Integrated supply of stemwood and residual biomass to forest-based biorefineries

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Forest biomass may increasingly become demanded as raw materials for a wide range of products in the developing bioeconomy. Along with a constant pressure on forestry to increase its productivity, this development has led to the search for new procurement methods and new assortments. The present study assessed innovative supply chain practices, with a particular focus on the integrated supply of stemwood and residual tree parts. The assortments considered included tree sections, long tops, saw logs with stump cores and small whole trees from thinnings. The assessment included geographically explicit modelling of the supply chain operations and estimation of supply cost and energy use for three industrial locations in Northern Sweden. The innovative supply chains were compared to conventional, separate, harvest of stem wood and logging residues.

We conclude that integrated harvest of tops and branches with stem wood assortments, as well as whole-tree harvest in early thinnings, has a significant potential to reduce the supply cost for the non-stem wood assortments. Stump wood generally remains the most expensive assortment. The energy use analysis confirms earlier research showing that the energy input is relatively small compared to the energy content of the harvested feedstock.

Keywords: wood supply chain; forest fuels; harvesting system; forest feedstock assortment; supply cost; energy use

Acronym list

Locations

UME= Umeå, ORN= Örnsköldsvik, STO= Storuman

Supply systems

A= conventional forestry regime and separated supply system options, B= conventional forestry regime and integrated supply system options, C= biomass-dedicated and integrated supply system options

Forest treatments

PCT= pre-commercial thinning, FT= first thinning, ST= second thinning, FF = final felling, ET= energy thinning

Assortments

SL= sawlogs, PL= pulpwood, LR= logging residues, SP= stumps, RS= roughly delimbed tree sections, LT= long tops, WT= whole small trees, BWT= bundled whole small trees, SPC= stump core

Units

EUR= Euro, GJ= Giga Joule, m^3 o-b= solid m^3 over-bark, PM_0h= productive machine hours excluding delays, $PM_{15}h$= productive machine hours, t= oven dry tonne

Introduction

The harvest of roundwood in Sweden has increased continuously since the early 20th century, while at the same time the forest stock has increased as a result of active forest management. Swedish forestry has developed into an efficient supplier of stemwood to pulp mills and sawmills and its productivity has improved through mechanization and technical development.

Several driving forces are currently affecting the forest industry (Sörensson & Jonsson 2014). The demand for graphical paper is declining on several markets and the Swedish industry is encountering new competition from regions with fast-growing feedstock. At the same time, concerns about climate change and about the security of supply of fossil resources have acted to drive a search for new forest-based concepts for the production of material, energy and chemical products. Special attention has been paid to the concept of biorefining, where several products are co-produced in order to optimally utilize different fractions of the feedstock. This could lead to new uses of stemwood as well as an increased demand for other tree parts.

The harvesting system presently dominating in Sweden is the cut-to-length (CTL) system, where the tree is delimbed and the stem is cut into logs of appropriate length in the forest and then extracted to road side. Coarse logs of good quality are supplied to sawmills while low quality and smaller-diameter logs in general are supplied to pulp mills. The harvest residues – tops and branches – have, increasingly, been recovered separately, mainly for the production of heat and power. Tree stumps are recovered only at a very modest rate (Routa et al. 2013; Helmisaari et al. 2014). Certain adjustments in the harvesting operations have been made to facilitate the collection of the residues in order to improve productivity and fuel quality throughout the supply chain (Skogforsk 2010). The basic principles of the harvesting operations have, however, remained the same over the past 20 years. An alternative to present practice is to use supply systems where the residual biomass supply chain is integrated with the stem wood supply chain. Such systems were scrutinized in the late 1970s in Sweden, when the global oil crisis motivated increased efforts to utilize domestic forest biomass in order to secure the supply of energy (Whole Tree Utilization 1975-1980). However, the crisis was temporary and although the single-grip harvester was introduced in the early 80s together with the CTL system, the extraction of undelimbed wood (tree parts/sections) declined and finally fell out of use by the late 80s (Nordfjell et al. 2010). The current increasing demand for forest biomass has resulted in new developments in "integrated" forest harvesting systems (c.f. Berg et al. 2014). Understanding of the potential consequences of new practices can guide development efforts and increase the knowledge about future feedstock availability. The potential of the new integrated systems will depend on regional conditions such as forest composition and distribution, transportation distances and design of the full supply chain. To our knowledge, there are no studies aiming to quantify this potential for the selected systems.

The objective of the present study has been to assess the costs and energy use associated with supply chains that integrate the harvest of residue assortments into the stemwood supply chain. The integrated harvesting systems were compared to present conventional systems. The assessment was applied to three industrial locations suitable for biorefineries in Northern Sweden, using geographically explicit forest inventory data.

Materials and Methods

System description

An integral component of evaluating the forest feedstock supply and its implications is the understanding of the quantities of forest resources that might be available at any given price, i.e. a supply curve (Lundmark 2004). Based on observed productivity and energy use during forestry operations, we modeled the costs and energy used in the supply of conventional and new forest feedstock assortments. Three sites in Northern Sweden were selected for the study (Fig. 1). Two are on the coast, Umeå (UME) and Örnsköldsvik (ORN). Both have existing biomass-fired combined heat and power plants as well as large pulp mills and potential locations for new types of biorefinery industries. The third location, Storuman (STO), is located inland and is a potential location for a biorefinery or an industrial-scale hub for feedstock handling and upgrading before further transport to more distant industries. The three industrial sites are assumed to be located in the centre of the three cities and a supply area with a radius of 120 km around each of the locations was considered.

Cost and energy use curves were calculated by modelling and adding together the costs and energy use for all operations from harvest to delivery to industry. Results are presented as supply cost curves and energy use curves for conventional and new forest feedstock assortments. The energy use and supply cost are given per oven dry tonne (t) of feedstock delivered. Costs in Swedish currency (SEK) have been converted to euro using a conversion rate of 1 EUR (€)= 9.2 SEK.

<Figure 1 left> <Figure 1 right>

A conventional forestry regime was considered, in which a forest cycle was assumed to include pre-commercial thinning (PCT), first thinning (FT), second thinning (ST) and final felling (FF). The main assortments extracted from the forest in conventional forestry are sawlogs (SL) and pulpwood (PL). In addition, logging residues (LR) and stumps (SP) can be harvested. Two harvesting systems were compared within the conventional forestry regime (Systems A and B in Table 5). In system A stemwood and residual assortments are harvested separately while in system B stemwood and residual assortments are harvested together either as roughly delimbed tree sections (RS), long tops (LT) or sawlogs with a stump core (SPC) (see Berg et al. 2014). An alternative forestry regime was also considered which included an energy thinning (ET) instead of PCT. In ET, unprocessed tree sections from whole small trees (WT) are extracted whereas in PCT the cut trees are left on site. The WT can be extracted loose or in bundles (BWT) (System C in Table 5). The length of a forest cycle for both regimes was fixed to 95 years. The assortments considered are defined in Table 2 and the harvesting systems are described in Table 5.

<Table 1 >

To ensure comparability, all studied supply systems were assumed to follow a general scheme where harvested feedstock is forwarded to the roadside and then transported by truck to a terminal in the vicinity of the receiving industry. The distance between the terminal and the industry was set to 5 km. LR were assumed to be chipped at the roadside before transport to the terminal. All the other assortments are transported untreated to the terminal where they are further processed before delivery to industry. We also considered two scenarios, I and II, for the terminal operations. In scenario I, PL and the pulpwood part of RS and LT assortments is separated from residues (bark, branches and tops) at the terminal by means of a chain flail delimber/debarker and the assortments obtained are separately supplied to the industry in the form of debarked PL and chipped residues. In scenario II, all material (pulpwood and residues) is chipped and delivered directly without sorting at the terminal. Assortments SP, WT, BWT and SPC are chipped without sorting in both scenarios. The operations and associated dry matter losses for each supply chain are summarized in Table 3. Energy use for general stand management operations, such as soil preparation, planting, and PCT was not included in the analyses. The costs associated with these operations were included indirectly in the land owner compensation.

<Table 2 >
<Table 3 >

The stand density and timing for each treatment (Table 1) were chosen based on the recommendations of Karlsson (2013) and the Swedish Forest Agency (2008). The stand development and tree size characteristics at each treatment stage were based on inventoried sample stands dominated by pine and spruce and were selected to be representative of the study region (SFA 2008). For each stage of development, the characteristics of one pine dominated and one spruce dominated stand were averaged. The characteristics of the stands were based on Gustavsson (1974) for PCT (stands 301 and 501) and for early thinning (stands 303 and 502). Type stands in Bredberg (1972) were used for FT (stands 310 and 401) and ST (stands 217 and 224). For FF, stands were based on Herlitz (1975) (stands 154 and 451).

In the alternative forest regime (system C), the ET is performed at a later stage than the PCT, and the FT is also delayed. The impact of the ET on the subsequent thinning operations is uncertain and will depend on stand characteristics (Karlsson 2013). We assumed that the difference in yield between the FT with and without ET is negligible. We assumed that ET would be performed using the boom-corridor technique (Bergström & Di Fulvio 2014).

Allocation
Several of the operations in this study yield two or more products and in order to determine the production cost and energy use for each of the products, process costs and energy use have to be allocated between them. Costs in systems B & C were calculated for the full supply chains and allocated between the products based on the change in costs and energy use compared to a reference case (A). For example, in system B with integrated harvest of roundwood and residues, only the *additional* cost of the integrated operation compared to separate roundwood harvest was allocated to the residue fraction. The cost and energy use allocated to the roundwood fraction is identical in all three alternative supply systems. For conventional system (A), harvester costs or energy use were allocated between stemwood assortments on a mass basis, whereas no harvester costs or energy use were allocated to the SP and the LR. Since the stemwood is considered the main product, the felling and delimbing process is carried out essentially in the same way irrespective of whether the SP and LR are recovered or not.

Geographical distribution

In calculating the terrain transport distance, the Network Analyst module in ArcGIS was used, and a winding coefficient of 1.2 was applied to the geodetic distance, following Athanassiadis et al. (2009). Transportation distances according to the Swedish road network were used in the calculations of road transportation.

Forest biomass harvest was modelled based on data from the Swedish National Forest Inventory (SNFI). The SNFI data were merged with the SFA (2008) data to model the growth, the yearly harvestable surface and the volume represented by each forest inventory plot over years 2010-2019. Each plot was used as a silvicultural decision unit and contained information on its geographical coordinates (X, Y), the management (FT, ST or FF), and soil characteristics. For each plot, the annual average amount of feedstock available from harvesting operations was calculated as well as average costs for harvest, forwarding and transportation of the feedstock to a terminal followed by delivery to the end user. Therefore the supply curves represent a 10 year average. Within the 120 km radius area, 268 inventory plots were included for UME, 279 for ORN and 150 for STO. Of this number of plots, 30 plots for UME, 29 for ORN and 11 for STO were excluded because of environmental protection reasons. A separate dataset from the SNFI contained information for PCT and early ET stands, adding 32 plots for UME, 42 plots for ORN and 30 plots for STO. The biomass functions in Petersson (1999) and Petersson and Ståhl (2006) were used to estimate the amounts (t/ha) of roundwood, bark, branches, needles, tops and stumpwood including root system from the SNFI data. Broadleave stumps were excluded (i.e. assumed to be left on site).

Available feedstock amounts
The proportions of wood assortments were calculated according to Ollas (1980). The top diameter for SL and PL logs was fixed respectively at 12 and 5 cm under bark. The mass of LR at FF in system A was calculated as the sum of the mass of branches and tops. The RS mass was calculated as the sum of the PL, tops, and the respective portion of branch mass as in Table 4. The mass of LT in the ST was calculated as the sum of PL mass and tops and by adding branches according to Table 4. The LT mass in FF was calculated as the sum of PL and mass of tops. The amount of wood for each assortment was added to the bark proportion given in Table 4, in order to obtain the mass over bark of SL, PL, LR, RS, LT.

<Table 4 >

The annual potential for harvesting WT from ET stands was calculated in plots where the average height was between 5.5 m and 8 m and where the removal biomass exceeded 25 t/ha. The WT and BWT mass was obtained as the sum of PL, tops, bark and total branches mass. Plots where the average height was between 2.0 m and 5.5 m and the removal biomass exceeded 10 t/ha were classified as PCT stands. The total SP mass was given in the inventory plots. The stump core mass (SPC) was calculated by multiplying the total stemwood mass (SL, PL, tops and bark) by 0.085, following Berg et al. (2014). Dry densities in Table 4 were used for volume-to-mass conversions.

Cost functions

The supply cost functions were composed of harvest cost, forwarding cost, landing operation cost, truck transport cost, terminal cost, cost of transport from terminal to industry, land owner compensation, overhead costs. The compensation per biomass unit (t) to landowners (i.e. the stumpage price for the stand) in a FT, a ST and a FF was based on actual local prices (Norra skogsägarna pers. comm., October 2013). The land owner was assumed to receive economic compensation for the removal of LR, but not for SP removal, as in current practices. The compensation paid to the land owner is lower for PL from thinnings than from FF due to the limited profitability of thinning operations. In a FT the PL compensation is 14.13 €/t, in the ST it is 29.35 €/t and in a FF it is 59.78 €/t. The LR compensation from FF is 7.61 €/ t and WT as energy-wood do not provide any compensation to the landowner. An overhead cost of 2.72 €/t for administration of forest operations was added (Brunberg 2013).

