.4	2.2	2.9
*Average forwarding distance in stands selected for needle sourcing, m	172	171	192	165	187

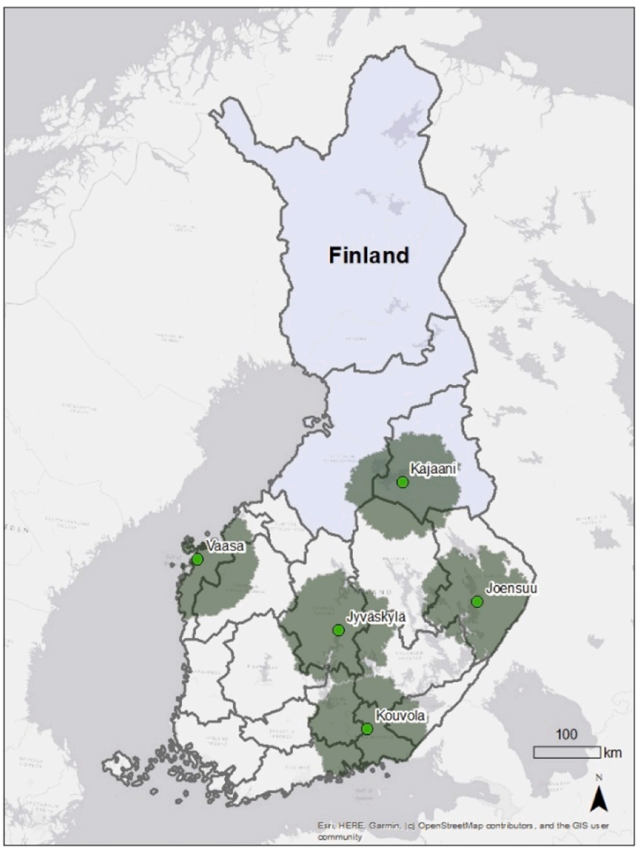

Fig. 1. The procurement areas of the fresh Norway spruce logging residues for the delivery points located in Jyväskylä, Joensuu, Kajaani, and Kouvola. Road transportation distance was limited to a maximum of 100 km along the existing road network. The procurement area of Kajaani is mainly located in northern Finland, which is highlighted in light blue on the map.

official statistics (Prices of energy wood quarterly, 2024). The piling cost of logging residues (0.5 € per harvested cubic metre of Norway spruce roundwood; Pekkarinen et al., 2024) was allocated proportionally to the amount of accumulated logging residues, resulting in a piling cost of 1.1 €/m^3 in northern Finland and 1.7 €/m^3 in southern Finland (see Table 2). Compensation for the piling of logging residues is based on an observed increase of approximately 10 % in harvester time consumption associated with residue recovery (Jylhä et al. 2019). The capital cost (interest cost for working capital) tied up in feedstock (including stumpage price, harvesting, and overhead cost) was calculated assuming an interest rate of 5 % and a holding period of 1.0 month.

When calculating the productivity of forwarding logging residues, the time consumption model of Asikainen et al. (2001) which is analysed in detail by Ranta (2002) was applied (1–6). The stand parameters influencing forwarding productivity were the removal of logging residues (m^3/ha) and the forwarding distance (m^3). The forwarder payload was set to 7.8 m^3 (Table 4), based on the study of Laitila et al. (2016b). An average strip road spacing of 20 m was assumed, resulting in a strip road network with a total length of 600 m/ha (Niemistö 1992). The hourly operating cost of €89.4 (Table 4) for the forwarding is based on the calculation by Laitila and Repola (2023), which was updated using the cost indexes for forwarders (Statistics Finland, 2024). The forwarding productivity per productive machine hour (PMh) was converted to operating hour productivity (scheduled machine hour productivity, SMh) using a coefficient of 1.2 (Laitila et al., 2016b).

The productive forwarding time of logging residues (1) by the forwarder T_{Tot} (min/m^3) was the sum of the main working elements (2−5) driving unloaded ($T_{Empty\ load}$, min/m^3), loading logging residues at the stand ($T_{Loading}$, min/m^3), moving between loading points (T_{Moving}, min/m^3), driving with full load ($T_{Driving\ with\ load}$, min/m^3), and unloading ($T_{Unloading}$, min/m^3) at the roadside landing:

$$T_{Tot}=T_{Empty\ load}+T_{Loading}+T_{Moving}+T_{Driving\ with\ load}+T_{Unloading} \quad (1)$$

The time consumptions of individual work elements were calculated as follows:

$$T_{Empty\ load}=(0.5+0.018\times(1.06\times Fd))/Pl \quad (2)$$

Where Fd = Forwarding distance, m
Pl = Payload, m^3

$$T_{Loading}=0.6+(0.059\text{-}0.78\times \ln(V_{L\ Grapple})) \quad (3)$$

Where $V_{L\ Grapple}$ = Grapple load size during loading, m^3
$V_{L\ Grapple}=0.29+0.12\times \ln(0.06\times Z)$
Where Z = Logging residue concentration (m^3/100 m strip road)

$$T_{Moving}=0.04/(0.06\times Z)+0.25+(2.44/Z) \quad (4)$$

Where Z = Logging residue concentration (m^3/100 m strip road)

$$T_{Driving\ with\ load}=((0.87+0.019\times(0.94\times Fd))/(Pl\times 0.74) \quad (5)$$

Where Fd = Forwarding distance, m
Pl = Payload, m^3

$$T_{Unloading}=0.2+(0.28\text{-}0.3979\times \ln(V_{UL\ Grapple})) \quad (6)$$

Where $V_{UL\ Grapple}$ = Grapple load size during unloading (default value 0.38 m^3)

Logging residues were assumed to be chipped at the roadside landing using a truck-mounted drum chipper with a productivity of 52.8 m^3/PMh (Föhr et al., 2010; Kärhä et al. 2011). The direct loading time of the truck-trailer used for chip transportation was determined based on this productivity. For chip transportation, a modern 69-tonne truck-trailer

Table 2
Dry mass of Norway spruce logging residues in kilograms (kg) per m^3 of industrial roundwood by forest biomass components. Solid volume (m^3) of industrial roundwood (sawlogs & pulpwood) is measured over the bark.

	Unmerchantable tree top section, kg	Needles, kg	Live branches, kg	Dead branches, kg	Total biomass, kg	Basic density of logging residues, kg/m^3
Dry mass per m^3 of industrial roundwood, southern Finland	21.4	59.4	98.4	6.6	185.8	425
Dry mass per m^3 of industrial roundwood, northern Finland	71.1	76.3	131.5	9.7	288.6	425

Table 3
The basic harvesting parameters for stands selected for sourcing fresh Norway spruce logging residues by procurement area. The abbreviation SD = standard deviation.

	Jyväskylä	Joensuu	Kajaani	Kouvola	Vaasa
Average forwarding distance, m	172 (SD 73)	171 (SD 72)	192 (SD 88)	165 (SD 73)	187 (SD 84)
Average harvesting removal, m^3/ha	64 (SD 20)	60 (SD 20)	61 (SD 21)	68 (SD 23)	48 (SD 14)
Average stand size, m^3/stand	159 (SD 141)	164 (SD 133)	207 (SD 186)	146 (SD 119)	132 (SD 99)
Average transport distance, km	64 (SD 24)	67 (SD 23)	67 (SD 26)	69 (SD 25)	65 (SD 24)

with a maximum permissible load of 42.0 tonnes and a load capacity of 157.4 m^3 was used. The high moisture content and typical solid content of the chips (53 % and 40 %, respectively; Laitila et al., 2016a) limited the payload (Tables 4) to 46.4 m^3 (116.2 bulk-m^3). The indirect loading time, which includes waiting and manoeuvring of the truck and trailer during loading activities was assumed to be 25 min per load (Windisch et al., 2015). The time consumption for driving both loaded and unloaded was calculated as a function of the transportation distance (7–8), using the models by Nurminen and Heinonen (2007). In the analysis, the same distance was assumed for both driving with a maximum allowable load to the delivery point and returning unloaded to the roadside storage to retrieve the next load. Queuing and unloading of the chips at the delivery point was estimated to take 30 min per load (Laitila et al., 2015).

