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Fuel Consumption, Greenhouse Gas Emissions, and Energy Efficiency of Wood-Harvesting Operations: A Case Study of Stora Enso in Finland

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Abstract

The EU's climate and energy framework and Energy Efficiency Directive drive European companies to improve their energy efficiency. In Finland, the aim is to achieve carbon neutrality by 2035. Stora Enso Wood Supply Finland (WSF) had a target, by 2020, to improve its energy efficiency by 4% from the 2015 level. This case study researches the use of the forest machine fleet contracted to Stora Enso WSF. The aims were to 1) clarify the forest machine fleet energy-efficiency as related to the engine power; 2) determine the fuel consumption and greenhouse gas (GHG) emissions from wood-harvesting operations, including relocations of forest machines by trucks; and 3) investigate the energy efficiency of wood-harvesting operations. The study data consisted of Stora Enso WSF's industrial roundwood harvest of 8.9 million m^3 *(solid over bark) in 2016. The results illustrated that forest machinery was not allocated to the different cutting methods (thinning or final felling) based on the engine power. The calculated fuel consumption totalled 14.2 million litres (ML) for harvesting 8.9 million m*^{3}*, and the calculated fuel consumption of relocations totalled 1.2 ML, for a total of 15.4 ML. The share of fuel consumption was 52.5% for harvesters (cutting), 39.5% for forwarders (forest haulage), and 8.0% for forest machine relocations. The average calculated cubic-based fuel consumption of wood harvesting was 1.6 L/m*^{3}*, ranging from the lowest of 1.2 L/m*^{3} *for final fellings to the highest of 2.8 L/m*^{3} *in first thinnings. The calculated fuel consumption from machine relocations was, on average, 0.13 L/m*^{3}*. The calculated carbon dioxide equivalent (*CO_2 *eq.) emissions totalled 40,872 tonnes (t), of which 21,676 t were from cutting, 16,295 t were from forwarding, and 2901 t from relocation trucks. By cutting method, the highest calculated* CO_2 *eq. emissions were recorded in first thinnings (7340 g* CO_2 *eq./m*^{3}*) and the lowest in final fellings (3140 g* CO_2 *eq./m*^{3}*). The calculated* CO_2 *eq. emissions in the forest machine relocations averaged 325 g* CO_2 *eq./m*^{3}*. The results underlined that there is a remarkable gap between the actual and optimal allocation of forest machine fleets. Minimizing the gap could result in higher work productivity, lower fuel consumption and GHG emissions, and higher energy efficiency in wood-harvesting operations in the future.*

Keywords: greenhouse gas (GHG) emissions, carbon dioxide equivalent (CO_2 *eq.), carbon neutrality, logging, roundwood, forest machines, engine power, machine relocations*

1. Introduction

In the 2020s, climate change is one of the biggest issues in the world. Human activities are estimated to have caused approximately 1.0°C of global warming above pre-industrial levels, with a likely range of 0.8°C to 1.2°C because of greenhouse gas (*GHG*) emissions – among others carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) (Masson-Delmotte et al. 2018). Furthermore, the IPCC forecasts that global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (Masson-Delmotte et al. 2018). Globally, human *GHG* emissions were over 36 billion tonnes of carbon dioxide equivalent

(CO_2 eq.) in 2018 (World Economic Forum 2019). In this respect, the EU's *GHG* emissions totalled 4483 million tonnes of CO_2 eq., the lowest level since 1990 (European Commission 2019). In fact, *GHG* emissions were 23% below the 1990 level, while gross domestic product in the EU area had increased by 61%. The EU's climate and energy framework (European Union 2014) has set three challenging targets for 2030: 1) decrease *GHG* emissions by at least 40%, 2) increase share of renewable energy sources (RESs) by at least 27%, and 3) improve energy efficiency by at least 27% from the 1990 level. There is an even more ambitious target for 2050: to cut *GHG* emissions 80% below the 1990 level (European Union 2011).