<Table 5 >

Harvesting

The time consumption for each machine and operation was expressed as $PM_{15}h/t$ ($PM_{15}h$= productive machine hours including delays shorter than 15 minutes).

The effective time consumption per tree for the harvesters was deterministically calculated by means of literature functions (Eq.1-11, Table 6). The time consumption formulas assumed ideal terrain condition (c.f. Berg, 1992). For the harvester's time consumption formulas, 50% pine and 50% spruce removal was assumed. In the case of harvesting RS in FT following ET (supply system C), the same time consumption per hectare as in system B was used.

<Table 6 >

The stem volumes and densities of trees per hectare used as parameters for calculations of time consumption were based on the stands in Table 1. The time consumption per tree (Eq. 1-11) was divided by the total mass of assortments harvested in each operation (cf. Table 6, column 1) to obtain the time consumption per unit of mass (PM_0h/t). The average mass of extracted SP was calculated according to Larsson (2011). The PM_0 time was converted to PM_{15} by multiplying values by the coefficient 1.30 (Kuitto et al. 1994) for the harvesters and by multiplying by 1.33 in case of PCT (Ligné et al. 2005).

Forwarding

The time consumption for wood extraction with forwarders included a fixed terminal time (i.e. loading and unloading) added to a variable extraction time that was distance-dependent. The PM_0h/t for each assortment and operation was calculated by means of Eq. 12-25 using the load sizes and models given in Table 7. The PM_0 time for forwarders was converted to PM_{15} by multiplying the value by the coefficient 1.2 (Kuitto et al. 1994).

<Table 7 >

Landing operations

The time consumption for a truck-mounted drum chipper for LR at the roadside was assumed to be 0.086 PM_{15} h/t according to Karlsson (2010). In the case of pre-crushing the SP at the roadside, the productivity of a horizontal low speed shredder was assumed to be 0.050 PM_{15}h/t according to Bertilsson (2011), in this case also a wheel loader was included in the system.

Road transportation

In road transportation, standard 24 m long truck and trailer systems of 22-32 t (un-loaded) with a crane for self-loading were considered for all products. The gross mass was set to 60 t. The time consumption models were given by the sum of terminal activities (i.e. loading and unloading) and driving time (Table 8). The distribution of traveling speeds was set according to Fjeld (2012) and applied in the range 5-120 km (Eq. 26-34) and the load sizes were set according to Table 8.

The PM_0 time was converted into PM_{15} by adding a delay time of 8 min. per load, according to Nurminen and Heinonen (2007).

<Table 8 >

Forest machinery cost rate

The hourly cost for each forest machine (excluding VAT) was analytically calculated in €/PM_{15}h according to Harstela (1993) and Bergström & Di Fulvio (2014a) (Table 9). Purchase prices for forest machines were obtained directly from machine dealers in Sweden. For a thinning harvester equipped with a boom-corridor head, the purchase price was assumed to be 30% higher than a conventional thinning harvester. For a small forwarder, the installation of compacting stakes was assumed to increase the purchase price by 5% compared to a normal one. Fuel and lubricant consumption values used are presented in Table 12 (c.f. energy calculation methods). Prices for diesel and lubricants were set to 1.29 and 2.59 €/l (www.energy.eu/fuelprices).

<Table 9 >

The operating cost for a bundler-harvester producing BWT was assumed to be 84% higher than a "medium sized forwarder" according to assumptions in Kärhä et al. (2011), giving 156.09 €/PM_{15}h. For a feller-puller for extraction of SP the operating cost was assumed to be a 36% more than for a "large harvester" according to Berg et al. (2014), giving 160.00 €/PM_{15}h. A fixed relocation cost of 271.74 €/machine/relocation was considered for all machines which needed to be relocated using a truck (harvesters, forwarders, roadside chipper, shredder); the average relocation distance between harvested plots was assumed to be 25 km; the relocation cost and distance was representative of the normal situation in the studied Region (cf. Di Fulvio et al. 2011).

Road transportation cost rate

The truck and trailer unit purchase prices were based on information from contractor companies (Table 10). The fixed hourly cost (F_h), variable cost for driving (V_{km}) and variable cost for the crane (V_{ld}) (Table 10) were calculated according to Bergström & Di Fulvio (2014a) and used for assessing trucking fixed (Tr_f) and variable costs (Tr_v) per tonne.

<Table 10 >

The forest harvesting and road transportation cost models are presented in Appendix 1.

Terminal operations cost rate

For all the assortments a storage period of 1 month in the terminal before re-loading and transportation of 5 km to the end user was assumed and the storage cost for using the terminal area was calculated according to Table 11. Two different scenarios were considered for delivery from the terminal to the end user:

I) delivery of debarked PL and chipped residues;

II) all woody material delivered after chipping (i.e. no PL debarking or delimbing);

In terminal scenario I: PL, RS and LT were considered to be delimbed and debarked with a chain flail delimber/debarker at the terminal. After the debarking/delimbing, chipping of the residual fractions from RS and LT (bark, branches and tops) with a large crusher was assumed.

The costs per t for a chain flail delimber/debarker were obtained by actualizing the cost figures in the literature with an inflation rate of 79%. The same delimbing/debarking cost per t was assumed for logs and residues (bark, branches, tree tops) (cf. Table 11). In terminal scenario II: PL, RS, LT were considered to be chipped directly (i.e. no debarking/delimbing) with a large disc chipper. In both terminal scenarios, WT and BWT were considered to be chipped directly at the terminal with a large disc chipper, without delimbing/debarking; the cost of chipping WT was assumed to be the same as for RS, and for BWT was assumed to be the same as for PL (c.f. Table 11). For SP it was considered that crushing was conducted in the terminal using a large crusher. For pre-crushed SP, it was considered that refining to smaller dimensions was achieved by means of a large crusher. The cost of sieving the SPC from SL was based on industrial figures for bucking the logs using a large saw blade driven by a 11 kW electric motor (cf. Table 11). All PL logs obtained in the terminal were assumed to be re-loaded onto trucks and trailers, while woodchips were assumed to be re-loaded into container trucks with capacities according to Table 8, in both cases the re-loading was assumed to be undertaken with a front wheeled loader with costs as in Table 11. The final transportation to the end user was assumed to take the same time for all trucks and calculated as 0.37 $PM_{15}h$/load, as the time required for trucks to be driven from the terminal to the industry (i.e. no unloading cost at industry is included). The final transportation costs were calculated according to Table 11.

<Table 11 >

Energy use functions

The energy use was calculated for each assortment supply chain in each location applying a life cycle perspective. A number of assumptions were made when defining the energy use functions:

- Average relocation distance of machinery and workers between sites was set to 25 kilometers.
- Trucks were assumed to be fully loaded for transport, with empty returns. The number of truck transports needed from each harvesting site was rounded to an integer number assuming that a truck could transport 10% more than its nominal capacity.
- The loading/unloading time for forestry machinery from/to a truck was assumed to be 8 minutes.
- The energy content of lubricants was assumed to be the same as the energy content of diesel.
- Each working day was considered to be 8 hours.
- Energy and materials needed for construction and maintenance of machinery, forestry roads, and ancillary materials were not included in the analysis.

Energy functions

The energy use was calculated per assortment in liters of diesel per t according to the equation below:

$$E = Tw + Tm + Lm + Ha + Hafp + Fo + Ex + Cc + Ls + Ch + Tr + To \text{ (Eq. 35)}$$

Where:

- *Tw* is the fuel consumption for transporting workers to and from the harvesting site (l/t)

$$Tw = \frac{2 \times D \times pfc \times Wd \times Nhs}{m} \text{ (Eq. 36)}$$

D: distance from one harvesting site to the next harvesting site (km); *pfc*: fuel consumption of a pick-up truck (0.11 l/km); *Wd*: number of working days needed to harvest a site (rounded up to the closest integer number); *Nhs*: number of harvesting sites in each inventory plot; *m*: assortment removal mass of the yearly harvesting area in each inventory plot with total material losses (t).

- *Tm* is the fuel consumption for transporting machinery to and from the harvesting site (l/t)

$$Tm = \frac{D \times tfc \times Nhs}{m} \text{ (Eq. 37)}$$

tfc: fuel consumption of a truck while driving (0.56 l/km)

The total "*Tm*" allocated to each assortment was obtained by multiplying "*Tm*" by the number of machines involved in extraction of that assortment.

- *Lm* is the fuel consumption by loading/unloading of machinery (l/t)

$$Lm = \frac{2 \times t \times mfc \times Nhs}{m} \text{ (Eq. 38)}$$

t: time to load and unload the machine from the truck; *mfc*: machine fuel consumption (l/h);

The total "*Lm*" allocated to each assortment was obtained by adding together the "*Lm*" of all the machines involved in the extraction of that assortment.

- The fuel consumption (l/t) for harvesting and processing with harvester (*Ha*), harvesting with feller-puller (*Hafp*), forwarding (*Fo*), excavating SP (*Ex*), coarse crushing (*Cc*), loading SP to shredder (*ls*) and chipping (*Ch*), was obtained by multiplying the operational time consumption ($PM_{15}h/t$) by the respective hourly fuel consumption (l/h) (Table 12) as in the following example:

  $Ha = hp \times hfc$

  Ha (l/t): fuel consumption of harvesting and processing with harvester; *hp*: harvester time consumption for each assortment ($PM_{15}h/t$); *hfc*: harvester hourly fuel consumption (l/h)

- *Tr* is the fuel consumption for road transportation (l/t)

$$Tr = driving fc + load, unload fc = \frac{(2 \times Trdist \times tfc + ltfc \times Tt) \times n \times Nhs}{m} \text{ (Eq. 39)}$$

Tr_{dist}: road transportation distance from the harvesting site to industry (km); *ltfc*: fuel consumption for loading and unloading a truck (7.70 l/h); *Tt*: truck terminal time (h/load, unload and complementary activities); *n*: number of trucks needed at each harvesting site to transport the assortments.

To is the fuel consumption during terminal operations.

Fuel and lubricant consumption by forestry machinery and machinery in terminals was based on figures from the literature, according to Tables 12 and 13. The fuel consumption by trucks was assumed to follow Lindholm and Berg (2005), the fuel consumption by the pick-up truck was based on Fuel economy (2014). The lubricant consumption of trucks and pick-up trucks was assumed to be 0.2% of the fuel consumption (Lindholm et al. 2010).

<Table 12 >
<Table 13 >

The energy use for each supply chain is expressed as a percentage of the energy content of the delivered material. The energy content of wood was calculated on a lower heating value (LHV) basis. Assuming a LHV of 17.3 GJ/t for all biomass assortments and 35 GJ/m^3 for diesel.

Sensitivity analysis

Important parameters of the study were varied in a sensitivity analysis. In the integrated harvesting systems it was assumed that there were no losses of branches on site when handling LT. Technical solutions may need to be developed in order to release some portion of the logging residues (eg. needles) at the harvesting site so as not to compromise the soil fertility, especially during thinnings (cf. Egnell 2011). Rough delimbing heads are under development for use in ET; it could be expected that 10-15% of the total biomass can be left on site when harvesting WT in ET (c.f. Bergström & Di Fulvio 2014b).

- Variation 1: Assume harvesting losses of 20% of the residue part and from the LT in system B-C in the ST and FF.

If residues are harvested and transported as loose WT or LT, usually it is not possible to reach the maximum load capacities of trucks, due to the material's bulkiness. Therefore, the trucks for WT and LT in B-C could be equipped with compacting stakes to increase the biomass density for road transportation.

- Variation 2: Assume an increase in trucking load capacity of 25% and 15%, respectively, for WT and LT. An extra investment of 50,000 € on the purchase price of the LR truck and trailer unit is added.

For some of the machinery included in the innovative systems it was not possible to calculate analytically the costs, and their operating costs were based on assumptions, due to the fact that the machinery is still a prototype (bundle-harvester) or at the concept stage (feller-puller). Similarly, the productivity of such new machines is uncertain. The productivity assumed for a feller-puller was obtained from a simulation study. When comparing simulation results to field studies, overestimates of productivities of ca. 15% were found (eg. Sangstuvall et al. 2011). This is due to possible simplification of working environments in simulations compared to real forests. In the case of a bundler-harvester it was assumed that the machinery would be able to operate with the same efficiency as a boom-corridor harvester, which is an expected evolution of current machinery (c.f. Bergström & Di Fulvio 2014b). However, as recently observed by Björheden and Nuutinen (2014), the productivities of a novel prototype of bundle-harvester doubled compared to the previous version, and the current level is ca. 15% lower than the one considered in our study. However, a significant increase in productivity can be expected in future when the machine is also equipped with a head for boom-corridor thinning (c.f. Sangstuvall et al. 2011). Increased hourly costs and reduced productivity would both have a similar impact on the costs per t.