The driving time (min/truck load) as a function of transportation distance (D = km) with a full load and without a load were formulated as follows (Nurminen and Heinonen, 2007):

$$\text{Driving time with a full load} = 2.561 \times D^{0.785} \quad (7)$$

$$\text{Driving without a load} = 3.820 \times D^{0.688} \quad (8)$$

When calculating the operating-hour productivity for chipping, both the direct and indirect times described above were considered, resulting in a productivity of 35.8 €/SMh. To calculate the unit cost (€/m^3) for

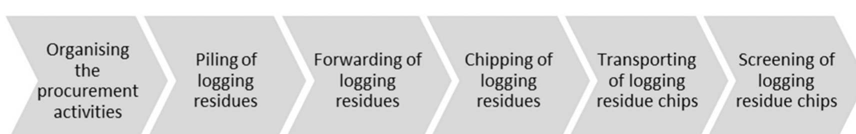

Fig. 2. Flow chart for the logistics chain of fresh Norway spruce logging residue chips.

Table 4
The cost parameters for the logistics chain of fresh Norway spruce logging residue chips and needles.

	Organising	Stumpage price	Piling*	Forwarding**	Chipping	Transporting**	Screening
Unit cost, €/m^3	3.9	7.7	1.1 or 1.7	7.7–8.4	14.4	6.5–6.8	3.7
Hourly cost, €/SMh	-	-	-	89.4	516.0	89.1 and 59.6	-
Payload, m^3	-	-	-	7.8	-	46.4	-

* The cost of piling was calculated separately for the northern and southern regions (see Table 2).
** The average unit costs are different in each procurement area (see Table 4).

Table 5
The average cost (€/dry tonne) of harvesting and transporting for each delivery point based on harvesting conditions and location of the regeneration fellings stands in the each procurement area. The abbreviation SD = standard deviation.

	Jyväskylä	Joensuu	Kajaani	Kouvola	Vaasa
Average piling cost, €/dry tonne	4.1 (-)	4.1 (-)	3.3 (SD 0.7)	4.1 (-)	4.1 (-)
Average forwarding cost, €/dry tonne	18.5 (SD 2.0)	18.7 (SD 1.9)	19.2 (SD 2.3)	18.2 (SD 2.0)	19.8 (SD 2.3)
Average interest cost, €/dry tonne	0.2 (SD 0.01)	0.2 (SD 0.01)	0.2 (SD 0.01	0.2 (SD 0.01)	0.2 (SD 0.01)
Average transporting cost, €/dry tonne	15.4 (SD 2.8)	15.7 (SD 2.7)	15.6 (SD 3.1)	15.9 (SD 3.0)	15.5 (SD 2.9)

chipping and chip transportation, the hourly cost estimates by Laitila et al. (2017) were updated to reflect the prevailing cost level using the cost indexes for chippers and truck-trailer units (Statistics Finland, 2024). This resulted in an hourly operating cost of €516.0 and a corresponding unit cost of 14.4 €/m^3 for chipping (Table 4). The hourly costs of the truck-trailer for driving and terminal activities – defined as the time required for both direct and indirect loading, as well as queuing and unloading – were €89.1 and €59.6, respectively (Table 4).

At the delivery point, needles were separated from logging residue chips using a mobile star screen unit (Huber et al., 2017; Eliasson et al., 2022). The star screen employs shafts equipped with rotating star-shaped discs that fractionate material flow based on particle size. Material is fed onto the screen hopper with wheel loader and the rotating stars propel larger pieces forward, while smaller pieces such as loose needles fall through the gaps between them (Huber et al., 2017). The effect of chipping and screening on the properties of fresh chip fractions has not been thoroughly investigated (e.g. Huber et al., 2017). Therefore, sensitivity analyses were conducted to assess the impact of screening yield on the availability and procurement costs of the needle feedstock fraction. The recovery rate for needles was assumed to be 100 %, 75 %, 50 %, or 25 %. A baseline recovery rate of 50 % was adopted, based on our unpublished test results obtained using a star screen with typical settings for logging residue chips. The unit cost of logging residue chips screening was estimated at 3.7 €/m^3 (Table 4), based on interviews with professionals. This estimate is consistent with the results of Eliasson et al. (2022).

3. Results

3.1. The technical potential Norway spruce logging residues and needles

With the specifications for stand selection (see Ch. 2.1), the annual technical harvesting potential of fresh Norway spruce logging residues varied from 47,000 to 198,000 dry tonnes across the five delivery points (Fig. 3). With a recovery rate of 100 %, the needle yield varied from 15,000 to 63,000 dry tonnes per year. When the recovery rate of needles decreased from 100 % to 25 %, the availability needles declined to 4,000–16,000 dry tonnes per year (Fig. 3). The inland sites (Jyväskylä, Joensuu, Kajaani, and Kouvola), with circular procurement areas, were more feasible locations for potential biorefineries than Vaasa, which is located on the western coast (Fig. 1). The highest technical harvesting potentials for fresh Norway spruce logging residues and needles were around Jyväskylä, Kouvola, and Joensuu (Fig. 3).

The regional logging residue and needle potentials also reflected the geographical variation in regeneration felling site composition (see Table 1). In the western and northern parts of Finland, regeneration felling sites were dominated by Scots pine (*Pinus sylvestris*) (Ranta, 2002, 2005), which resulted in a lower availability of fresh Norway spruce logging residues around Vaasa and Kajaani (Fig. 3).

In Jyväskylä, the cumulative harvesting potential of Norway spruce logging residues increased rapidly with increasing transport distance, while availability in Vaasa and Kajaani was less sensitive to changes in transport distance (Fig. 4). This means that for inland sites such as Jyväskylä, Kouvola, and Joensuu, the same amount of Norway spruce logging residues can be harvested within shorter transport distances than in the Vaasa or Kajaani regions.

3.2. Procurement cost of fresh Norway spruce logging residue chips

The average regional procurement cost of fresh Norway spruce logging residue chips ranged from 99.1 to 100.6 €/dry tonne, and the differences in the cost structures were negligible (Fig. 5). The average cost was the lowest at Jyväskylä and the highest at Vaasa. The differences between the delivery points (Table 5) occurred for the piling of logging residues (3.3–4.1 €/dry tonne), forwarding (18.2–19.8 €/dry tonne), interest costs (0.206–0.213 €/dry tonne) and truck transport of chips (15.2–16.0 €/dry tonne). The stumpage price for logging residues (18.0 €/dry tonne), organisation cost (9.2 €/dry tonne) and chipping cost (33.9 €/dry tonne) were independent of the operating environment in the procurement cost analysis and thus constant between end-use facilities (Fig. 5).

Compared to the other delivery points (Table 5), the average piling costs for logging residues were 0.8 € per dry tonne lower in Kajaani, due to the higher ratio of logging residues per harvested roundwood volume in northern Finland (see Table 2). On the other hand, the stand-wise cutting removal of Norway spruce roundwood (m^3/ha) was lower around Vaasa and Kajaani compared to the regeneration felling stands around Jyväskylä, Joensuu and Kouvola (Table 1), which materialized as a somewhat lower logging residue removal per hectare (Table 3) and thus higher forwarding costs (Table 5).