In Finland, a plan announced by the country's new coalition government states an aim for carbon neutrality by 2035 (Finnish Government 2020). In 2018, the *GHG* emissions totalled 56.4 million tonnes of CO_2 eq., a 21% decrease compared to the 1990 level in Finland (Official Statistics of Finland 2019). The main part of the *GHG* emissions was CO_2 (82%). The share of CH_4 was 8%, as was the share of N_2O, and the share of F gases (i.e. fluorinated *GHGs*: HFC, PFC compounds, SF6, and NF3) was 2% of the total *GHG* emissions (Official Statistics of Finland 2019). Correspondingly, the carbon sink of the LULUCF sector (i.e. the land use, land use change and forestry sector) in Finland was –14.2 million tonnes of CO_2 eq. in 2018 (Official Statistics of Finland 2019). Regarding the forestry sector, the total use of industrial roundwood was 73.6 million m^3 solid over bark (henceforth referred to as m^3), of which 64.5 million m^3 (88%) came from domestic wood procurement (Ylitalo 2019). On the other hand, the annual increment of growing stock on forest land and on poorly productive forest land totalled 108 million m^3 (Ihalainen and Vaahtera 2019), which provided the forest industry with forest stands of 100% renewable wood (Palander et al. 2020). However, on a long-term rotation basis (e.g. 50 years), it is apparent that forests viable carbon sink can only be retained by increasing the country's forest thinning and final felling. In this respect, wood-harvesting operations have increased too slowly during recent decades (Palander et al. 2020). Therefore, the National Forest Strategy 2025 in Finland has set a goal to increase the amount of industrial roundwood cuttings from the 2013 level (around 65 Mm^3) to 80 million m^3 by 2025 (Ministry of Agriculture and Forestry 2019).

In 2012, the Energy Efficiency Directive (Directive 2012/27/EU) was launched to implement the targets of the 2030 climate and energy framework in Europe. These targets and energy-efficiency agreements will guide European companies to improve their energy efficiency. Since 2014, the Energy Efficiency Directive has steered the energy-efficiency work in large Finnish companies. This law requires them to set and follow up on their energy-efficiency targets, as well as to hold an energy audit every fourth year (Energiatehokkuuslaki 2014). Stora Enso is one of the companies required to follow up on the provisions of the Energy Efficiency Directive in Finland. Stora Enso's ambitions are to drive down fossil fuel use so that the company can get as close to zero as possible within the decade using technically and commercially feasible means, and to seek to substitute fossil-based and other non-renewable materials with renewable raw materials and products (Stora Enso 2019). In practice, Stora Enso's main target is to reduce fossil CO_2 and other *GHG* emissions in its operations (e.g. wood-supply operations) by 31% per tonne of pulp, paper, and board produced by 2030, compared to a 2010 baseline (Stora Enso 2019).

In 2018, the total wood volume supplied by Stora Enso WSF from forests to internal (own) and external mill customers was 23 million m^3. Currently, in 2020, wood-procurement services are produced by more than, primarily independent, 300 harvesting systems (i.e. harvesters and forwarders) and approximately 250 timber trucks. The target of Stora Enso WSF was, by 2020, to improve its energy efficiency by 4% from the 2015 level (Stora Enso 2015). It is necessary to improve energy efficiency throughout the company, to provide close cooperation throughout the whole wood-supply chain and to secure more accurate knowledge of the energy efficiency in the supply chain (Haavikko et al. 2019); for instance, accurate and reliable information on the total and average fuel consumption and *GHG* emissions. To improve energy efficiency in the wood-supply chain, it is crucial that harvesting machines and timber trucks are optimally directed at their tasks; for instance, the harvesting machinery is carefully allocated and utilized in different cutting methods by paying attention to its properties (i.e. engine power, weight of machine, boom reach, carrying capacity of forwarder) and other equipment (e.g. tracks). Forest machines equipped with smaller engine power and lower work productivity should be directed at thinning stands with a smaller stem size of removals, and the larger machines should be directed at final fellings in which more powerful forest machinery is needed because the average size of trees is larger.