- Variation 3: Increased cost by 20% for operation of feller-puller (integrated log and SPC harvest) and bundle-harvester (integrated bundling and harvesting of WT in ET).

Results

The three locations differ mainly in the total feedstock amount that could be produced: 1.3 Mt/yr for STO, 2.1 Mt/yr for UME and 2.3 Mt/yr for ORN, with supply system A (Table 14). The distribution between different assortments was, on average, 41% SL (including bark), 25% PL (including bark), 12% LR and 20% SP, for supply system A and differs only by a few percentage points between the three locations.

The supply of LR via supply system B increased the amount of residues compared to system A by 25% for ORN (UME: 15%, STO: 34%). The harvest of small trees during energy thinnings in supply system C adds 84000 t/yr for ORN (UME: 77000t/yr, STO: 86000 t/yr). The contribution of WT was comparatively large for the STO case, considering that the total feedstock amount was much smaller for STO than for UME and ORN. SPC harvest delivers only about 20% of the stump biomass, compared to conventional SP harvest.

<Table 14 >

Supply cost by assortment

The total costs for the 120 km radius supply area for the ORN case is given in Table 15. Combing data from Tables 14 and 15 gives that the assortments with the highest supply cost are SP and SPC with, on average, 12% and 10% higher supply cost than PL. For SP, road transportation (29%) and forwarding (27%) accounted for the largest cost shares, while increased harvesting cost accounted for the largest cost share (55%) for SPC. A small reduction in the productivity of the harvester may result in a high specific cost allocated to the SPC. LR supply cost was 12% lower than for PL, on average. The largest LR cost components were forwarding (31%) and road transportation (22%). RS and LT averaged a supply cost 7% and 15% lower, respectively, than for PL in system A. The largest cost components for RS are the transportation (29%) followed by forwarding (19%) and harvest (18%). For LT, land-owner compensation accounted for 32%, transportation for 29% and terminal operations for 18% of the cost. The cost of procuring WT is similar to that for RS or LT, and it is 5% lower than for PL. The main cost components in this case are road transportation (30%) and harvesting (29%). The supply cost of BWT is 15% lower than PL, and harvesting represents 42% of total costs.

<Table 15 >

Pulpwood

The cost and energy use curves for supply of PL to the three locations are shown in Figure 2. The PL cost and energy use are, by definition, the same in all systems A-C. The costs excluding land-owner revenue are highest for FT and lowest for FF, which is expected due to the larger amounts harvested – and thus higher productivity of the machines - in FF. When landowner compensation is included, costs are similar for all three types of harvesting operations, in the range 85-100 €/t for the main part of the curve. Energy use in the supply accounts for about 1.5-3% of the energy content of the delivered feedstock.

The cost and energy use levels are similar between the three locations, and differences are mainly found in the total feedstock amounts available within the 120 km radius. There are also some differences in the distribution of the amounts between the different harvesting operations, where a relatively large share of the PL comes from FF in the UME case compared to STO, and with ORN falling somewhere between.

<Figure 2>

Tops and branches

Supply cost curves for logging residues– tops and branches – obtained with the integrated supply system options B andC are shown in Figure 3, and compared to the corresponding curve for LR from FF with the conventional supply system A. The curve for B and C is generally below the curve for A. This means that more feedstock can be supplied at a given cost level. For example, at a marginal cost of 87 €/t, 100 000 t can be delivered by the conventional system A in UME and 240 000 t by B-C. Similar results can be observed in the case of ORN and STO. The energy use curve is similar for the conventional (A) and the integrated systems B andC. The main part of the curve stretches between 2% and 6%, which corresponds to 10-30 l of diesel use per t of biomass delivered. The supplied amounts from individual plots are ranked by increasing supply cost and the supply cost curve thus forms a smooth, increasing line. The corresponding energy use for each plot is shown in the energy use curve. The energy use is not perfectly correlated to the supply cost and hence shows a more uneven curve. However, it follows the same general trend as the costs, indicating that the more expensive parts of the curve also require more energy.

The maximum amounts of delivered residual assortments from LT and RS are 275 000 t, 341 000 t and 203 000 t per year for UME, ORN and STO, respectively. For conventional LR, the amounts are 239 000, 273 000, 151 000 t per year. The characteristics of the supply cost and energy use curves are similar between the three locations.

<Figure 3>

Stump wood
The supply cost per t for a given harvest site is, on average, 3.3 € lower for SPC harvest than for conventional SP harvest (112 €/t vs. 115 €/t). The amount of biomass harvested with SPC harvest is, however, only 20% (on average) of the amount with conventional harvest. The supply cost curve for stump wood with SPC harvest therefore lies well above the curve for conventional harvest (Figure 4). The energy use curve for SPC, on the other hand, lies below the curve for conventional harvest. This can be explained by the fact that the SPC cost is dominated by increased costs of the harvesting operation, which has low energy intensity (energy use per cost) whereas for conventional SP harvest, the cost share is higher for operations with high energy intensity (such as transport). Energy use is about 2-3% and 4-6% of feedstock energy content, for SPC harvest and conventional SP harvest, respectively.

<Figure 4>

Energy thinning trees
The harvested amounts are about 80.000 t/year for all three locations. The alternative which involves bundling of the whole trees at harvest has markedly lower supply costs (typically below 87 €/t) than the alternative where the trees are handled loose (typically around or above 87 €/t). In addition, energy use is lower for the bundling alternative by a little less than one percentage point and lies around 2-3% of the energy content of the delivered feedstock (Figure 5).

<Figure 5>

Chipping of all assortments without sorting (terminal alternative II)
The total recovered amount of biomass is 8-12% larger in the conventional-separated supply system option A than in B and C, due to the much larger amount of SP wood extracted compared to SPC. If SP harvest is employed instead of SPC in system C, the harvested amount is larger for C than for A (Figure 6.). The supply cost for chipped feedstock lies mainly in the 75-110 €/t range (Figure 6). The integrated systems B andC have markedly lower supply costs per t biomass compared to the conventional system A. Energy use figures lie around 2-4% of biomass energy content, as shown for the ORN case in Figure 7. The cost variation is larger for the conventional case, which could be expected since PL and LR are handled independently and require different amounts of energy, whereas in the integrated system, the stemwood and residual biomass are handled together and hence are processed in the same way, and that results in a significant reduction in supply costs for large amounts. For example, if assuming a marginal cost of 87 €/t, approximately 1 Mt more chips can be supplied in UME, ORN and STO together in system C than in the conventional case A, corresponding to an increase of approximately 330%.

<Figure 6>

<Figure 7>

Sensitivity Analysis

A 20% loss of residues in LT harvesting (Variation 1) would reduce the total potential by about 10%. The cost curve of system C would shift upwards, but it would still be well below the system A curve except at high supply levels (Figure 8). Increased load capacities (Variation 2) for trucking of LT would significantly reduce the total supply cost of system C.

<Figure 8>

Increased load capacity would also reduce the cost of unbundled WT (not shown in Figure 8), but it would still be higher than the BWT cost. Combining variation 2 with increased cost rate (variation 3) for the BWT system would result in more or less the same cost for BWT and WT. Hence, BWT was used for all the system C curves in Figure 8. The increased cost rate for BWT in Variation 3 has a small impact on the overall supply curve (visible in the first half of the supply curve, mainly at around 350-600 thousand t). Increased cost rate for the SPC system on the other hand, would have a significant impact on the supply cost for stump wood in system C (visible in the latter part of the curve, at about 1050-1200 thousand t). The reason for this is that the harvesting cost is dominating the supply cost for SPC wood in system C and all of the extra harvesting cost is allocated to the SPC and nothing to the stemwood or branches.

Kons et al. (2014) show that terminals in Sweden are, on average, located 44 km from CHP, 66 km from pulpmills and 18 km from sawmills. The variable transportation cost used in our calculations was approximately 0.12 €/t, km. A transportation distance of 66 km instead of 5 km would increase costs by 7.3 €/t, compared with the total costs for chipped material of about 65-110 €/t. This increase would, however, affect all assortments equally.

Discussion

The specific cost of individual operations and the amounts of feedstock extracted are key findings in the present analysis. The results indicate that there is a potential for decreasing the supply cost of forest biomass by using integrated harvest of stemwood with tree tops and branches, as compared to separate harvests. Also, small trees could be recovered from energy thinnings at an attractive cost, compared to conventional LR. SPC harvest has, on average, similar or slightly lower costs per t than SP harvest. However, it only results in about 20% of the stump biomass recovered during conventional stump harvest. On the other hand, SPC can be expected to be much cleaner than SP, which is typically contaminated with dirt, sand and rocks (Laitila et al. 2008; Athanassiadis et al. 2011). The SPC harvest system is probably the least developed of the systems studied, and the calculations therefore carry large uncertainties. Also harvest and bundling technologies in ET are under development, which leads to uncertainties in the input data used in the present study. ET could replace PCT fully or partially giving an additional benefit of avoided PCT costs. This was not included in our calculations, but could further improve the economics of energy thinning. However, it has been suggested that ET could affect the yield of FT. In modeling studies, the reduction in PL yield from FT was 8% in one case (Karlsson 2013). The actual effect on the yield will, however, depend on stand characteristics. No yield reductions in subsequent harvesting operations were taken into account here.

This paper provides a potential figure for the biomass supply based on geographically explicit forest inventory data along with projections of forest growth. Geographically explicit information was partly taken into account in the modeling of unit operations. In practice, each harvesting site will be unique, thus there will be variation and uncertainties that are not captured in this type of study. Harvested areas were derived from yield and harvest simulations for the period between 2010–2110, based on assumptions about the forest management cycle which were developed in the SKA-VB 08 study (SFA 2008). Losses were included only from handling and not from the decay of material during storage. For the tops and branches, we can expect that the innovative systems would benefit compared to the conventional ones from chipping at the terminal compared to chipping at the roadside, given the greater flexibility of operations in a terminal. A few months storage of chipped woody biomass can lead to microbial decay and significant losses (10-15%) of dry matter (Jirjis 1995). Therefore, collecting and storing the unchipped residues at a terminal and adapting the chipping to the demands of the destination industry could lead to a reduction in dry matter losses and preserve the heating values and chemical properties. However, it will depend on how and for how long time unchipped residues are stored at terminals. Routa et al. (2015) found that the dry matter losses of unchipped logging residues can vary up to 3% per month.

The actual feedstock availability and cost to a given industry depends on the forest resources and supply systems, but also on a variety of factors such as the feedstock quality requirements, the kind of contracts negotiated and the competition for the feedstock. The supply curves created in this study are not sufficient to predict feedstock costs to individual industries. However, the selected methodology provides relevant information for understanding potential consequences with new practices and strikes an adequate compromise between general and site-specific results.

To generate curves for the systems studied, we adopted an approach where the conventional roundwood harvest operation was used as a reference and the changes in cost and energy use with new practices were allocated to the new assortments. Implicitly, the costs and energy use allocated to SL and PL were kept constant. This gives a good idea of the benefits (and costs) referable to the new practices, but it does not take into account for example how the changed costs affect the prices of different assortments on the market. A reduced total cost could, for example, be absorbed by entrepreneurs as increased profit or lead to lower saw timber prices, as well as cheaper feedstock prices for biorefining industries, depending on the market situation.

For practical reasons, the number of supply chain alternatives was limited. For example, it is common practice to chip LR at roadside as was assumed in the conventional system (Routa et al. 2013). For short transportation distances, however, it could be more efficient to transport the residues loose, or compacted, without chipping. Tahvanainen and Anttila (2011) report that up to 60 km distance to the heating plant transport of loose logging residues was the most cost competitive option. Also, in the conventional case we assumed that tops and branches were only recovered in final harvest, whereas in the innovative systems B and C, part of the tops and branches were also harvested during thinning operations.

Separate supply chains give greater flexibility in the supply as the demand for different assortments may vary. For example, in some Swedish regions, the demand for energy assortments is presently met by processing residues from pulp mills and sawmills, and there is little demand for forest fuels such as logging residues, whereas it is more attractive to harvest residues in other locations. Integrated supply of stemwood and residues appears to be an attractive option for industrial sites that process both types of forest feedstock. In addition, forest terminals may act as important hubs receiving integrated assortments and separating these for different users (Kons et al. 2014).

Geographical differences

The geographical area considered was limited to a 120 km radius around each of the three locations. For the coastal locations, the sea covers about half of this area, and hence the land area covered is smaller than for the inland location. Somewhat surprisingly, the inland location yielded the smallest feedstock amounts. There may be several reasons for this. First, part of the inland area falls in a mountainous region, with little or no forest growth (Swedish Forest Agency 2013). Second, the forest growth is much slower in the inland regions than in the coastal area, which means that the productivity of the forest is lower. Third, there may be a difference in age structure between the three areas. Indeed, a comparatively large share of the pulpwood in the inland area originated from thinning operations, relative to FF and the yields from ET were higher for the inland location than the coastal locations. However, no in-depth study was undertaken to examine the reasons for the geographical differences.