At Vaasa and Kajaani the average forwarding costs were 19.8 and 19.1 € per dry tonne, whereas in Kouvola, Jyväskylä and Joensuu the average costs were 18.2–18.7 € per dry tonne (Fig. 5, Table 5). The average forwarding distance in the regeneration felling stands within the procurement areas ranged from 165 to 192 m. The longest forwarding distances were recorded for material delivered to Vaasa and Kajaani (Table 3).The small variation in average truck transport costs (15.2–16.0 €/dry tonne, Table 5) was the consequence of the average transport distances from the forest regeneration stands to the delivery points, which varied in the range of 64–69 km (Table 3), e.g. because of

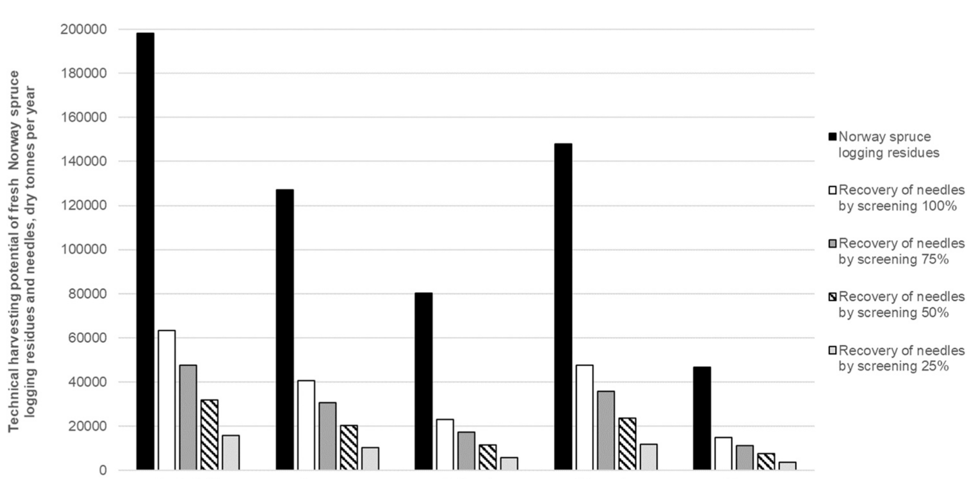

Fig. 3. The technical harvesting potential of fresh Norway spruce logging residues and needles around the five delivery points with alternative recovery rates (25–100 %) for needles screened from logging residue chips.

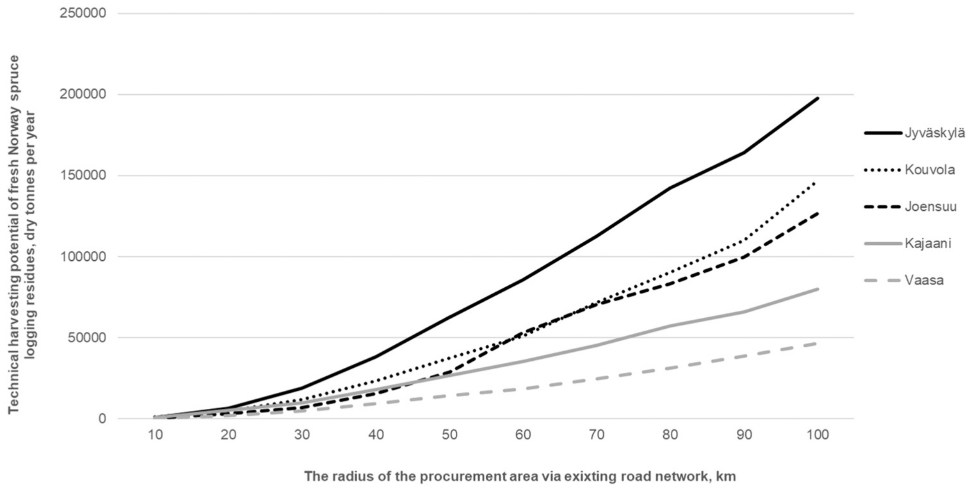

Fig. 4. The technical harvesting potential of fresh Norway spruce logging residues around the five delivery points as a function of transport distance (km).

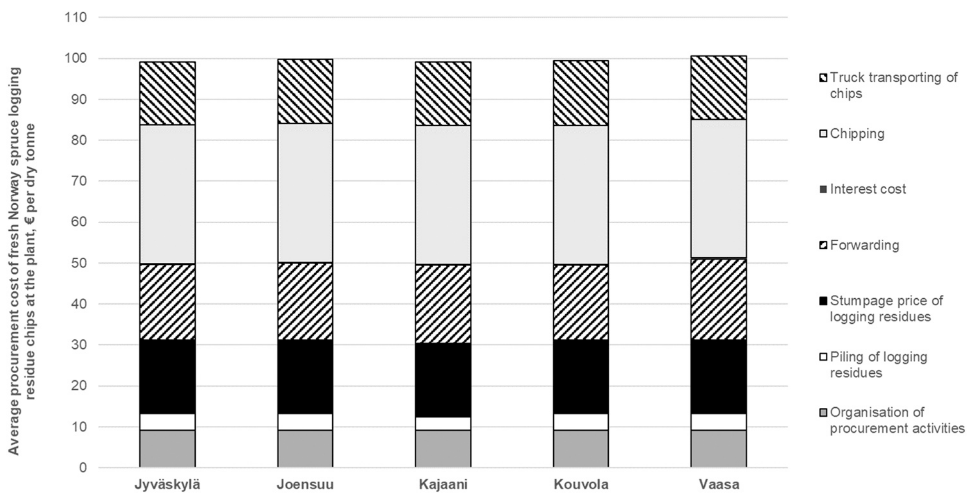

Fig. 5. The average procurement cost for fresh Norway spruce logging residues chips at the five delivery points by work phases.

the road infrastructure, its straightness and location of the regeneration felling stands.

Fig. 6 shows the amount of fresh Norway spruce logging residue chips that can be delivered to Jyväskylä, Joensuu, Kajaani, Kouvola and Vaasa at a given marginal procurement cost (€ per dry tonne), based on the stand-wise accumulation and procurement cost. Increasing demand for raw material calls for expanding the sourcing area, which is reflected in the upward-sloping cost curves. Consequently, transport distances

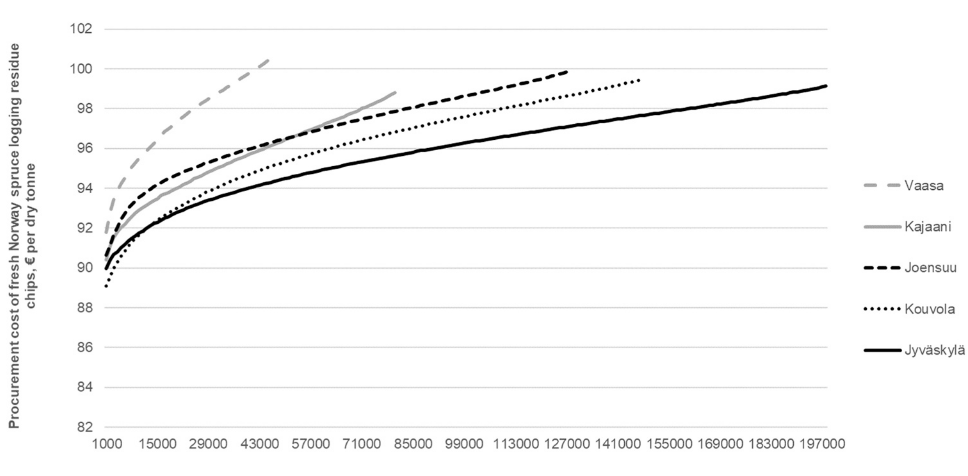

Fig. 6. The effect of annual procurement volume (dry tonnes) of fresh Norway spruce logging residue chips on the procurement cost around the five delivery points.

increase, and logging residues must be harvested from less favourable conditions from a harvesting cost perspective. The procurement costs for fresh Norway spruce logging residue chips were the lowest at Jyväskylä (Fig. 6) and the highest at Vaasa, respectively.

At the procurement cost of 94.0 € per dry tonne, the annual procurement volume (40,000 vs. 4000 dry tonnes per year) were 10-fold at Jyväskylä compared to Vaasa (Fig. 6). Correspondingly, at the procurement cost of 96.0 € per dry tonne, the annual procurement volume at Jyväskylä was approximately 6.8 times that of Vaasa and 1.4- to 2.2-fold that of Kouvola, Kajaani, and Joensuu. The highest marginal procurement costs were within the range of 98.8–100.5 € per dry tonne, when the technical harvesting potential varied between 47,000 and 198,000 dry tonnes per year among the five delivery points (Fig. 6).