In Nordic cut-to-length (CTL) wood-harvesting operations with both harvesters and forwarders, Brunberg et al. (2004), Brunberg (2007, 2013), and Holzleitner et al. (2011) reported that fuel consumption (litres per hour, L/h) depends very strongly on machine size and engine power (kW). Furthermore, Ghaffariyan et al. (2018) pointed out that fuel consumption is impacted by machine design. Jylhä et al. (2019) noted that, currently in Finland, the allocation of wood-harvesting machinery is not completely optimal. In addition to harvesters and forwarders, trucks are used for relocation of machines in wood-harvesting operations. Haavikko et al. (2019) stressed in their forest machine entrepreneur interview survey that forest machine entrepreneurs frequently regard forest machine relocation distances between harvesting sites as one of the most essential factors to energy-efficient wood-harvesting operations. In his relocation truck study, Kauppinen (2010) measured that, when driving a loaded relocation truck, the fuel consumption is, on average, 50 L/100 km, while for an empty relocation truck, the fuel consumption averages 29 L/100 km.

Wildmark (2014) noted that in Sweden, the machine relocation distance (i.e. driving a loaded truck) from one harvesting site to another is, on average, 14 km. In Finland forest machine relocation distance between harvesting sites averages approximately 30 km (Kuitto et al. 1994, Kärhä et al. 2007, Väätäinen et al. 2006, 2008, 2019, Kauppinen 2010, Haavikko et al. 2019), noticeably longer than in Sweden. Kuitto et al. (1994), Väätäinen et al. (2006, 2008) and Kauppinen (2010) indicated that total driving distance for one machine relocation is approximately 70–100 km per forest machine – and further around 140–200 km per harvesting system. Hence, the effect of fuel consumption and *GHG* emissions caused by forest machine relocations is important. Harvesting conditions and forest stand inventory volumes also affect the energy-efficiency modelling of wood-harvesting operations (Palander et al. 2018). In this respect, the combined emission and energy-efficiency calculation procedure developed in this study will be tested to advance the energy-efficiency optimization model of wood procurement (Palander et al. 2020).

This study focused on the energy efficiency of the Stora Enso WSF wood-supply chain, particularly in the wood-harvesting operations and forest machine relocations in Finland. The aims of the study were as follows:

⇒ to clarify the allocation of the forest machine fleet for cutting methods from the energy-efficiency point of view related to the engine power of forest machines
⇒ to determine the total and average fuel consumption and *GHG* emissions caused by wood-harvesting operations including cutting and forwarding in the forests and the relocation of forest machines transported by relocation trucks on the roads, and
⇒ to investigate the energy efficiency of wood-harvesting operations.

2. Materials and Methods

2.1 Collection of Forest Machine Data and Classification of Machinery

The research data was collected from the enterprise resource planning (ERP) system of Stora Enso WSF. Data collection was the first stage of the energy-efficiency calculation procedure of wood-harvesting operations (Fig. 1). The research data consisted of the removals harvested by 34 forest machine contractors by Stora Enso WSF from the 1st of January to the 31st of December 2016. In the study, there were 18,114 harvesting sites in total. Harvesting data collected from the ERP system included the following information by harvesting site:

⇒ Forest machine contractor: identification code
⇒ Forest machine: identification code, type (harvester & forwarder), brand, model, year of manufacturing; and
⇒ Harvesting site: geographical location (coordinates) (Fig. 2), date of cutting, cutting method (first thinning, later thinning, final felling), total number of stems removed, total removals (m^3), average stem size of removals in the stand (m^3/stem), and forwarding distance (m).

After capturing the ERP system data, forest machine entrepreneur interviews were conducted, and the forest machine fleet used in the harvests of 2016 was checked (i.e. Was machinery information correct in the ERP system data?) and if required, corrected. Furthermore, the interviewees were asked for the number of wheels on forest machines used. Then, the corrected machine data was enriched with accurate machine information (i.e. model of engine, engine power [kW], and carrying capacity [tonnes] for

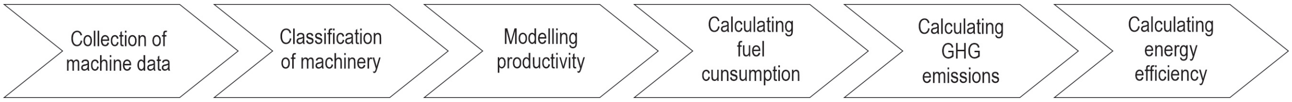

Fig. 1 Procedure for producing fuel consumption, *GHG* emission, and energy-efficiency figures for the forest machine fleet of the study