Energy use

Energy use and supply cost are fairly well, but not entirely, correlated. This is not surprising, since the operation of machines is a main factor in both supply cost and energy use. Almost all energy used in the operations is in the form of diesel. The amount of energy used corresponds to approximately 2-6% of the energy content of the delivered wood feedstock. This energy ratio agrees well with results reported from Ireland for logging residues and stumps with a similar conventional harvesting system (Murphy et al. 2014). For the innovative supply systems and when all material is chipped without prior separation, the corresponding energy ratio is about 2-4%. These numbers are in relatively good agreement with other studies of supply chain energy use (De Jong et al. 2014). These studies, however, have mainly dealt with conventional assortments.

Hence, it can be concluded that the energy input to the forestry operations is relatively small compared to the energy value of the output products. It is still, however, one of the key contributors to costs and emissions in forestry operations, and hence, should not be ignored.

Environmental considerations

Although the use of energy wood can be considered environmentally beneficial in order to reduce greenhouse gas emissions compared to fossil fuel, it can have negative environmental implications such as changes in soil nutrient content and structure, and their possible effect on forest productivity, changes in water quality, and reduction of deadwood with the associated adverse consequences for biodiversity (Ferranti 2014). However, De Jong et al. (2014) indicated that the extraction of spruce residues in FF seems to have a minor impact on biodiversity compared to the total effects of other forest operations. In the present study, extraction of green residues has been considered. However, foliage may account for up to 50% of the nutrient content of the tree (Pelkonen et al. 2014). Foliage extraction could reduce nutrient availability in the soil whereas the extraction of SPC instead of SP would leave the root system in situ, mitigating the nutrient depletion and reducing soil disturbance (Berg et al. 2014). It has been observed for sensitive areas (eg. pine stands on mineral soils), that a decline in productivity can follow removal of logging residues (Egnell & Valinger 2003). Harvesting operations may also result in soil disturbance, with adverse impacts (Walmsley and Godbold 2010; Ferranti 2014). LR are commonly placed on the ground to act as soil protection during harvesting operations, thereby limiting their potential use as feedstock. Simultaneous extraction of stemwood and residues could, however, reduce the total amount of driving over the terrain compared to the case where there is separate extraction (Walmsley and Godbold 2010). Other environmental synergies can also be identified between energy wood production and other ecosystem functions such as forest fire protection, reduction of pest risks and root rot (in the case of stump harvesting), and maintenance of nitrogen balance at sites with high nitrogen deposition (Ferranti 2014). Clearly, several environmental concerns should be addressed if forestry practices are changed. This would be an interesting topic for further studies.

Feedstock properties in relation to industry quality demands

Clean feedstock with low variability in properties is a general requirement of the biorefinery industry. For certain applications, some components of a tree are more valuable while some substances can be detrimental. For example, cellulose is the key component utilized in chemical pulping and in envisioned, future biochemical ethanol production, while ash components can often be detrimental in thermochemical applications. Different parts of the tree have different properties and it may be desirable to achieve a separation of the tree parts. With the conventional harvest system, fractionation of logs and residual assortments is undertaken at harvest. With the integrated systems, fractionation may have to be performed at an intermediate terminal or at the receiving industry. Potential disadvantages with the integrated systems are that there is no separation of valuable and less valuable components early in the chain; the feedstock is bulkier to transport and handle; and there are fewer opportunities to pass different fractions directly from harvest to different users. Advantages with the integrated systems may, on the other hand, include easier handling with lower risk of contamination of residual assortments; better control over comminution and fractionation if undertaken at a large-scale or at the site of the destination industry; lower risk of storage losses if comminution takes place later in the chain; potentially more efficient comminution and fractionation when performed at a large-scale at a terminal or industry site. The integrated systems would probably have an advantage in cases where the receiving industry accepts unsorted feedstock components.

Conclusions

Integrated harvest of tops and branches with stemwood assortments, as well as WT harvest during ET, has significant potential to reduce the supply cost of non-stemwood assortments. SP wood generally remains the most expensive assortment, and the SPC harvest system studied here does not reduce the cost. However, this system is the least studied and is particularly sensitive to uncertainties in the assumptions.

There is a cost reduction potential, but a change in practices is likely to require a steady demand for the residual assortments. This could be created by the expansion of biomass-based heat and power generation or through new biorefinery industries producing, for example, transportation fuels. Integrated supply would seem most interesting to industrial sites with the capacity to process both stemwood and residual assortments. In addition, increased use of terminals as hubs for fractionation and buffering of feedstock could be an interesting option which requires further study.

The energy use analysis confirms earlier research showing that the energy input is relatively small compared to the energy content of the harvested feedstock. The energy intensity curves largely follow the supply cost curves for the individual assortments, while the correlation is smaller for the combined supply curves.

Finally, changes in harvesting practices should be considered from an environmental perspective, especially when new practices lead to increased amounts of biomass being extracted. This was outside the scope of this study, but is an important field for future studies, along with full-scale field trials to verify the results of the study and to test the demand for new assortments.

Acknowledgements

This work was performed within the Forest Refine project and has been funded by the Botnia Atlantica program of the European Union regional development fund, the Region Västerbotten, the County Administrative Board of Västernorrland and the Regional Councils of Ostrobothnia and Central Ostrobothnia. The research leading to these results has been supported by the EU through the Marie Curie Initial Training Networks (ITN) action CASTLE, grant agreement no. 316020. The contents of this publication reflect only the authors' views and the European Union is not liable for any use that may be made of the information contained herein.

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Table 1. Alternative forestry regimes considered in the analyses.

Conventional	Removal stem volume (m^3 o-b)*	Initial trees/ha	Removal trees/ha	Biomass-dedicated	Removal stem volume (m^3 o-b)*	Initial trees/ha	Removal trees/ha
PCT (10 years)	0.003	10,000	7,500	*ET (25 years)*	0.01	10,000	6,000
FT (45 year)	0.05	2,500	1,000	*FT (50 years)*	0.02	4,000	2,500
ST (70 years)	0.16	1,500	800	*ST (75 years)*	0.16	1,500	800
FF (95 years)	0.3	700	700	*FF (95 years)*	0.3	700	700

*Solid m^3 over-bark.

Table 2. Definition of assortments.

	Definition	Silvicultural treatment
Pulpwood (PL)*	Delimbed small-diameter logs with bark with a top diameter ≥ 5cm under bark (u-b).	FT, ST, FF
Logging residues (LR)*	Tree-tops (diameter ≤ 5 cm u-b) and branches removed from the stem at conventional round-wood harvest.	FF
Stumps (SP)*	The stump left when a tree is cut including part of the roots.	FF
Rough-delimbed tree sections (RS)**	Partly delimbed stemwood cut into sections (50% branch mass is included).	FT
Long tops (LT)**	The pulpwood part of a stem (diameter u-b ≤ 12 cm) with the tree-top and branches still attached.	ST, FF
Whole trees (WT)**	Small trees from thinning operations with top and all branches still attached.	ET
Bundled whole trees (BWT)**	As whole trees but cut into sections which are compressed and tied together into ca. 0.5 m^3 solid bundles at the harvest site.	ET
Stump core (SPC)**	The extension of the stem into the stump, which can be cut out together with the lower part of the stem.	FF

* Separate stemwood and residual assortments (conventional assortments) ** Integrated stemwood and residual assortments (new assortments)

Table 3. Summary of supply systems used. Dry matter losses for each operation are given as percentages (%) in brackets. Assortments are abbreviated according to Table 2.

	System A						Systems B & C							
Product		PL		SL*	LR	SP		RS, LT		SL*		SL+SPC	WT	BWT
Harvest		(-)			(-)	(-)		(-)				(-)	(-)	(5)
Forwarding		(-)			(20)	(-)		(-)				(-)	(5)	(-)
Roadside operations		(-)			Chipping (10)	(-)		(-)				(-)	(-)	(-)
Transport		(-)			(-)	(-)		(-)				(-)	(-)	(-)
Terminal		I:	II:					I:	II:			Sieving stump core from log (1)		
Primary operation		Debarking	-					Delimbing & Debarking	-					
	Debarked log	Bark	Log & bark				Debarked log	Residues	Log & residues		SL*	SPC		
Secondary operation	-	-	Chipping (5)		-	Crushing (5)	-	Chipping (5)	chipping (5)		-	Chipping (2.5)	Chipping (2.5)	Chipping (2.5)
Final transport	(-)	(-)	(-)		(-)	(-)	(-)	(-)	(-)			(-)	(-)	(-)

* Sawlogs were not further considered in the study.

Table 4. Mass percentage of stem bark and branches used in the calculations for the different assortments (treatments are given in brackets) as well as dry densities assumed in the conversions.

	Dry density (ODkg/m^3 solid)	Stem bark (%)	Branches (%)
SL	400[a]	43 (ST), 66 (FF)	-
PL	400[a]	80 (FT), 43 (ST), 29 (FF)	-
LR	450[a]	5	100
RS	410[b]	100	50
LT	420[a]	57 (ST), 34 (FF)	93 (ST pine), 81 (ST spruce) 59 (ST pine), 56 (ST spruce)[c]
WT	420[a]	-	-
SP	452[a]	-	-
SPC	410[b]	-	-

[a]according to the WeCalc calculation tool. [b]Calculated value. [c] The The percentage masses of branches were calculated using the Tahvanainen and Forss (2008) functions.

Table 5. Description of the supply systems included into the analyses from the forest to the terminal: A=conventional forestry regime and separated supply system options, B= conventional forestry regime and integrated supply system options, C= biomass-dedicated and integrated supply system options.

A		B		C	
Treatment > Product	Machinery	Treatment > product	Machinery	Treatment > product	Machinery
PCT > WT left in forest	Cleaning saw (2.2 kW)	PCT > WT left in stand	Cleaning saw (2.2 kW)	ET > WT	Thinning harvester (150 kW) with accumulating felling head for boom corridors Small forwarder (140 kW) with compacting stakes Logging residues truck and trailer
				ET > BWT	Bundle harvester (150 kW) Small forwarder (140 kW) Timber truck and trailer
FT > PL	Thinning harvester (150 kW) with harvesting head multi-tree handling Small forwarder (140 kW) Timber truck and trailer	FT > RS	Thinning harvester (150 kW) with accumulating felling head for rough delimbing Small forwarder (140 kW) Logging residues truck and trailer	FT > RS	Thinning harvester (150 kW) with accumulating felling head for rough delimbing Small forwarder (140 kW) Logging residues truck and trailer
ST > SL+PL	Medium harvester (170 kW) Medium forwarder (150 kW) Timber truck and trailer	ST > SL+LT	Medium harvester (170 kW) Medium forwarder (150 kW) Timber truck and trailer (SL) Logging residues truck and trailer (LT)	ST > SL+LT	Medium harvester (170 kW) Medium forwarder (150 kW) Timber truck and trailer (SL) Logging residues truck and trailer (LT)
FF > SL+PL	Large harvester (190 kW) Large forwarder (180 kW) Timber truck and trailer	FF > SPC+SL+LT	Feller-puller (220 kW) Large harvester (190 kW) Large forwarder (180 kW) Timber truck and trailer (SPC+SL) Logging residues truck and trailer (LT)	FF > SPC+SL+LT	Feller-puller (220 kW) Large harvester (190 kW) Large forwarder (180 kW) Timber truck and trailer (SPC+SL) Logging residues truck and trailer (LT)
FF > LR chipped	Large forwarder (180 kW) Drum chipper truck mounted (331 kW) Woodchips truck and trailer				
FF > SP	Excavator (130 kW) with extraction/splitting device Large forwarder (180 kW) Logging residues truck and trailer				

FF > SP pre-crushed	Excavator (130 kW) with extraction/splitting device Large forwarder (180 kW) Shredder (328 kW) Grapple loader (120 kW) Woodchips truck and trailer

Table 6. Effective time consumption equations and parameters used for the harvesters.