3.3. Procurement cost of Norway spruce needles

Fig. 7 shows the amount of fresh Norway spruce needles that can be delivered as a by-product of logging residue chips to Jyväskylä, Joensuu, Kajaani, Kouvola and Vaasa at a given marginal procurement cost (€ per dry tonne), when the recovery rate of needles by screening is estimated to be 50 % of the total. Compared to logging residue chips, the procurement cost for the needles was 11.1–16.6 € per dry tonne higher depending on the delivery point and annual demand for needles. From the procurement cost and availability point of view, the most favourable location for biorefining Norway spruce needles was Jyväskylä, and Vaasa was the least feasible location.

At a procurement cost of 108.0 € per dry tonne, the annual procurement volume of fresh Norway spruce needles was 26,000 dry tonnes in Jyväskylä, 18,000 dry tonnes in Kouvola, 14000 dry tonnes in Joensuu, 7000 dry tonnes in Kajaani, and 4000 dry tonnes in Vaasa (Fig. 7). In northern Finland the relative proportion of needles was smaller in the composition of logging residues (Table 1). Due to this, the average screening cost for needles from logging residues was 0.9 € per dry tonne higher in Kajaani compared to other delivery points in this study, which reduced the cost competitiveness in proportion to the procurement of pure logging residue chips (cf. Figs. 6 and 7).

Figs. 8 and 9 show the impact of the recovery rates on the screening and procurement cost of Norway spruce needles at the delivery point in Jyväskylä. The screening cost for needles was 4.9 € per dry tonne when the screening cost for logging residue chips was 1.6 € per dry tonne (3.7 €/m^3) and the recovery rate of the needles were 100 % of the total needle mass (Fig. 8). Decreasing the recovery rate to 50 % increased the screening cost to 9.9 € per dry tonne and further to the cost level of 19.7 € per dry tonne when recovery rate was 25 %. In proportion to the average procurement costs, the screening of needles accounted for 4.7–16.6 % of the total costs, respectively.

At Jyväskylä the availability of Norway spruce needles varied between 16,000 and 63,000 dry tonnes per year and the procurement costs were at their lowest when the raw material recovery by screening was at its highest from the produced logging residue chips (Fig. 9). With an annual needle procurement volume of 16,000 dry tonnes, the procurement cost was 99.4, 101.8, 106.2 or 118.9 € per dry tonne, depending on the needle recovery rate in screening (25–100 %) (Fig. 9). Procurement cost curves for the needles were very sensitive to the recovery rate of the needles, which affects both the screening cost and especially the availability of needles. Thus, even minor changes in the needle recovery rate have a significant effect on the needle potential and procurement cost within the procurement area (Fig. 9).

4. Discussion

Reliable knowledge on the availability of raw material and their procurement costs is crucial when making strategic (e.g. about plant investments, Möller and Nielsen, 2007) or operational-level decisions (Rauch, 2013). In the present study, real stand data from regeneration fellings and time consumption models for various production stages enabled a site-specific analysis on the costs and availability of raw material for potential biorefinery utilising feedstock separated from fresh Norway spruce logging residues. Fresh logging residue chips produced at the roadside landing were transported directly to the biorefinery to prevent self-heating of the feedstock, which poses a significant risk during buffer-storage if indirect chip deliveries, e.g. via feed-in terminals are used (Väätäinen et al., 2017). A large proportion of needles and fine bark particles boost the degradation processes, which in turn leads to a temperature rise with an increased losses of volatile compounds and dry matter (Nilsson, 2016; Krigstin and Wetzel, 2016).

The analyses were performed at a regional level using a static approach that did not account for the unpredictable interactions between various activities, such as chipping, transporting, queuing and unloading at the delivery point (Laitila et al., 2016b). The interactions directly affect machine and vehicle utilisation rates, as well as the number of vehicles required, depending on the transportation distance (Eliasson et al., 2017). The interactions leading to additional waiting and queuing result in increased costs. Since random factors were not considered, the results may be more optimistic than those obtained through dynamic simulation (Asikainen, 2010). However, a biorefinery requires a constant flow of feedstock throughout the year, which is advantageous for logistics planning compared to heating and power plants, whose fuel demand is much more variable and unpredictable (Wolfsmayr and Rauch, 2014; Väätäinen et al., 2017; Fernandez-Lacruz

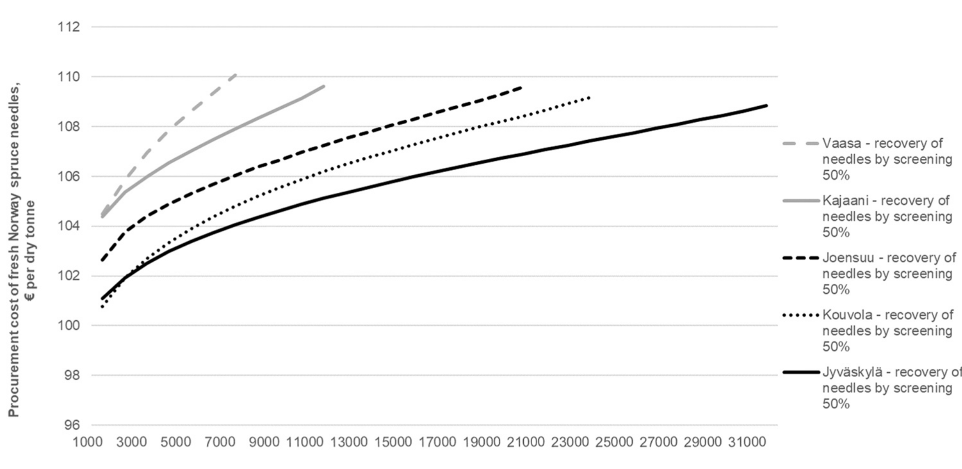

Fig. 7. The procurement cost of fresh Norway spruce needles around the five delivery points as a function of the annual procurement volume when the recovery rate of needles screened from logging residue chips was 50 %.

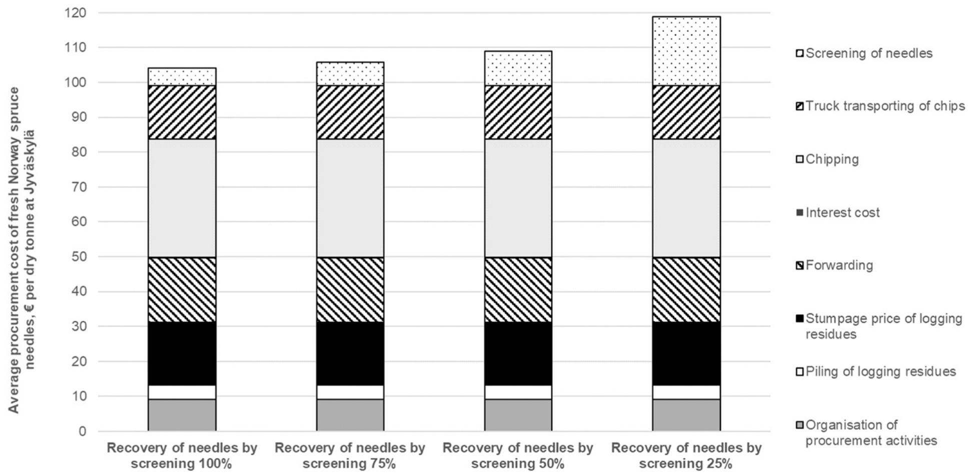

Fig. 8. The average procurement cost of fresh Norway spruce needles at Jyväskylä by work phases, when using alternative recovery rates (25–100 %) for needles screened from logging residue chips.