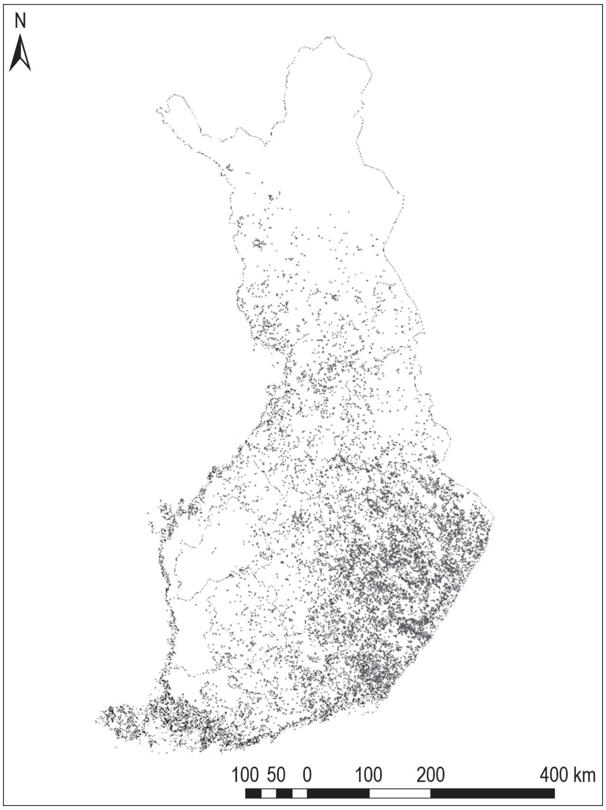

Fig. 2 Locations of the harvesting sites (n=18,114; small grey plots on the map) of the study

forwarders). The accurate machine information was mainly found in the Koneyrittäjät Machine Catalogues annually published by the Trade Association of Finnish Forestry and Earth Moving Contractors (1996–2016). Some detailed machine information was also found and checked from the Internet pages and machine booklets of the forest machine manufacturers John Deere, Komatsu, Logset, and Ponsse.

There were 418 harvesters and 336 forwarders in the final study data. The three main brands of machines were Ponsse (59.1% of harvesters and 57.7% of forwarders), John Deere(/Timberjack) (20.1% of harvesters and 17.5% of forwarders), and Komatsu (/Valmet) (7.5% of harvesters and 8.6% of forwarders). The most common harvester model used was Ponsse Ergo (6-wheeled; 6WD), and the most common forwarder model was Ponsse Elk (8WD). The carrying capacity of forwarders averaged 12.7 tonnes, varying from 8.5 tonnes to 18.0 tonnes. The mean age of the harvesters was 4.3 years, and it was 5.4 years for the forwarders.

The variation range of the harvesters engine power was 70–240 kW, and that of forwarders was 82–210 kW. The harvesters engine power averaged 169 kW, and that of the forwarders averaged 149 kW. To investigate the use of the forest machines used and the allocation of harvesters and forwarders with different engine power in 2016 by engine power and by cutting method, both harvesters and forwarders were classified by engine power classes of 20 kW, from less than 100 kW to more than 199 kW. The biggest group of harvesters and forwarders was the 140–159 kW class (Fig. 3). Harvesters and forwarders equipped with engine power of 120–139 kW and >199 kW were also commonly used (Fig. 3).