Supply system option/ Extraction phase/Assortment	Equation Parameters	Eq.	Reference
A/PCT/-	$-4.83 + 0.000186 \times n_b + 0.630 \times h_b + 0.0466 \times (h_b/d_b)$; (PM0h/ha) n_b = number of trees per hectare before harvest (trees/ha), h_b = average height of trees before harvest, (m), d_b=DBH before harvest, (m)	1	Ligné et al. (2005)
A/FT/PL	$6.0 + 35.6 \times m^3_b + 4544 \times \frac{1}{n_b}$; (Second/tree) m^3_b = average stem volume before harvest, (m^3)	2	Sängstuvall et al. (2011)
A/ST/SL+PL	$[4.3 + \frac{1000000}{280.8 \times n_r \times [50/n_r]} + dm^3_r \times 0.128 + \frac{n_a}{1000} \times 23.45] \times 0.6$; (Second/tree) dm^3_r= removal stem volume under bark (dm^3), n_r =number of removal trees per hectare (trees/ha), n_a = remaining trees after thinning per hectare (trees/ha)	3	Brunberg (1997)
A/FF/SL+PL	$[24.7 + \frac{1000000}{364 \times n_r \times [0.8+(50/n_r)]} + 41 \times m^3_r] \times 0.646$; (Second/tree) m^3_r = removal stem volume under bark (m^3)	4	Brunberg (2007)
A/FF/SP pine	$11.8 + e^{3.5+0.03 \times d_s}$; (Second/stump) ds = diameter at the stump (cm)	5	Larsson (2011)
A/FF/SP spruce	$11.8 + e^{3.38+0.03 \times d_s}$; (Second/stump)	6	Larsson (2011)
B/FT/RS	$6.04 + 38.7 \times m^3_b + 5091 \times \frac{1}{n_b}$;(Second/tree)	7	Sängstuvall et al. (2011)
B/ST/SL+LT [a]	$\{[4.3 + \frac{1000000}{280.8 \times n_r \times [50/n_r]} + dm^3_r \times 0.128 + \frac{n_a}{1000} \times 23.45] \times 0.6\} \times 0.82$; (Second/tree)	8	Brunberg (1997) Danielsson & Liss (2010)
B/FF/SPC+SL+ LT feller-puller [b, c]	$8.4 + \{[24.7 + \frac{1000000}{364 \times n_r \times [0.8+(50/n_r)]} + 41 \times m^3_r] \times 0.646 \times 0.82 \times 0.53\}$; (Second/tree)	9	Berg et al. (2014) Brunberg (2007)

B/FF/ SPC+SL+ LT Harvester [b]	$\{[24.7 + \frac{1000000}{364 \times n_r \times [0.8+(50/n_r)]} + 41 \times m^3_r] \times 0.646\} \times 0.82 \times 0.47$; (Second/tree)	10	Danielsson & Liss (2010) Brunberg (2007) Danielsson & Liss (2010)
C/ET/WT, BWT	$1.05 + [(0.862 + 12.2 \times m^3_b + 15434 \times \frac{1}{n_b}) \times 0.822]$; (Second/tree)	11	Sängstuvall et al. (2011)
	m^3_b = average stem volume before harvest, (m^3), n_b = number of trees per hectare before harvest		

[a] In the case of harvesting of LT together with SL (supply system B), the time consumption per tree was reduced by 18% compared to system A, according to Danielsson and Liss (2010). [b] According to Danielsson and Liss (2010), the felling time consumption in the integrated harvesting of SPC, SL and LT is 53% of the total work-time per tree, while the remaining share of work-time per tree (47%) was allocated to the harvester used for processing SPC, SL and LT. [c] According to the simulation presented by Berg et al. (2014), the time for extracting the SPC is 8.4 s/tree, this extra time was added to the feller-puller work-time per tree.

Table 7. Forwarder time consumption models, with PM0h/t as the response variable and forwarding distance (dist; m) as the independent variable. Model: Y=a+ b × dist.

Supply system option	Extraction phase	Assortment	a	b	Load size (t)*	Eq.	Time consumption Ref.
A	FT	PL	0.16017	0.00014	4.4	12	Brunberg (2004)
A	ST	SL	0.13674	0.00010	6.0	13	Brunberg (2004)
A	ST	PL	0.13668	0.00010	5.7	14	Brunberg (2004)
A	FF	SL	0.07255	0.00008	6.5	15	Brunberg (2004)
A	FF	PL	0.09430	0.00008	6.1	16	Brunberg (2004)
A	FF	LR	0.11509	0.00015	4.0	17	Nurmi (2007)
A	FF	SP	0.27119	0.00013	5.9	18	Laitila et al. (2008)
B	FT	RS	0.14021	0.00026	3.5	19	Laitila et al. (2007)
B	ST	LT	0.14504	0.00009	6.1	20	Danielsson and Liss (2010)
B	FF	SL+SPC	0.06975	0.00008	6.5	21	Brunberg (2004)
B	FF	LT	0.07084	0.00008	6.8	22	Danielsson and Liss (2010)
C	ET	WT	0.12134	0.00026	3.4	23	Laitila et al. (2007)
C	ET	BWT	0.07574	0.00016	4.2	24	Laitila et al. (2009)
C	FT	RS	0.14374	0.00027	3.5	25	Laitila et al. (2007)

*Fresh tonnes obtained by multiplying ODt by 2.

Table 8. Trucking terminal times (sum of loading, unloading and complementary times), load capacities and driving time ($PM_{15}h/km/t$) as the response variables and trucking distance (dist; km) as the independent variable. Model: Y=a × dist.[b]

Assortment	Terminal time ($PM_{15}h$/load)	Truck capacity (t)	a	b	Eq.	Terminal time Ref.
SL, SPC	1.061	19.60	0.0052	-0.2783	26	Nurminen and Heinonen (2007)
PL	1.034	18.80	0.0054	-0.2783	27	Nurminen and Heinonen (2007)
BWT	1.132	18.06	0.0056	-0.2783	28	Laitila et al. (2009)
WT	0.995	12.60	0.0081	-0.2783	29	Laitila and Väätäinen (2012)
RS	0.996	13.53	0.0075	-0.2783	30	Laitila and Väätäinen (2012)
LT	0.998	13.53	0.0075	-0.2783	31	Laitila and Väätäinen (2012)
SP	1.421	11.35	0.0090	-0.2783	32	Lindberg (2008)
Wood chips:			0.0063	-0.2783	33	Liss and Johansson (2006)
- at roadside	1.384	16.20				
- at terminal	-	16.50				
$SP_{pre\text{-}crushed}$			0.0065	-0.2783	34	Von Hofsten and Granlund (2010)
- at roadside	1.531	15.64				
- at terminal	-	16.00				

Table 9. Hourly cost calculation for the forest machinery included in the analyses.

Description	Cleaning saw	Thinning harvester	Medium harvester	Large harvester	Small Forwarder	Medium Forwarder	Large Forwarder	Excavator for stump lifting	Chipper	Shredder	Grapple loader	Thinning harvester for boom corridor	Small Forwarder with compacting stakes
Purchase price (€)	924[a]	442935[b]	456522[b]	494565[b]	285326[b]	315217[b]	347826[b]	155435[c]	510870[d]	326087[e]	163043[c]	575815	299592
Economic Lifespan (Years)	2	4.8	4.8	4.8	4.8	4.8	4.8	6	6	6	6	4.8	4.8
Interest rate (%)	6	6	6	6	6	6	6	6	6	6	6	6	6
Salvage present value (€)	0	66973	69028	74780	43142	47662	52593	21915	72029	45976	22988	87065	45299
Depreciation (€/year)	504	92456	95292	103233	59558	65797	72604	27153	89244	56964	28482	120193	62536
General maintenance cost (€/year)[f]	18	8859	9130	9891	5707	6304	6957	3109	6522	6522	3261	11516	5992
Operating hours ($PM_{15}h$/year)	1000	2500	2500	2500	2500	2500	2500	1500	1500	1500	1500	2500	2500
Fixed cost (€/PM15h)	0.54	40.54	41.74	45.22	26.09	28.80	31.85	20.22	63.80	42.28	21.20	52.72	27.39
Fixed cost (€/$PM_{15}h$)*	0.54	42.50	43.80	47.50	27.39	30.33	33.37	21.20	67.07	44.46	22.17	55.33	28.80
Variable maintenance cost (€/$PM_{15}h$)[f]	0.40	12.93	13.37	14.46	7.17	7.93	8.70	9.02	21.74	21.74	7.61	16.85	7.50
Fuel and lubricant cost (€/$PM_{15}h$)	2.72	20.33	22.72	25.22	16.09	16.96	19.46	23.15	67.07	48.70	16.41	20.33	16.09
Labor cost (€/$PM_{15}h$)	27.17	27.17	27.17	27.17	27.17	27.17	27.17	27.17	27.17	27.17	27.17	27.17	27.17
Variable cost (€/$PM_{15}h$)	30.22	60.43	63.26	66.74	50.43	51.96	55.33	59.35	115.98	97.61	51.20	64.35	50.76
Variable cost (€/$PM_{15}h$)*	31.74	63.48	66.41	70.11	52.93	54.57	58.04	62.28	121.85	102.39	53.70	67.50	53.26
Total cost (€/PM_{15} h)*	32.28	105.98	110.22	117.61	80.33	84.89	91.52	83.48	188.80	146.85	75.98	122.83	82.07

a,b,c,d,e = Reference for purchase price: (a) *Stihl GmbH* (*www.stihl.se*), (b) *John Deere forestry Oy* (*pers. comm.*), (c) *Volvo AB* (*pers comm.*), (d) *Bruks AB* (*pers. comm.*), (e) *Doppstadt GmbH* (*OP System AB, pers. comm.*).

f = Information on fixed costs and repair and maintenance costs for the harvesters and the forwarders were obtained from Nurminen et al. (2009); for the chipper from Karlsson (2010), for shredders from *OP System AB*; for cleaning saws and grapple loaders from professional operators; and for the excavators from Kärhä (2012).

=Including a 5% profit

Table 10. Costs elements included in the road transportation cost calculations.

Cost element*	Timber truck and trailer SL, PL, SPC	Timber truck and trailer BWT	Logging residues truck and trailer WS, RS	Logging residues truck and trailer LT	Logging residues truck and trailer SP	Woodchips truck and trailer chipped LR	Woodchips truck and trailer pre-crushed SP
Purchase price (€)	282609	282609	380435	380435	380435	358696	358696
Fh* (€/PM_{15}h)	36.74	36.74	37.61	37.61	37.61	37.39	37.39
Vkm* (€/km)	1.05	1.05	1.20	1.20	1.20	1.12	1.12
Vld* (€/load)	19.35	19.02	19.89	21.96	25.54	25.00	29.78

*Annual utilization of 3 700 PM_{15}h was considered for all trucks. The lifetime was set to 1 000 000 km for the truck, 1 500 000 km for the trailer and 5 000 loads for the crane. The salvage value was assumed to be 10% of the initial investment for the truck and 7% for the trailer and the crane. The fuel consumption for terminal and driving activities were set respectively to 7.7 l/PM_{15}h and 0.56 l/km.

Table 11. Assumed time consumption and costs of terminal operations.

Operation	Assortment	Time consumption ($PM_{15}h/t$)	Hourly cost (€/$PM_{15}h$)	Cost (€/t)	Ref. time consumption	Ref. Hourly cost	Ref. Cost/t
Storage	All	-	-	2.48	-	-	Södeström (2006)
Debarking	PL	-	-	3.58	-	-	Watson et al. (1993)
Delimbing & debarking	RS, LT	-	-	6.88	-	-	Watson et al. (1993)
Chipping	PL, BWT	0.016	391.30	6.42	Eliasson & Granlund (2010)	Karlsson (2010)	-
Grinding	LR	0.023	380.43	8.84	Eliasson & Granlund (2010)	Karlsson (2010)	-
Chipping	RS, LT, WT	0.021	391.30	8.41	Eliasson et al. (2012)	Karlsson (2010)	-
Pre-crushing	SP	0.034	380.43	12.91	Eliasson & Granlund (2010)	Karlsson (2010)	-
Re-fining	SP pre-crushed	0.025	380.43	9.33	Von Hofsten & Granlund (2010)	Karlsson (2010)	-
Sieving	SPC	0.200	17.39	3.45	-[a]	*DIMEC Srl. Pers. comm.*	-
Grinding	SPC	0.025	380.43	9.33	Von Hofsten and Granlund (2010)	Karlsson (2010)	-

Re-loading	PL	0.016	81.52	1.32	-[b]	cf. Table 10	-
Re-loading	woodchips	0.030	81.52	2.30	Laitila and Väätäinen 2012	cf. Table 10	-
Re-loading	SP pre-crushed	0.031	81.52	2.38	Laitila and Väätäinen 2012[c]	cf. Table 10	-
Transportation 5km logs	PL	0.020	65.50	1.28	-[d]	cf. Table 11	-
Transportation 5km	wood chips	0.022	64.20	1.43	-[d]	-[e]	-
Transportation 5km	SP pre-crushed	0.023	64.20	1.47	-[d]	-[e]	-

a=estimated from measurements carried out using similar machinery by the Authors; b= measured in a terminal by the authors for similar operations; c= based on Laitila and Väätäinen 2012 and the density of pre-crushed stumps assumed according to Von Hofsten and Granlund (2010); d= calculated for a transportation distance of 5 km; e=the costs of 36.63 €/PM_{15}h and 1.01 €/Km were used for a container truck.

Table 12. Fuel and lubricant consumption of forest machinery.