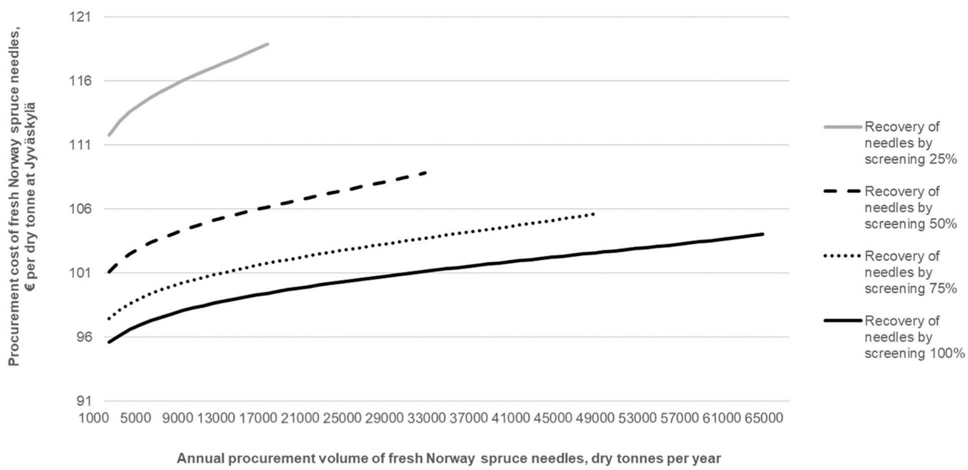

Fig. 9. The procurement cost of fresh Norway spruce needles at Jyväskylä with alternative recovery rates (25 % –100 %) for needles screened from logging residue chips.

et al., 2020). The static approach applied in this study is, in any case, well suited for pre-feasibility assessments, in which raw material procurement costs are compared between different delivery points based on stand-level or forest resource data (Ranta, 2002; Laitila, 2012). Once the feedstock demand of the biorefinery is known, the benefits of using a dynamic, discrete-event simulation model become more evident. A dynamic approach is particularly useful e.g. for sizing the receiving capacity of the facility and estimating the number of chippers and transport vehicles required in the supply chain.

To minimise material loss and ensure the homogeneity of the material to be biorefined, the chips produced from logging residues were delivered to the biorefinery within a month of roundwood felling. In practice, limited forwarding capacity and storage space may restrict the feasibility of a model based on the rapid delivery of fresh logging residue chips within few days, as both roundwood and space-consuming logging residues must be harvested and stored simultaneously. The supply chain is more flexible in the winter, spring and autumn, when feedstock is either frozen or ambient temperatures are low. In summer, however, both industrial roundwood and logging residue chips must be delivered to processing facilities without delay to prevent material losses and deterioration in quality. From an economic perspective, scheduling predictable maintenance and repair shutdowns at the biorefinery during the summer could be a viable option, following the prevailing practice at many Finnish sawmills.

Concerns regarding needle recovery and the harvesting of logging residues are linked to soil fertility and the growth of the subsequent tree generation after final felling, as spruce needles are rich in nitrogen, calcium, and trace elements (Laurén et al., 2008; Nilsson et al., 2018; Koistinen et al., 2019). However, based on a field experiment with a 20–21-year monitoring period, Makinen and Smolander (2025) concluded that nutrient removal following the harvest of logging residues does not pose significant risks to soil nutrient availability. In addition to maintaining soil nutrient levels, logging residues left on site help sustain soil carbon stocks, microbial decomposition processes, and flora and fauna dependent on decaying wood (Koistinen et al., 2019). To avoid negative impacts from logging residue harvesting, it is recommended that at least 30 % of the residues are left on site, as assumed in the present study. Also, infertile sites or those with known nutrient deficiencies should be excluded from logging residue recovery (Koistinen et al., 2019). In this study, in addition to 30 % of the fresh Norway spruce logging residues, all residues from the other tree species (e.g. Scots pine) were assumed to be left on site.

In the present study, the whole logging site reserve of three companies was considered an integral entity. In practice, the entire potential is not available for an individual company, which significantly reduces plant-level raw material availability and increases procurement costs, as a larger procurement area is required to satisfy demand. Furthermore, factors such as the competing use of logging residues by existing heating and power plants (Anttila et al., 2018), forest owners' willingness to sell logging residues, and market-driven fluctuations in the harvesting volume of industrial roundwood were not considered (Ranta and Korpinen, 2011). A thorough analysis of the forest chip market situation and its future development is required when planning investments on the biorefining industry (Ranta and Korpinen, 2011). In addition, spatial and temporal variation in the logging residue potential should be considered, as the harvesting of logging residues depends on the harvesting of industrial roundwood from regeneration felling sites. Despite fluctuations in felling activities, it is likely that the relationships between the stand factors affecting the availability of logging will likely remain stable across geographical areas. Consequently, biorefineries with high availability of feedstock and low procurement costs can better mitigate the risks associated with roundwood market fluctuations (Martinkus et al., 2017).

In the future, the availability of logging residues in Finland may decrease due to abiotic and biotic forest damage caused by climate change in Finland. However, so far, the effects have been minor compared to those in Central Europe (Viiri et al., 2019), but in Finland as well, the greatest risk of damage primarily concerns old Norway spruce stands that are at final felling age. In addition, continuous-cover forestry may partly replace rotational forestry based on regeneration fellings, which limits the supply of logging residues but does not rule out that option completely (Pekkarinen et al., 2024). A transition to continuous cover forestry would, in any case, increase the seasonal variability of timber harvesting operations (Ahtikoski et al., 2024). In spruce-dominated stands, harvesting is typically restricted to the winter season—when the ground is frozen and snow-covered to minimize soil and root damage. Furthermore, compared to clear-cutting, the volume of logging residues generated is lower, resulting in higher harvesting costs (Pekkarinen et al., 2024). So far, changes in the forest management practices have been moderate particularly in southern and central Finland (Laitila et al., 2025). The greatest logging residue potential lies in southern and eastern Finland, where the harvesting potential for Norway spruce roundwood is the highest (Anttila et al., 2018).

One challenge in converting Norway spruce logging residues into novel, marketable products is the green biomass's highly complex physical and chemical composition and susceptibility to biological and chemical degradation processes (Krigstin and Wetzel, 2016). Therefore, fast and efficient biomass fractionation is a crucial step in the biorefining system, occurring immediately after delivery of the chips. This will likely necessitate the adoption of new practices and technologies for the pretreatment and processing of the feedstock (Klavins et al., 2023). So far, little is known about the effect of chipping and screening on the properties of the fresh chip fractions and their proportions (e.g. Huber et al., 2017). Therefore, the impact of needle yield on the regional availability and costs of feedstock was assessed based on sensitivity analyses (Figs. 3, 7, 8 and 9). Additionally, an option in which the chips were assumed to be used as such, without screening, was included in the analysis (Figs. 3, 4, 5 and 6).

In the mechanical fractionating of logging residue chips, the physical adhesion of components must be disrupted under conditions that weaken this bond (Eriksson et al., 2013). Basically, the aim of screening is to control the amount of oversized and small particles (Spinelli et al., 2011; Bäckman et al., 2020). With drum chippers, factors such as infeed speed, cut length, and chipping tool sharpness affect the incidence of both fine and oversized particles, while the size of screen apertures determines the mean particle size in the major particle fraction (Spinelli et al., 2014; Eliasson et al., 2015; Kuptz and Hartmann, 2015). Trommel screens and vibrating decks are solely designed to remove fine particles from the material, whereas the star screens assumed in the present study can separate both fine and oversized fractions at once (Huber et al., 2017).

Sorting based on particle size variation can be utilised to separate loose needles (Huber et al., 2017; Eliasson et al., 2022). In fresh logging residue chips, needles are mostly still attached to the branch particles. While a part of them falls off during screening, others remain attached and are processed with the larger branch particles (Huber et al., 2017). In case adequate feedstock quality is not achieved with a single fractionation stage, more complex processes including multiple handling phases, can be used (Eriksson et al., 2013). This is mainly possible with a larger stationary sieving unit integrated into the processes of the biorefinery. Artificial drying may facilitate needle removal (Laitila et al., 2017), but drying increases costs and promotes the loss of valuable extractives. On the other hand, drying improves the storage stability and increases the heating value of the chip fraction that ends up in energy generation (Roitto, 2014; Huber et al., 2017; Eliasson et al., 2022). Moreover, some extraction processes require dry feedstock (Jylhä et al. 2021).