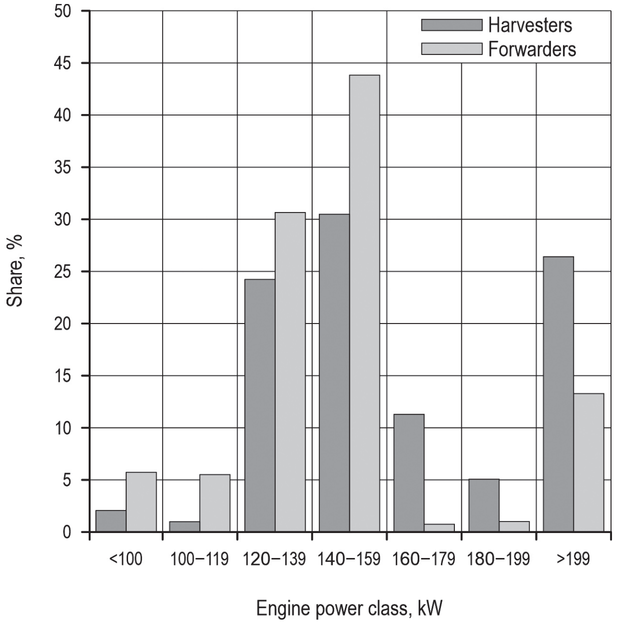

Fig. 3 Distribution of the number of harvesters (n=418) and forwarders (n=336) related to their engine power

The total volume of harvested removals in the study data was 8.9 million m^3, and more than 48 million stems were cut (Table 1). The total harvested removals divided by the cutting method were as follows: first thinnings 8%, later thinnings 37%, and final fellings 55%. The stem size of removals in the stand averaged 0.080 m^3 for first thinnings, 0.139 m^3 for later thinnings, and 0.305 m^3 for final fellings (Table 1).

2.2 Modelling of Forest Machine Fleet Productivity

Modelling of the productivity with harvesters in both thinnings (Eq. 1) and final fellings (Eq. 2) was conducted by applying the functions by Eriksson and Lindroos (2014), with the mean stem size of removal in the stand (V) as the independent variable. The conversion from the under-bark volume by Eriksson and Lindroos (2014) to the over-bark volume was achieved

Table 1 Description of total data and the average harvesting conditions at harvesting sites by cutting method

	First thinning	Later thinning	Final felling	Total	Average
Number of harvesting sites	– *	– *	– *	18,114	–
Roundwood removals, m^3 (%)	723,900 (8.1)	3,250,000 (36.5)	4,942,100 (55.4)	8,916,000	–
Removal/harvesting site, m^3	– *	– *	– *	–	492
Number of stems removed, *n* (%)	9,001,800 (18.5)	23,438,800 (48.2)	16,219,400 (33.3)	48,660,000	–
Stem size of removals, m^3	0.080	0.139	0.305	–	0.183
Forwarding distance, m	323	318	286	–	301

* The number of harvesting sites of first thinnings, later thinnings, and final fellings could not be determined because more than one cutting method was used at some harvesting sites

using a coefficient of 1.14 (cf. Hakkila et al. 2002). Furthermore, the effective (E_0) hour cutting productivity by Eriksson and Lindroos (2014) was converted to operating (E_{15}) hour productivity in both thinnings and final cuttings using a coefficient of 0.88 (cf. Rajamäki et al. 1996). When cutting with the harvesters equipped with an engine power of <100 kW, the productivity of cutting work was lowered by 3.0 m^3/E_{15} hour in all final-felling stands (cf. Eriksson and Lindroos 2014).

$$Ln(P_{CutThin}) = (3.466 + 0.211 \times Ln(V \times 1.14) - 0.112 \times (Ln(V \times 1.14))^2\ ) \times b_c \times h_{Cut} \quad (1)$$

Where:

$P_{CutThin}$	cutting productivity in thinnings, m^3/E_{15} hours
V	mean stem size of removals in the stand, m^3/stem
b_c	coefficient for conversion from the under-bark volume to over-bark volume (1.14)
h_{Cut}	coefficient for conversion from effective (E_0) hour cutting productivity to operating (E_{15}) hour productivity (0.88).

$$Ln(P_{CutFin}) = (3.704 + 0.134 \times Ln(V \times 1.14) - 0.161 \times (Ln(V \times 1.14))^2\ ) \times \mathrm{b_c} \times \mathrm{h_{Cut}} \quad (2)$$

Where:

P_{CutFin}	cutting productivity in final fellings, m^3/E_{15} hours.