Machinery	Engine power (kW)	Fuel consumption (L_{diesel}/h)	Reference	Lubricant consumption (% of fuel consumption or l/h for shredder and chipper)	Reference
Cleaning saw	2.2	0.75*	(Stihl GmbH www.stihl.se.)		
Harvester	150	14.0	(Brunberg 2006)	6.0	(Berg & Lindholm 2005)
	170	15.7	(Brunberg 2006)	6.0	(Berg & Lindholm 2005)
	190	17.4	(Brunberg 2006)	6.0	(Berg & Lindholm 2005)
Fixteri baler-harvester	150	16.0	(Jylhä 2011)	6.0	(Berg & Lindholm 2005)
Forwarder	140	11.8	(Brunberg 2006)	3.0	(Nurminen et al. 2009)
	150	12.4	(Brunberg 2006)	3.0	(Nurminen et al. 2009)
	180	14.2	(Brunberg 2006)	3.0	(Nurminen et al. 2009)
Excavator	130	16.0	(Von Hofsten, H. 2011)	6.0	(Berg & Lindholm 2005)
Shredder	328	36.8	(Skogforsk 2010)	0.45	(“*OP System AB*” Pers. Comm.)
Grapple loader	120	12.0	(“Domsjo Fiber AB” Pers. Comm.)	3.0	(Nurminen et al. 2009)
Chipper	331	51.1	(Karlsson 2010)	0.45	“*OP System AB*” Pers. Comm.)
Feller-puller	220	20.0	(Brunberg 2006)	6.0	(Berg & Lindholm 2005)

*Liters of gasoline

Table 13. Fuel and lubricant consumption of terminal machinery.

Machinery	Engine power (kW)	Fuel consumption (L_{diesel}/t)	Reference	Lubricant consumption (l/h or % of fuel consumption for loaders)	Reference
Large disc chipper for WT. RS. LT	930	2.8	(Eliasson et al. 2012)	0.45	(“*OP System AB*” Pers. Comm.)
Large disc chipper for BWT and PL	930	1.8	(Eliasson et al. 2012)	0.45	(“*OP System AB*” Pers. Comm.)
Large grinder for residues (energy fraction)	780	2.0	Eliasson & Granlund P. 2010)	0.45	(“*OP System AB*” Pers. Comm.)
Large grinder to refine SP	780	1.4	(Von Hofsten & Granlund 2010))	0.45	(“*OP System AB*” Pers. Comm.)
Large grinder to crush whole SP	780	2.6	(Eliasson L. & Granlund P. 2010)	0.45	(“*OP System AB*” Pers. Comm.)
Loader for chips and pre-crushed SP	120	0.4	(“Domsjö Fiber AB” Pers. Comm.)	3.00	(Nurminen et al. 2009)
Front lift loader for wood	120	0.2	(“Domsjö Fiber AB” Pers. Comm.))	3.00	(Nurminen et al. 2009)
Chain flail delimber/debarker for RS and LT	180	1.9	(Kons & Läspä 2013)	0.45	(“*OP System AB*” Pers. Comm.)
Chain flail delimber/debarker only in debarking PL (bark fraction: same fuel consumption)	180	1.3	(Kons & Läspä 2013)	0.45	(“*OP System AB*” Pers. Comm.)
Saw-blade	11	0.2*	(“DIMEC srl”. Pers. Comm.)		

*transformed to diesel equivalent from electric consumption.

Table 14. Potential production (1000 t) in total for the 120 km radius supply area of the ORN location. Sawlogs are delivered with bark, pulpwood as debarked logs and the other assortments are chipped.

Supply system	Harvest operation		Sawlogs	Pulpwood	PL bark	tops and branches	Stump-wood	small trees	Total
A	FT		0	39	4	0	0	0	43
	ST		111	223	15	0	0	0	349
	FF	Roundwood harvest	835	328	31	0	0	0	1194
		Residue recovery	0	0	0	273	0	0	273
		Stump extraction	0	0	0	0	479	0	479
	Total		946	590	50	273	479	0	2338
B	FT		0	39	4	12	0	0	54
	ST		111	223	15	115	0	0	464
	FF	Without SPC harvest	835	328	31	215	0	0	1408
	or	With SPC harvest	*835*	*328*	*31*	*215*	*100*	*0*	*1509*
	Total, with SPC harvest		946	590	50	341	100	0	2027
	Total, with conventional SP extraction		946	590	50	341	479	0	2406
C	Same as B, plus	Energy thinning	0	0	0	0	0	84	84
	Total, with SPC harvest		946	590	50	341	100	84	2111
	Total, with conventional SP harvest		946	590	50	341	479	84	2490

Table 15. Total costs (M EUR) to supply the amounts of feedstock according to Table 14, by harvest type and operation.

Supply system	Operation		Harvest	Forward	Roadside	Transport	Terminal	Machine relocation	Land owner compensation	OH*	Total
A	FT		1.1	0.7	0.0	0.8	0.4	0.1	0.6	0.1	3.8
	ST		7.8	5.2	0.0	5.9	2.4	1.0	9.9	1.0	33.2
	FF	Roundwood harvest	11.8	11.9	0.0	18.6	3.6	0.8	76.3	3.3	126.3
		Residue recovery	0.0	7.6	5.0	5.6	1.7	0.8	2.9	1.1	24.7
		Stump extraction	11.6	14.9	0.0	16.1	10.4	0.8	0.0	1.5	55.2
	Total		32.2	40.3	5.0	46.9	18.5	3.6	89.7	6.9	243.2
B	FT		0.9	1.0	0.0	1.5	0.8	0.1	0.7	0.2	5.2
	ST		5.5	7.2	0.0	11.1	5.8	1.0	10.8	1.3	42.7
	FF	Without SPC harvest or	7.6	13.2	0.0	27.0	9.8	0.8	78.0	3.9	140.4
		With SPC harvest	13.9	13.9	0.0	28.6	11.8	1.2	78.0	4.2	151.7
	Total, with SPC harvest		20.3	22.0	0.0	41.2	18.4	2.4	89.6	5.7	199.6
	Total, with conventional SP harvest		25.6	36.2	0.0	55.7	26.8	2.8	89.6	6.9	243.5
C	Same as B, plus	Energy thinning, WT	2.3	1.3	0.0	2.3	1.3	0.4	0.0	0.3	7.8
	or	Energy thinning, BWT	2.9	0.8	0.0	1.5	1.1	0.4	0.0	0.3	6.9

*Overheads

Figure list

Figure 1. Map of Sweden with the study area indicated by a circle (on the left) and geographical representation of the three potential "biorefineries" considered (on the right). UME is denoted as A, ORN as C and STO as B.
Figure 2. Supply cost and energy use curves for pulpwood logs, arranged by type of harvesting operation.
Figure 3. Supply cost and energy use curves for chipped tops and branches.
Figure 4. Supply cost and energy use curves for chipped stump wood.
Figure 5. Supply cost and energy use curves for chipped small trees from energy thinnings.
Figure 6. Aggregated supply cost curves for all assortments combined. All assortments are chipped without sorting.
Figure 7. Aggregated energy use curves corresponding to the ORN cost curves in Figure 6.
Figure 8. Aggregated supply cost curves for all assortments combined under three variations of key input parameters. All assortments are chipped without sorting.

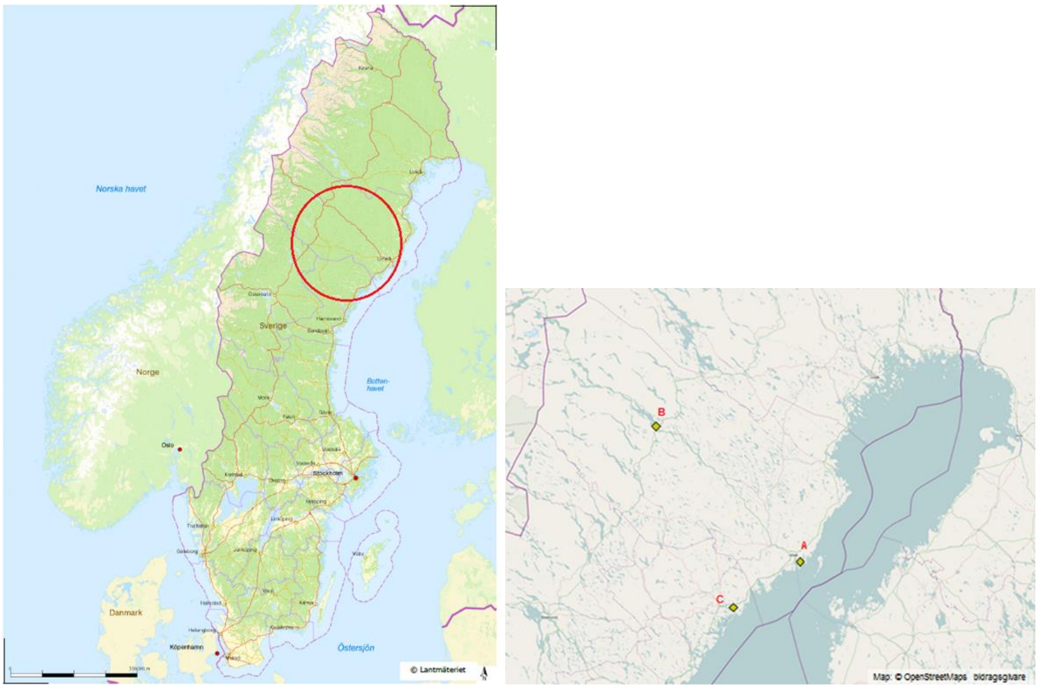
Norska havet
Norge
Sverige
Danmark
Östersjön
© Lantmäteriet
B
A
C
Map: © OpenStreetMaps bidragsgivare

Figure 1

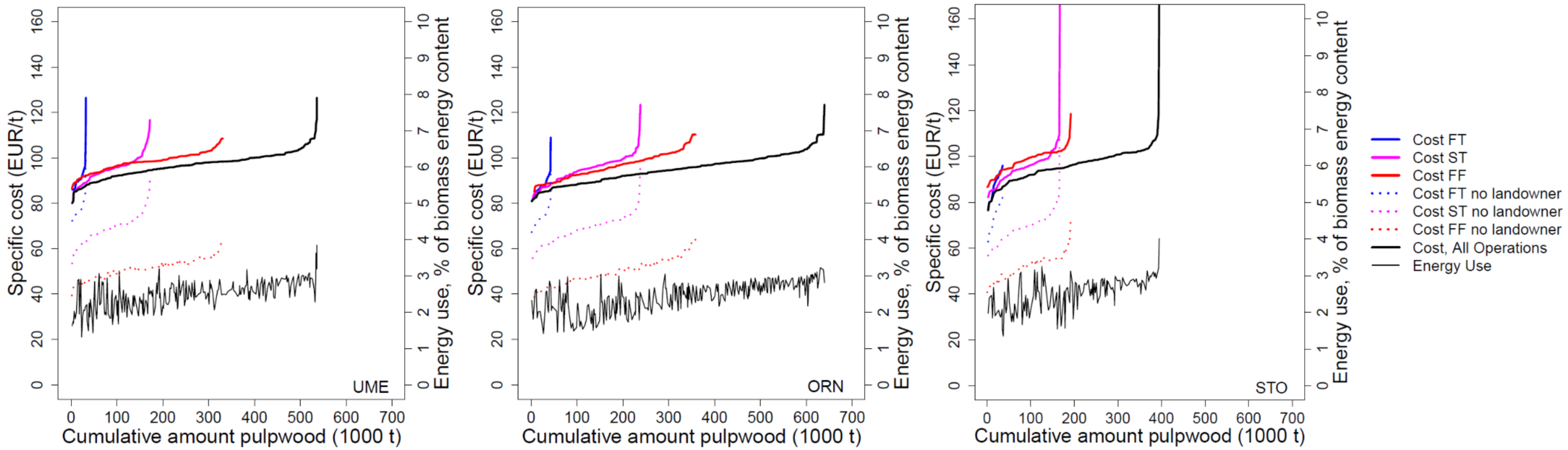
Specific cost (EUR/t)
Energy use, % of biomass energy content
Cumulative amount pulpwood (1000 t)
UME
ORN
STO
Cost FT
Cost ST
Cost FF
Cost FT no landowner
Cost ST no landowner
Cost FF no landowner
Cost, All Operations
Energy Use