5. Conclusions

Logging residues of Norway spruce (Picea abies), particularly needles, are considered a valuable raw material for biorefineries due to their high extractives content. So far, no established procurement chains exist for needles, but integrating their sourcing with the procurement of fresh logging chips with existing machinery and prevalent supply system could provide synergies.

The aim of this study was to determine the availability and procurement costs of fresh Norway spruce logging residue chips and needles for five hypothetical sites in different parts of Finland through a region-level system analysis. The results obtained can, for example, be used to estimate the economic feasibility of using needles and logging residues as raw materials for various biorefinery products, as well as to assess the value of biorefinering residues for energy production following needle separation or the extraction of valuable compounds. At present, commercially available end products and publicly disclosed data on their production costs or market prices are lacking. Nevertheless, the insights generated in this study provide industry stakeholders with a stronger basis for making strategic decisions regarding research and development investments. These findings support more targeted resource allocation toward commercially viable products that meet market demand and can be produced profitably at an industrial scale.

The procurement cost curves were upward sloping, because logging residues must be harvested from larger geographic areas when the annual demand increases. As a result, transport distances become longer, and logging residues must be harvested from less favourable regeneration felling stands from a harvesting cost perspective. The procurement costs for fresh Norway spruce logging residue chips and needles were the lowest at Jyväskylä surrounded by circular procurement area, and the highest at Vaasa, located on the western coast of Finland.

The procurement costs for needles were sensitive to their recovery rate, which affects both the screening cost and, especially, the availability of needles. Therefore, even minor changes in the recovery rate by screening will significantly affect the regional availability of feedstock at certain cost levels. Due to the limited number of studies, data on the effect of chipping and screening on the yield and quality of the chip fractions are insufficient, and further research is needed. It is crucial to determine whether all refining processes require feedstock upgrading through screening, and what level of cleanliness level is required. There may be alternative processes for which needle enrichment is not necessary. In the latter case, one processing step and its associated costs could be eliminated. This approach may also facilitate the recovery of wider spectrum of valuable compounds.

CRediT authorship contribution statement

Antti Asikainen: Writing – original draft, Supervision, Methodology, Formal analysis, Conceptualization. **Hanna Brännström:** Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Tapio Ranta:** Writing –

original draft, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Juha Laitila:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Paula Jylhä:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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.

Acknowledgements

The study was conducted as a part of the BIO4P project (Bioproducts from nature) funded by Business Finland (decision Dnro 1510/31/2023). The authors also thank Dr Perttu Anttila for creating the procurement area map based on the GIS data from the regeneration felling stands.

Data availability

Data will be made available on request.

References

Ahtikoski, A., Väätäinen, K., Anttila, P., Laitila, J., Mutanen, A., Lindblad, J., Sikanen, L., Routa, J., 2024. The effects of the EU's forest-related policies on harvesting costs in Finland. article id 23018. 20 p. https://doi.org/ Silva Fenn. 58 (3). https://doi.org/10.14214/sf.23018.

Alakangas, E., Hurskainen, M., Laatikainen-Luntama, J., Korhonen, J., 2016. Suomessa käytettävien polttoaineiden ominaisuuksia [Properties of indigenous fuels in Finland]. VTT Technology 258. VTT Technical Research Centre of Finland Ltd. Espoo. 263 p. (In Finnish)..

Anttila, P., Nivala, V., Salminen, O., Hurskainen, M., Kärki, J., Lindroos, T.J., Asikainen, A., 2018. Regional balance of forest chip supply and demand in Finland in 2030. article id 9902. 20 p. https://doi.org/ Silva Fenn. 52 (2). https://doi.org/10.14214/sf.9902.

Asikainen, A., 2010. Simulation of stump crushing and truck transport of chips. Scand. J. For. Res. 25 (3), 245–250. https://doi.org/10.1080/02827581.2010.488656.

Asikainen, A., Ranta, T., Laitila, J., Hämäläinen, J., 2001. Hakkuutähdehakkeen kustannustekijät ja suurimittakaavainen hankinta [Cost factors and large-scale procurement of logging residue chips]. research notes 131. University of joensuu. Fac. For. Joensuu 107.

Bäckman, M.B., Strandberg, A., Thyrel, M., Bergström, D., Larsson, S.H., 2020. Does mechanical screening of contaminated forest fuels improve ash chemistry for thermal conversion? Energy Fuels 34 (12), 16294–16301. ⟨https://pubs.acs.org/doi/10.1021/acs.energyfuels.0c03196⟩.

Dessbesell, L., Xu, C., Pulkki, R., Leitch, M., Mahmood, N., 2017. Forest biomass supply chain optimization for a biorefinery aiming to produce high-value bio-based materials and chemicals from lignin and forestry residues: a review of literature. Can. J. For. Res. 47 (3), 277–288. https://doi.org/10.1139/cjfr-2016-0336.

Eliasson, L., von Hofsten, H., Johanneson, T., Spinelli, R., Thierfelder, T., 2015. Effects of sieve size on chipper productivity, fuel consumption and chip size distribution for open drum chippers. Croat. J. For. Eng. 36 (1), 11–17.

Eliasson, L., Eriksson, A., Mohtashami, S., 2017. Analysis of factors affecting productivity and costs for a high-performance chip supply system. Appl. Energy 185 (1), 497–505. https://doi.org/10.1016/j.apenergy.2016.10.136.

Eliasson, L., Anerud, E., Eriksson, A., von Hofsten, H., 2022. Productivity and costs of sieving logging residue chips. Int. J. For. Eng. 33 (1), 80–86. https://doi.org/10.1080/14942119.2022.1993686.

Eriksson, A., Eliasson, L., Jirjis, R., 2014. Simulation-based evaluation of supply chains for stump fuel. Int. J. For. Eng. 25 (1), 23–36. https://doi.org/10.1080/14942119.2014.892293.

Eriksson, G., Bergström, D., Nordfjell, T., 2013. The state of the art in woody biomass comminution and sorting in Northern Europe. Int. J. For. Eng. 24 (3), 194–215. https://doi.org/10.1080/14942119.2013.852391.

Fernandez-Lacruz, R., Eriksson, A., Bergström, D., 2020. Simulation-based cost analysis of industrial supply of chips from logging residues and small-diameter trees. Forests 11 (1), 1. https://doi.org/10.3390/f11010001.

Föhr, J., Karttunen, K., Ranta, T., 2010. Energiapuun tienvarsihaketus. [Chipping of energy wood at the roadside landing]. In: Karttunen K., Föhr J., Ranta T. (eds.). Energiapuuta Etelä-Savosta. Lappeenrannan teknillinen yliopisto, Tutkimusraportti 7: 71–79. (In Finnish)..

Hakkila, P., 1978. Pienpuun korjuu polttoaineeksi [Harvesting of small-sized wood for fuel]. Folia For. 342, 38 (Helsinki).

Hakkila, P., 1991. Hakkuupoistuman latvusmassa [Crown mass of trees in the harvesting phase]. Folia For. 773, 24 (Helsinki).

Hakkila, P., 2004. Developing technology for large-scale production of forest chips. Wood energy technology programme 1999–2003. Technology Programme Report 6/2004. National Technology Agency, Helsinki, p. 98.

Huber, C., Kroisleitner, H., Stampfer, K., 2017. Performance of a mobile star screen to improve woodchip quality of forest residues. Forests 8 (5), 171. https://doi.org/10.3390/f8050171.

Johnson, D.M., Jenkins, T.L., Zhang, F., 2012. Methods for optimally locating a forest biomass-to-biofuel facility. Biofuels 3 (4), 489–503. https://doi.org/10.4155/bfs.12.34.

Jylhä, P., Jounela, P., Koistinen, M., Korpunen, H., 2019. Koneellinen hakkuu: seurantatutkimus [Mechanised felling: a follow-up study]. Luonnon ja biotalouden Tutk. 11/2019. Luonnon 53 (Helsinki).