Modelling of the forest haulage productivity with forwarders in both thinnings (Eq. 3) and final fellings (Eq. 4) was also conducted by applying the functions by Eriksson and Lindroos (2014) with the mean stem size of removals (*V*), forwarding distance (D_{For}), and actual load size (*LS*) as the independent variables. The actual load size in forwarding was determined using a green density of 845 kg/m^3 of fresh timber cut (cf. Marjomaa 1992, Kainulainen and Lindblad 2005, Lindblad and Repola 2019), and it was assumed that the average filling rate of a load was 90% (Eq. 5). The effective (E_0) hour productivity by Eriksson and Lindroos (2014) was converted to operating (E_{15}) hour productivity in thinnings and final cuttings using a coefficient of 0.93 (cf. Väkevä et al. 2001).

$$Ln(P_{ForThin}) = (2.798 - 0.028 \times (Ln(D_{For}))^2 + 0.296 \times Ln(V \times 1.14) + 0.166 \times (Ln(D_{For} \times (LS \times 1.14)))) \times b_c \times h_{For} \quad (3)$$

Where:

$P_{ForThin}$	forwarding productivity in thinnings, m^3/E_{15} hour
D_{For}	forwarding distance, m
LS	actual load size, m^3
h_{For}	coefficient for conversion from effective (E_0) hour forwarding productivity to operating (E_{15}) hour productivity (0.93).

$$Ln(P_{ForFin}) = (0.327 - 0.073 \times (Ln(D_{For}))^2 + 0.188 \times Ln(V \times 1.14) + 0.636 \times (Ln(D_{For} \times (LS \times 1.14)))) \times b_c \times h_{For} \quad (4)$$

Where:

$P_{ForThin}$	forwarding productivity in final felllings, m^3/E_{15} hour.

$$LS = \left(\frac{CC}{gd}\right) \times fr \quad (5)$$

Where:

CC	maximum carrying capacity of forwarder, kg
gd	green density used (845), kg/m^3
fr	coefficient for the filling rate assumed of forwarder (0.90).

The average cutting and forest haulage productivity by cutting method is presented in Table 2. The payload in forwarding averaged 13.5 m^3, ranging between 9.1 m^3 and 19.1 m^3 by harvesting site.

Table 2 Average productivity of cutting and forwarding by cutting method

	First thinning	Later thinning	Final felling
	Productivity, m^3/E_{15}-hour		
Cutting	9.4	15.4	31.3
Forwarding	13.0	16.3	22.3

2.3 Calculating the Forest Machine Fleet Fuel Consumption and Emissions

The hour-based fuel consumption (litres per E_{15} hour; L/E_{15}) of the study harvesters (Eq. 6) and forwarders (Eq. 7) was calculated by applying the functions by Brunberg (2013) with the engine power (*E*) of the forest machine as the independent variable.

$$FC_{Cut\_H} = 4.1 + 0.068 \times E_{Harv} \quad (6)$$

Where:

FC_{Cut_H} hour-based fuel consumption in cutting, L/E_{15}-hour

E_{Harv} engine power of harvester, kW.

$$FC_{For\_H} = 0.9 + 0.078 \times E_{For} \quad (7)$$

Where:

FC_{For_H} hour-based fuel consumption in forwarding, L/E_{15}-hour

E_{For} engine power of forwarder, kW.

Furthermore, cubic-based fuel consumption (litres per m^3 harvested; L/m^3) for the study harvesters and forwarders was calculated by dividing hour-based fuel consumption by productivity (Eq. 8 and Eq. 9). Total fuel consumption per harvesting site (L/harvesting site) was determined by summing up the cubic-based fuel consumption in cutting and forwarding and multiplying it by the total removals at the harvesting site (Eq. 10).

$$FC_{Cut\_C} = FC_{Cut\_H} / P_{Cut} \quad (8)$$

Where:

FC_{Cut_C} cubic-based fuel consumption in cutting, L/m^3

P_{Cut} cutting productivity, m^3/E_{15}-hour.

$$FC_{For\_C} = FC_{For\_H} / P_{For} \quad (9)$$

Where:

FC_{For_C} cubic-based fuel consumption in forwarding, L/m^3

P_{For} forwarding productivity, m^3/E_{15} hour.