Figure 2

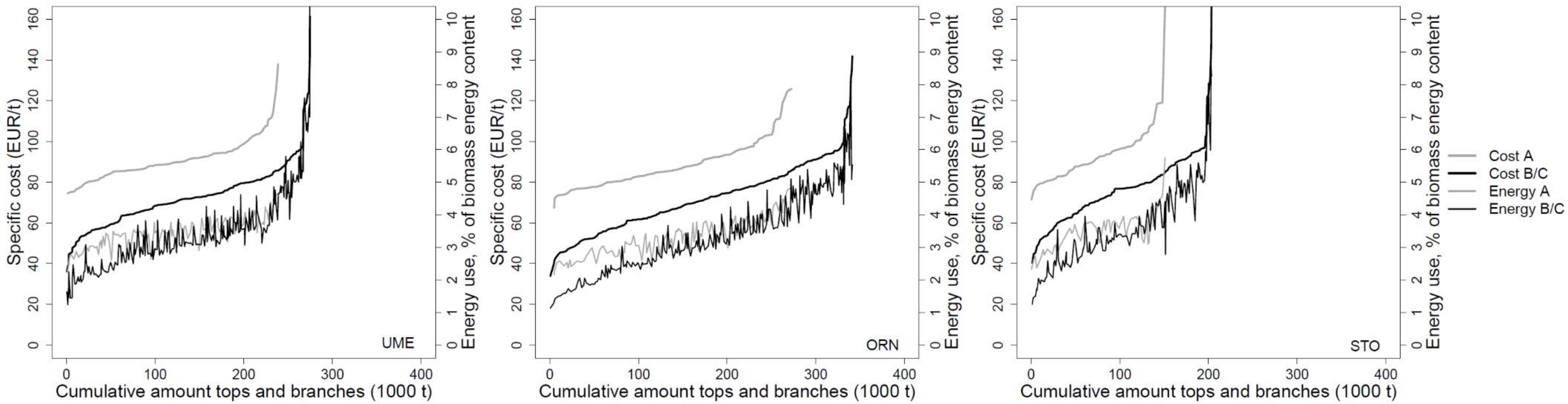
Specific cost (EUR/t)
Energy use, % of biomass energy content
Cumulative amount tops and branches (1000 t)
UME
ORN
STO
Cost A
Cost B/C
Energy A
Energy B/C

Figure 3

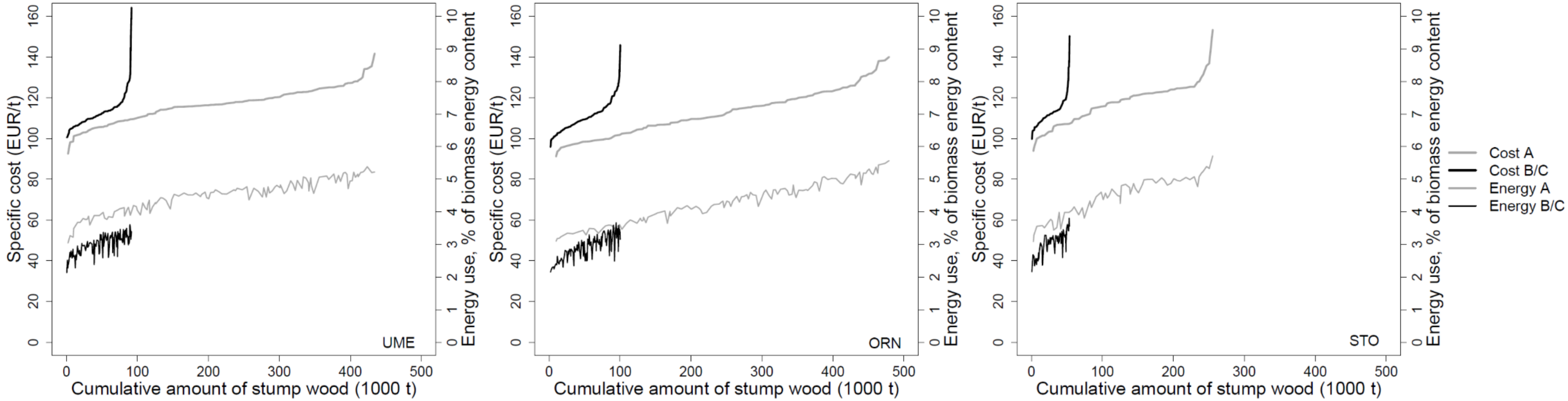
Specific cost (EUR/t)
Energy use, % of biomass energy content
Cumulative amount of stump wood (1000 t)
UME
ORN
STO
Cost A
Cost B/C
Energy A
Energy B/C

Figure 4

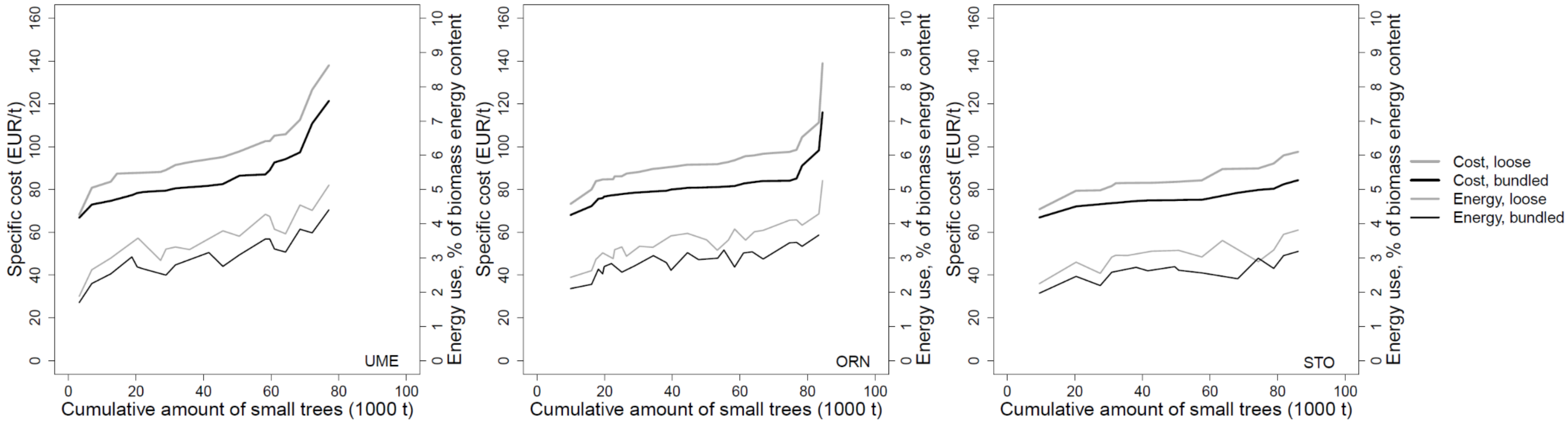
UME
ORN
STO
Specific cost (EUR/t)
Energy use, % of biomass energy content
Cumulative amount of small trees (1000 t)
Cost, loose
Cost, bundled
Energy, loose
Energy, bundled

Figure 5

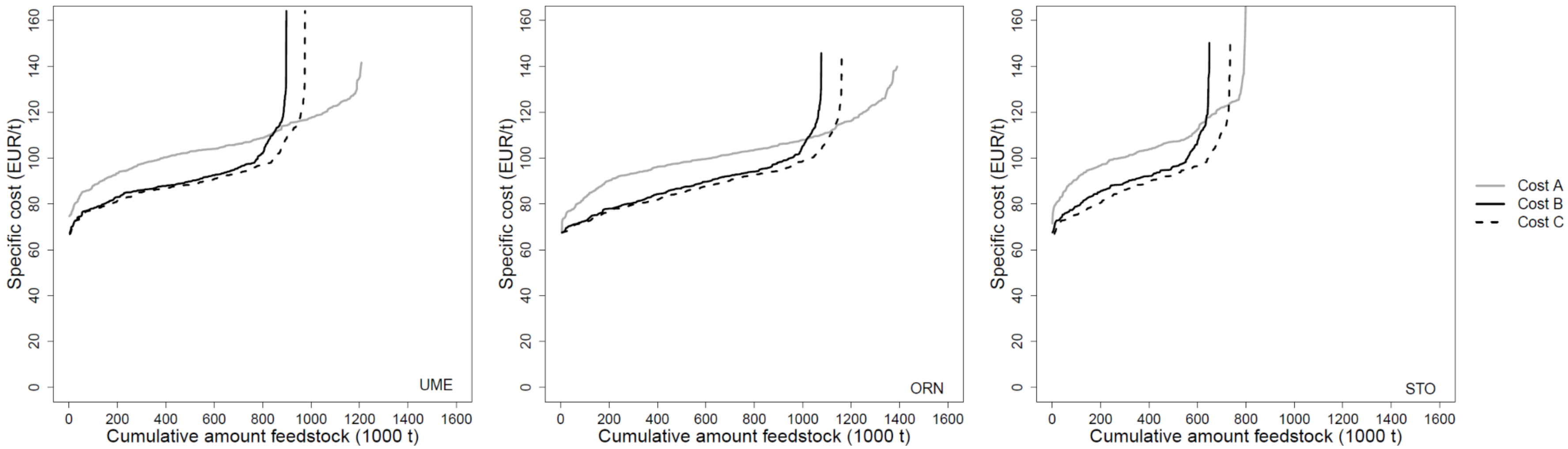
Specific cost (EUR/t)
Cumulative amount feedstock (1000 t)
0
20
40
60
80
100
120
140
160
0
200
400
600
800
1000
1200
1400
1600
UME
ORN
STO
Cost A
Cost B
Cost C

Figure 6

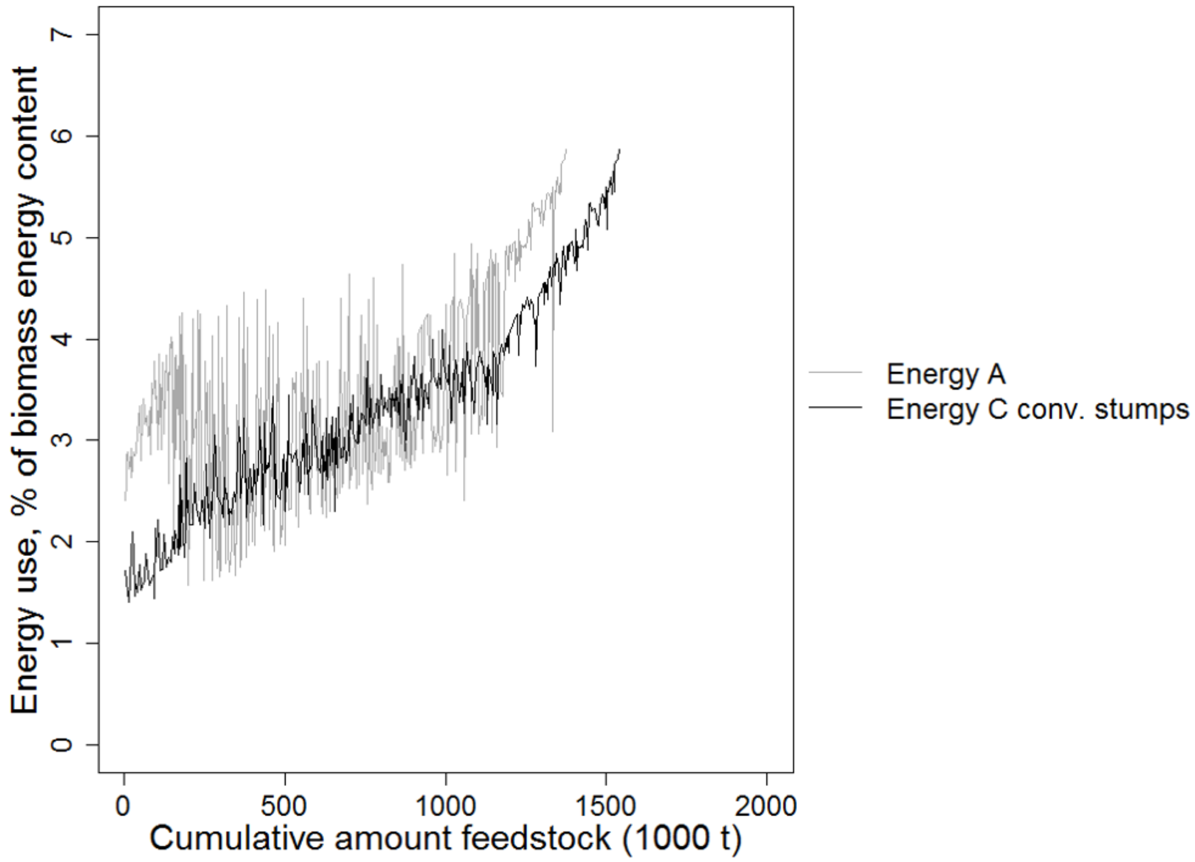
Energy use, % of biomass energy content
0
1
2
3
4
5
6
7
0
500
1000
1500
2000
Cumulative amount feedstock (1000 t)
Energy A
Energy C conv. stumps