Jylhä, P., Halmemies, E., Hellström, J., Hujala, M., Kilpeläinen, P., Brännström, H., 2021. The effect of thermal drying on the contents of condensed tannins and stilbenes in Norway spruce (Picea abies [L.] Karst.) sawmill bark. Ind. Crops Prod. 173 (2021), 114090. https://doi.org/10.1016/j.indcrop.2021.114090.

Kärhä, K., Hautala, A., Mutikainen, A., 2011. Heinola 1310 ES hakkuutähteiden ja pienpuun haketuksessa. [Chipping of logging residues and whole trees with Heinola 1350 ES drum chipper]. Metsätehon Tuloskalvosarja 9/2011. Helsinki 33.

Kiljunen, N., 2002. Estimating dry mass of logging residues from final cuttings using a harvester data management system. Int. J. For. Eng. 13 (1), 17–25. https://doi.org/10.1080/14942119.2002.10702452.

Klavins, L., Almonaitytė, K., Šalaševičienė, A., Zommere, A., Spalvis, K., Vincevica-Gaile, Z., Korpinen, R., Klavins, M., 2023. Strategy of coniferous needle biorefinery into value-added products to implement circular bioeconomy concepts in forestry side stream utilization. Molecules 28 (20), 7085. https://doi.org/10.3390/molecules28207085.

Koistinen, A., Luiro, J.-P., Vanhatalo, K. (eds.). 2019. Metsänhoidon suositukset energiapuun korjuuseen, työopas. [Forest management recommendations for energy wood harvesting, work guide]. Tapion julkaisuja. Helsinki. 74 p. (In Finnish)..

Kons, K., Blagojević, B., Mola-Yudego, B., Prinz, R., Routa, J., Kulisic, B., Gagnon, B., Bergström, D., 2022. Industrial end-users' preferred characteristics for wood biomass feedstocks. Energies 15 (10), 3721. https://doi.org/10.3390/en15103721.

Krigstin, S., Wetzel, S., 2016. A review of mechanisms responsible for changes to stored woody biomass fuels. Fuel 175, 75–86. https://doi.org/10.1016/j.fuel.2016.02.014.

Kuptz, D., Hartmann, H., 2015. The effect of raw material and machine setting on chipping performance and fuel quality – a German case study. Int. J. For. Eng. 26 (1), 60–70. https://doi.org/10.1080/14942119.2015.1021529.

Kurian, J.K., Nair, G.R., Hussain, A., Raghavan, G.S.V., 2013. Feedstocks, logistics and pre-treatment processes for sustainable lignocellulosic biorefineries: a comprehensive review. Renew. Sustain. Energy Rev. 25, 205–219. https://doi.org/10.1016/j.rser.2013.04.019.

Laitila, J., 2012. Methodology for choice of harvesting system for energy wood from early thinning. Diss. For. (143), 68. ⟨https://www.dissertationesforestales.fi/article/1929/author/5473⟩ (Joensuu).

Laitila, J., Repola, J., 2023. Korjuukustannukset lapin poimintahakkuukohteissa [Harvesting costs of selective harvesting in Lapland]. Luonnonvara- ja biotalouden tutkimus 45/2023. Luonnonvarakeskus 60 (Helsinki).

Laitila, J., Ranta, T., Asikainen, A., Jäppinen, E., Korpinen, O.-J., 2015. The cost competitiveness of conifer stumps in the procurement of forest chips for fuel in Southern and Northern Finland. article id 1280. https:// Silva Fenn. 49 (2). https://doi.org/10.14214/sf.1280.

Laitila, J., Asikainen, A., Ranta, T., 2016a. Cost analysis of transporting forest chips and forest industry by-products with large truck-trailers in Finland. Biomass.. Bioenergy 90, 252–261. https://doi.org/10.1016/j.biombioe.2016.04.011.

Laitila, J., Lehtonen, E., Ranta, T., Anttila, P., Rasi, S., Asikainen, A., 2016b. Procurement costs of cereal straw and forest chips for biorefining in South-East Finland. article id 1689 Silva Fenn. 50 (5), 21. https://doi.org/10.14214/sf.1689.

Laitila, J., Ahtikoski, A., Repola, J., Routa, J., 2017. Pre-feasibility study of supply systems based on artificial drying of delimbed stem forest chips. article id 5659 Silva Fenn. 51 (4), 18. https://doi.org/10.14214/sf.5659.

Laitila, J., Väätäinen, K., Kilpeläinen, H., 2019. Integrated harvesting of industrial roundwood and energy wood from clearcutting of a Scots pine-dominated peatland forest. Int. J. For. Eng. 31 (1), 19–28. https://doi.org/10.1080/14942119.2020.1672462.

Laitila, J., Repola, J., Holmström, E., 2025. Time consumption models for predicting harvester productivity when selection cutting, thinning from below, and clearcutting Scots pine-dominated stands in Finnish lapland. Int. J. For. Eng. 36 (2), 1–16. https://doi.org/10.1080/14942119.2024.2448935.

Laurén, A., Sikanen, L., Asikainen, A., Koivusalo, H., Palviainen, M., Kokkonen, T., Kellomäki, S., Finér, L., 2008. Impacts of logging residue and stump removal on nitrogen export to a stream: a modelling approach. Scand. J. For. Res. 23 (3), 227–235. https://doi.org/10.1080/02827580802116184.

Lindblad, J., Routa, J., Ruotsalainen, J., Kolström, M., Isokangas, A., Sikanen, L., 2018. Weather based moisture content modelling of harvesting residues in the stand. article id 7830. 16 p. Silva Fenn. 52 (2). https://doi.org/10.14214/sf.7830.

Makinen, H., Smolander, A., 2025. Effects of logging residue on the growth and properties of the humus layer in Scots pine and Norway spruce stands. For. Ecol. Manag. 580, 122526. https://doi.org/10.1016/j.foreco.2025.122526.

Martinkus, N., Latta, G., Morgan, T., Wolcott, M., 2017. A comparison of methodologies for estimating delivered forest residue volume and cost to a wood-based biorefinery.

Biomass.. Bioenergy 106 (ember 2017), 83–94. https://doi.org/10.1016/j.biombioe.2017.08.023.

Möller, B., Nielsen, P.S., 2007. Analysing transport costs of danish forest wood chip resources by means of continuous cost surfaces. Biomass.. Bioenergy 31 (5), 291–298. https://doi.org/10.1016/j.biombioe.2007.01.018.

Muukkonen, P., Lehtonen, A., 2004. Needle and branch biomass turnover rates of Norway spruce (Picea abies). Can. J. For. Res. 34 (12), 2517–2527. https://doi.org/10.1139/x04-133.

Niemistö, P., 1992. Runkolukuun perustuvat harvennusmallit. [Thinning models based on the number of stems]. Finnish forest research institute. Res. Pap. 432, 18 (Helsinki).

Nilsson, B., 2016. Extraction of logging residues for bioenergy – effects of operational methods on fuel quality and biomass losses in the forest. Linna Univ. Diss. No 270/2016 200. ⟨https://api.semanticscholar.org/CorpusID:132903194⟩.

Nilsson, B., Nilsson, D., Thörnqvist, T., 2015. Distributions and losses of logging residues at clear-felled areas during extraction for bioenergy: comparing dried- and fresh-stacked method. Forests 6 (11), 4212–4227. https://doi.org/10.3390/f6114212.

Nilsson, D., Nilsson, B., Thörnqvist, T., Bergh, J., 2018. Amount of nutrients extracted and left behind at a clear-felled area using the fresh-stacked and dried-stacked methods of logging residue extraction. Scand. J. For. Res. 33 (5), 437–445. https://doi.org/10.1080/02827581.2018.1427786.

Nurmi, J., 1999b. The storage of logging residue for fuel. Biomass.. Bioenergy 17 (1), 41–47. https://doi.org/10.1016/S0961-9534(99)00023-9.