Figure 7

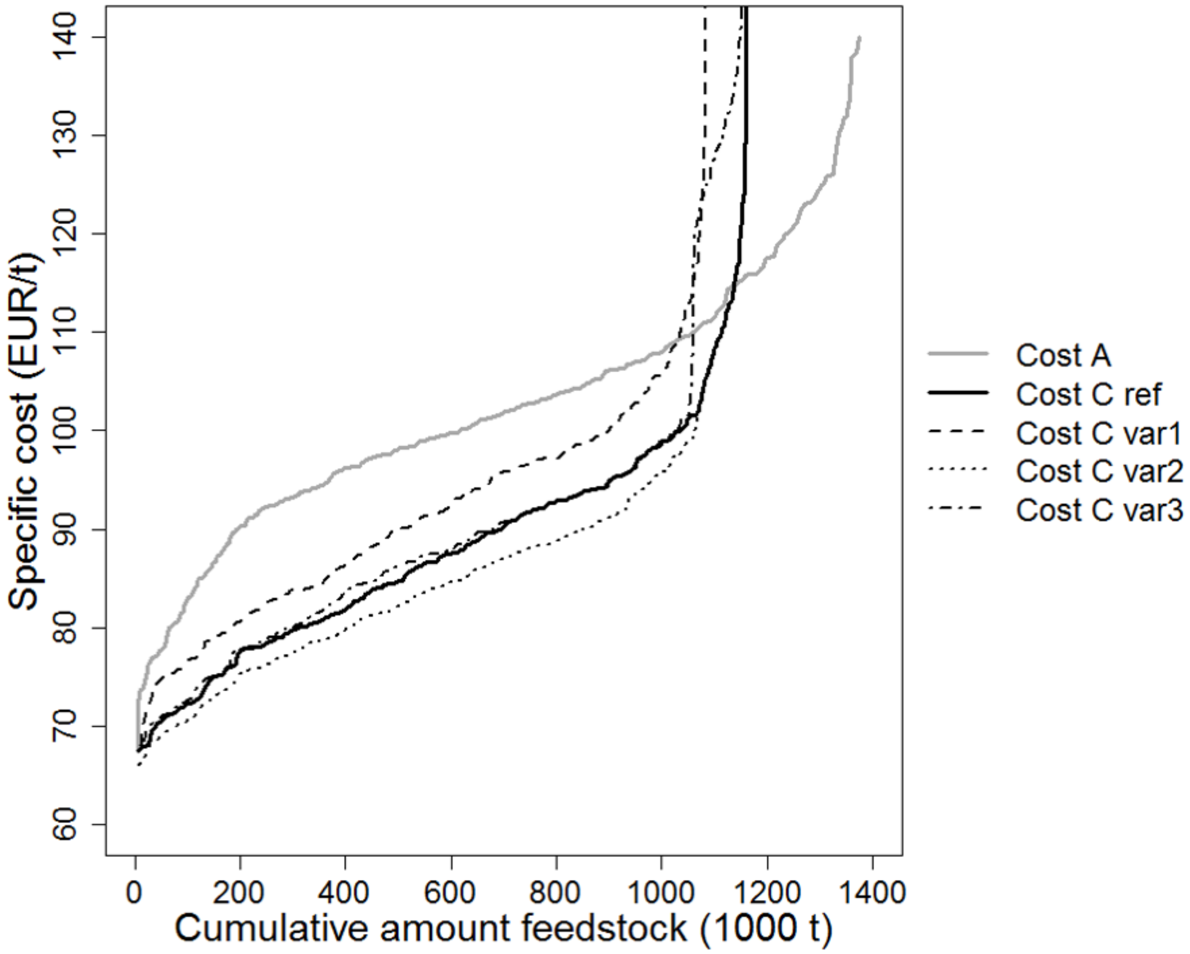
Specific cost (EUR/t)
60
70
80
90
100
110
120
130
140
Cumulative amount feedstock (1000 t)
0
200
400
600
800
1000
1200
1400
Cost A
Cost C ref
Cost C var1
Cost C var2
Cost C var3

Figure 8

Appendix 1. Forest harvesting and road transportation cost models (€/t) as function of forwarding distance=fd(m) and transportation distance=td(km)

A			B			C		
Treatment > Product	Fixed cost (€/t)	Variable cost (€/t)	Treatment > product	Fixed cost (€/t)	Variable cost (€/t)	Treatment > product	Fixed cost (€/t)	Variable cost (€/t)
PCT > WT left in forest	Cleaning saw =0.55×0.38	Cleaning saw =31.78×0.38	PCT > WT left in stand	Cleaning saw =0.55×0.38	Cleaning saw =31.78×0.38	ET > WT	Thinning harvester boom corridor =55.32×0.20	Thinning harvester boom corridor =67.52×0.20
							Small forwarder comp. =0.0076×fd(m)+3.50	Small forwarder comp. =0.014×fd(m)+6.50
							Logging residues truck and trailer =37.61×[0.079+(0.008 ×$td(km)^{-0.278}$) × td(km)]	Logging residues truck and trailer =[(1.20×2× td(km))/12.6] +(19.89/12.6)
						ET > BWT	Bundle harvester =62.45×0.20	Bundle harvester =93.68×0.20
							Small forwarder =0.0045×fd(m)+2.07	Small forwarder =0.0087×fd(m)+4.03
							Timber truck and trailer =36.74×[0.063+(0.006 ×$td(km)^{-0.278}$) × td(km)]	Timber truck and trailer =[(1.05×2× td(km))/18.1] +(19.02/18.1)
FT > PL	Thinning harvester =42.55×0.23	Thinning harvester =63.45×0.23	FT > RS	Thinning harvester =42.55×0.15	Thinning harvester =63.45×0.15	FT > RS	Thinning harvester =42.54×0.17	Thinning harvester =63.45×0.17
	Small forwarder =0.0037×fd(m)+4.39	Small forwarder =0.0073×fd(m)+ 8.53		Small forwarder =0.0071×fd(m)+3.84	Small forwarder =0.014×fd(m)+ 7.47		Small forwarder =0.0075×fd(m)+3.94	Small forwarder =0.015×fd(m)+ 7.66
	Timber truck and trailer =36.74×[0.055+(0.005×$td(km)^{-0.278}$) × td(km)]	Timber truck and trailer =[(1.05×2× td(km))/18.8] +(19.35/18.8)		Logging residues truck and trailer	Logging residues truck and trailer		Logging residues truck and trailer	Logging residues truck and trailer =[(1.20×2× td(km))/13.5]

				=37.61×[0.074+(0.008 ×td(km)$^{-0.278}$) × td(km)]	=[(1.20×2× td(km))/13.5] +(19.89/13.5)		=37.61×[0.074+(0.008 ×td(km)$^{-0.278}$) × td(km)]	+(19.89/13.5)
ST > SW+PL	Medium harvester (SW/PL) =43.86×0.20	Medium harvester (SL/PL) =66.41×0.20	ST > SL+LT	Medium harvester (SL) =43.86×0.11	Medium harvester (SL) =66.41×0.11	ST > SL+LT	Medium harvester (SL) =43.86×0.11	Medium harvester (SL) =66.41×0.11
	Medium forwarder (SL) =0.0030×fd(m) +4.15	Medium forwarder (SL) =0.0055×fd(m)+ 7.51		Medium harvester (LT) =43.86×0.10	Medium harvester (LT) =66.41×0.10		Medium harvester (LT) =43.86×0.10	Medium harvester (LT) =66.41×0.10
	Medium forwarder (PL) =0.0032×fd(m) +4.15	Medium forwarder (PL) =0.0057×fd(m)+ 7.50		Medium forwarder (SL) =0.0030×fd(m) +4.13	Medium forwarder (SL) =0.0055×fd(m)+ 7.48		Medium forwarder (SL) =0.0030×fd(m) +4.13	Medium forwarder (SL) =0.0055×fd(m)+ 7.48
	Timber truck and trailer (SL) =338×[0.054+(0.005×td(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (SL) =[(9.70×2× td(km))/19.6] +(178/19.6)		Medium forwarder (LT) =0.0027×fd(m) +4.40	Medium forwarder (LT) =0.0049×fd(m)+ 7.96		Medium forwarder (LT) =0.0027×fd(m) +4.40	Medium forwarder (LT) =0.0049×fd(m)+ 7.96
	Timber truck and trailer (PL) =36.74×[0.055+(0.005×t d(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (PL) =[(1.05×2× td(km))/18.8] +(19.35/18.8)		Timber truck and trailer (SL) =36.74×[0.054+(0.005 ×td(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (SL) =[(1.05×2× td(km))/19.6] +(19.35/19.6)		Timber truck and trailer (SL) =36.74×[0.054+(0.005 ×td(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (SL) =[(1.05×2× td(km))/19.6] +(19.35/19.6)
				Logging residues truck and trailer (LT) =37.61×[0.074+(0.008 ×td(km)$^{-0.278}$) × td(km)]	Logging residues truck and trailer (LT) =[(1.20×2× td(km))/13.5] +(21.96/13.5)		Logging residues truck and trailer (LT) =37.61×[0.074+(0.008 ×td(km)$^{-0.278}$) × td(km)]	Logging residues truck and trailer (LT) =[(1.20×2× td(km))/13.5] +(21.96/13.5)
FF > SL+PL	Large harvester (SL/PL) =47.51×0.08	Large harvester (SL/PL) =70.13×0.08	FF > SPC+SL +LT	Feller-puller (SPC+SL) =64.00×0.06	Feller-puller (SPC+SL) =96.00×0.06	FF > SPC+SL +LT	Feller-puller (SPC+SL) =64.00×0.06	Feller-puller (SPC+SL) =96.00×0.06
	Large forwarder (SL) =0.0026×fd(m) +2.42	Large forwarder (SL) =0.0046×fd(m)+ 4.24		Feller-puller (LT) =64.00×0.02	Feller-puller (LT) =96.00×0.02		Feller-puller (LT) =64.00×0.02	Feller-puller (LT) =96.00×0.02
	Large forwarder (PL) =0.0028×fd(m) +3.15	Large forwarder (PL) =0.0049×fd(m)+ 5.51		Large harvester (SPC+SL) =47.51×0.02	Large harvester (SPC+SL) =70.13×0.02		Large harvester (SPC+SL) =47.51×0.02	Large harvester (SPC+SL) =70.13×0.02
	Timber truck and trailer (SL)	Timber truck and trailer (SL)		Large harvester (LT)	Large harvester (SPC+SL)		Large harvester (LT)	Large harvester (SPC+SL)

	=36.74×[0.054+(0.005×td(km)$^{-0.278}$) × td(km)]	=[(1.05×2× td(km))/19.6] +(19.35/19.6)	=47.51×0.02	=70.13×0.02	=47.51×0.02	=70.13×0.02
	Timber truck and trailer (PL) =36.74×[0.055+(0.005×td(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (PL) =[(1.05×2× td(km))/18.8] +(19.35/18.8)	Large forwarder (SPC+SL) =0.0026×fd(m) +2.33	Large forwarder (SPC+SL) =0.0046×fd(m)+ 4.08	Large forwarder (SPC+SL) =0.0026×fd(m) +2.33	Large forwarder (SPC+SL) =0.0046×fd(m)+ 4.08
			Large forwarder (LT) =0.0027×fd(m) +2.36	Large forwarder (LT) =0.0048×fd(m)+ 4.14	Large forwarder (LT) =0.0027×fd(m) +2.36	Large forwarder (LT) =0.0048×fd(m)+ 4.14
			Timber truck and trailer (SPC+SL) =36.74×[0.054+(0.005×td(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (SPC+SL) =[(1.05×2× td(km))/19.6] +(19.35/19.6)	Timber truck and trailer (SPC+SL) =36.74×[0.054+(0.005×td(km)$^{-0.278}$) × td(km)]	Timber truck and trailer (SPC+SL) =[(1.05×2× td(km))/19.6] +(19.35/19.6)
			Logging residues truck and trailer (LT) =37.61×[0.074+(0.008×td(km)$^{-0.278}$) × td(km)]	Logging residues truck and trailer (LT) =[(1.20×2× td(km))/13.5] +(21.96/13.5)	Logging residues truck and trailer (LT) =37.61×[0.074+(0.008×td(km)$^{-0.278}$) × td(km)]	Logging residues truck and trailer (LT) =[(1.20×2× td(km))/13.5] +(21.96/13.5)
FF > LR chipped	Large forwarder =0.0073×fd(m) +4.58	Large forwarder =0.013×fd(m)+ 8.03				
	Drum chipper truck mounted =67.04×0.086	Drum chipper truck mounted =121.94×0.086				
	Woodchips truck and trailer =37.39×[0.085+(0.006×td(km)$^{-0.278}$) × td(km)]	Woodchips truck and trailer =[(1.12×2× td(km))/16.2] +(25.00/16.2)				
FF > SP	Excavator =21.18×0.27	Excavator =62.32×0.27				
	Large forwarder =0.0044×fd(m) +9.05	Large forwarder =0.0077×fd(m) +15.86				
	Logging residues truck and trailer =37.61×[0.125+(0.009×td(km)$^{-0.278}$) × td(km)]	Logging residues truck and trailer =[(1.20×2× td(km))/11.3] +(25.54/11.3)				

FF > SP pre-crushed	Excavator =21.18×0.27 Large forwarder =0.0044×fd(m) +9.05 Shredder =44.44×0.050 Grapple loader =22.22×0.050 Woodchips truck and trailer =37.39×[0.098+(0.007×td(km)$^{-0.278}$) × td(km)]	Excavator =62.32×0.27 Large forwarder =0.0077×fd(m) +15.86 Shredder =102.57×0.050 Grapple loader =53.74×0.050 Woodchips truck and trailer =[(1.12×2× td(km))/15.6] +(29.78/15.6)