Nurmi, J., 1999a. Hakkuutähteen ominaisuuksista [A study of the characteristics of logging residues]. Finnish forest research institute. Res. Pap. 722, 32 (Helsinki).

Nurmi, J., 2007. Recovery of logging residues for energy from spruce (*pices abies*) dominated stands. Biomass.. Bioenergy 31 (6), 375–380. https://doi.org/10.1016/j.biombioe.2007.01.011.

Nurminen, T., Heinonen, J., 2007. Characteristics and time consumption of timber trucking in Finland. Silva Fenn. 41 (3), 471–487. https://doi.org/10.14214/sf.284.

Official Statistics of Finland, 2024. Wood in energy generation 2023 [web publication]. Helsinki: natural resources institute Finland [referred: 29.11.2024]. Access Method. ⟨https://www.luke.fi/en/statistics/wood-consumption/wood-in-energy-generation-2023⟩.

Official Statistics of Finland. 2025. Total roundwood removals and drain [web publication]. Helsinki: Natural Resources Institute Finland [referred: 15.8.2025]. Access method: ⟨https://www.luke.fi/en/statistics/total-roundwood-removals-and-drain⟩.

Österberg, M., Karjalainen, M., Lintunen, J., Tammelin, T., Asikainen, A., Vakkilainen, E., Toivonen, R., Virta, P., Henn, A., Nuutinen, E.-M., Kohl, J., Hassinen, J., 2024. From timber to Medicine – value added for the forest sector through broadening the product portfolio. Report of the Finnish forest bioeconomy science panel 1/2024. Finn. For. Bioeconomy Sci. Panel Hels. 34.

Pekkarinen, A.-J., Laitila, J., Kumpula, J., Hallikainen, V., Rautio, P., Siitari, J., Hoppula, S., Aatsinki, P., Lahti, J., Holmström, E., 2024. HAKEMA: Hakkuutähteiden keruun mahdollisuudet poro- ja metsätalouden yhteensovittamisessa [Possibilities of logging residue harvesting to matching the requirements of reindeer husbandry and forestry]. Luonnonvara- ja biotalouden tutkimus 38/2024. Luonnon Hels. 66.

Prices of energy wood quarterly. 2024. Natural Resources Institute Finland. Access method: ⟨https://www.luke.fi/en/statistics/volumes-and-prices-in-energywood-trade⟩.

Ranta, T., 2002. Logging residues from regeneration fellings for biofuel production – a GIS-based availability and supply cost analysis. Doctoral thesis. Acta universitatis lappeenrantaensis 128. Lappeenranta university of technology. Lappeenranta 180.

Ranta, T., 2005. Logging residues from regeneration fellings for biofuel production – a GIS-based availability analysis in Finland. Biomass.. Bioenergy 28 (2), 171–182. https://doi.org/10.1016/j.biombioe.2004.08.010.

Ranta, T., Korpinen, O.-J., 2011. How to analyse and maximise the forest fuel supply availability to power plants in eastern Finland. Biomass.. Bioenergy 35 (5), 1841–1850. https://doi.org/10.1016/j.biombioe.2011.01.029.

Ranta, T., Rinne, S., 2006. The profitability of transporting uncomminuted raw materials in Finland. Biomass.. Bioenergy 30 (3), 231–237. https://doi.org/10.1016/j.biombioe.2005.11.012.

Ranta, T., Lahtinen, P., Elo, J., Laitila, J., 2007. The effect of CO2 emission trade on the wood fuel market in Finland. Biomass.. Bioenergy 31 (8), 535–542. https://doi.org/10.1016/j.biombioe.2007.01.006.

Ranta, T., Karhunen, A., Laihanen, M., 2017. Factors behind the development of forest chips use and pricing in Finland. Biomass.. Bioenergy 98, 243–251. https://doi.org/10.1016/j.biombioe.2017.02.004.

Rauch, P., 2013. Improving the primary forest fuel supply chain. Bull. Transilv. Univ. Brasov Ser. II 6 (55), 1–8.

Roitto, J., 2014. Puuhakkeen käsittely- ja poltto-ominaisuuksien parantaminen [Improvement of combustion and processing properties of woodchips]. Lappeenranta University of Technology. Master's thesis. Lappeenranta. 111 p. (In Finnish)..

Routa, J., Asikainen, A., Björheden, R., Laitila, J., Röser, D., 2013. Forest energy procurement - state of the art in Finland and Sweden. WIREs Energy Environ. 2 (6), 602–613. https://doi.org/10.1002/wene.24.

Spinelli, R., Ivorra, L., Magagnotti, N., Picchi, G., 2011. Performance of a mobile mechanical screen to improve the commercial quality of wood chips for energy. Bioresour. Technol. 102 (15), 7366–7370. https://doi.org/10.1016/j.biortech.2011.05.002.

Spinelli, R., Glushkov, S., Markov, I., 2014. 2014. Managing chipper knife wear to increase chip quality and reduce chipping cost. Biomass.. Bioenergy 62, 117–122. https://doi.org/10.1016/j.biombioe.2014.01.007.

Statistics Finland. 2024. Cost index of forest machinery and vehicles [e-publication]: ⟨https://www.stat.fi/tup/kustannusindeksit/metsaalan-kone-ja-autokustannusindeksi.html⟩.

Strandström, M., 2021. Metsähakkeen tuotantoketjut suomessa vuonna 2020 [Production systems of forest chips in Finland, Year 2020]. Metsätehon tuloskalvosarja 8/2021. Helsinki 20.

Strandström, M., 2024. Timber harvesting and long-distance transportation of roundwood 2023. Metsäteho Result Series 2-EN/2024. Helsinki. 32 p..

Tienaho, J., Fidelis, M., Brännström, H., Hellström, J., Rudolfsson, M., Kumar Das, A., Liimatainen, J., Kumar, A., Kurkilahti, M., Kilpeläinen, P., 2024. Valorizing assorted logging residues: response surface methodology in the extraction optimization of a Green Norway spruce needle-rich fraction to obtain valuable bioactive compounds. ACS Sustain. Resour. Manag. 1 (2), 237–249. https://doi.org/10.1021/acssusresmgt.3c00050.

Väätäinen, K., Prinz, R., Malinen, J., Laitila, J., Sikanen, L., 2017. Alternative operation models for using a feed-in terminal as a part of the forest chip supply system for a CHP plant. GCB Bioenergy 9 (11), 1657–1673. https://doi.org/10.1111/gcbb.12463.

Väätäinen, K., Anttila, P., Eliasson, L., Enström, J., Laitila, J., Prinz, R., Routa, J., 2021. Roundwood and biomass logistics in Finland and Sweden. Croat. J. For. Eng. 42 (1), 39–61. https://doi.org/10.5552/crojfe.2021.803.

Viiri, H., Viitanen, J., Mutanen, A., Leppänen, J., 2019. Metsätuhot vaikuttavat euroopan puumarkkinoihin – suomessa vaikutukset toistaiseksi vähäisiä [Forest damages affects the European timber market - in Finland the effects has been so far small]. Metsätieteen aikakauskirja, vuosikerta 2019, artikkeli 10200. Tieteen tori. Helsinki 7. https://doi.org/10.14214/ma.10200.

Wawro, A., Jakubowski, J., Gieparda, W., Pilarek, Z., Łacka, A., 2023. Potential of pine needle biomass for bioethanol production. Energies 16 (9), 3949. https://doi.org/10.3390/en16093949.

Windisch, J., Väätäinen, K., Anttila, P., Nivala, M., Laitila, J., Asikainen, A., Sikanen, L., 2015. Discrete-event simulation of and information-based raw material allocation process for increasing the efficiency of an energy wood supply chain, 315–325 Appl. Energy 149. https://doi.org/10.1016/j.apenergy.2015.03.122.

Wolfsmayr, U.J., Rauch, P., 2014. The primary forest fuel supply chain: a literature review. Biomass.. Bioenergy 60, 203–221. https://doi.org/10.1016/j.biombioe.2013.10.025.