Table 3 *GHG* emissions per fuel litre (g/L) used in the calculation of emissions for harvesters and forwarders by emission category (Lipasto database 2017)

Emission category	Harvesters	Forwarders
	Emissions, g/L	
CO_2 eq.	2674	2673
CO	5.7	7.9
HC	0.72	0.94
CH_4	0.15	0.15
N_2O	0.042	0.042
NO_X	3.9	6.0
SO_2	0.0081	0.0081
PM	0.082	0.200

$$FC_{TOT} = (FC_{Cut_C} + FC_{For_C}) \times R \quad (10)$$

Where:

FC_{TOT} total fuel consumption in cutting and forwarding at harvesting site, L

R total removals at harvesting site, m^3.

The *GHG* emissions of harvesters and forwarders were calculated by applying the VTT's Lipasto database (2017) of the average emissions (g per litre used; g/L) of work machinery in 2016 in Finland (Table 3). The following emissions were calculated: CO_2 eq., carbon monoxide (CO), hydrocarbons (HC), CH_4, N_2O, nitrogen oxides (NO_X), sulphur dioxide (SO_2), and total particulate matter (PM) of exhaust gases.

The cubic-based *GHG* emissions (g per m^3 harvested; g/m^3) by emission category and harvesting site for the study harvesters and forwarders were calculated by dividing total *GHG* emissions in each emission category by the total removals at the harvesting site (Eq. 11).

$$GHG_C = GHG_{TOT} / R \quad (11)$$

Where:

GHG_C cubic-based *GHG* emissions in each emission category, g/m^3

GHG_{TOT} total *GHG* emissions in each emission category, g.

2.4 Collection of Forest Machine Relocation Data

The research data of forest machine relocations from one harvesting site to another was detected using the same ERP system as for the forest machine fleet data

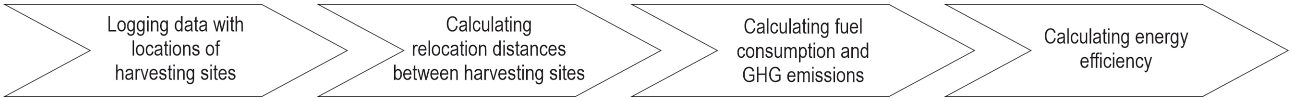

Fig. 4 Procedure for producing fuel consumption, *GHG* emission, and energy-efficiency figures for forest machine relocations with relocation trucks

(Figs 2 and 4). Thus, relocation data consisted of machine relocations between 18,114 harvesting sites from the 1st of January to the 31st of December 2016.

The distances of forest machine relocations were calculated by assuming that machine relocation was executed using the shortest route from the coordinate of harvesting site A to the coordinate of harvesting site B, travelling along the common road network. A national Digiroad (2020) network database was used for calculations. The distance from harvesting site A to B was calculated using Esri network analyst tools, applying Dijkstra's shortest path first (SPF) algorithm (Dijkstra 1959) for shortest path calculations on the Digiroad network dataset. There were 746 measured distances that were shorter than 500 meters (i.e. they were adjacent harvesting sites). Those very short (<0.5 km) relocation distances were removed from the final relocation data because it was evaluated that they would often drive with forest machines along gravel forest roads to the next harvesting site. Hence, the final relocation distance data consisted of 17,368 relocations (Fig. 5). The relocation distance (with loaded relocation truck) was, on average, 26.3 km.

In the study, it was assumed that each forest machine relocation is a separate operation; in other words, first, a harvester of the harvesting chain is relocated, then a relocation truck will go to relocate some other machine, and finally a relocation truck will come to relocate a forwarder of the harvesting chain in question (Fig. 6). Thus, the measured relocation distance between harvesting sites A and B was the relocation distance of driving a loaded truck. According to the forest machine entrepreneurs interviewed and earlier reports (e.g. Kuitto et al. 1994, Väätäinen et al. 2006, 2008, Kauppinen 2010), machine relocation distances with an empty truck are clearly longer (double or even triple) than those with a loaded truck. Hence, it was assumed that each driving distance with an empty relocation truck would be 30 km longer than driving distances with loaded trucks (Fig. 6, Eq. 12).

$$D_{\mathrm{Emp}} = D_{\mathrm{Load}} + 30 \qquad (12)$$

Where:

D_{Emp} driving distance of empty relocation truck, km

D_{Load} driving distance of loaded relocation truck, km.

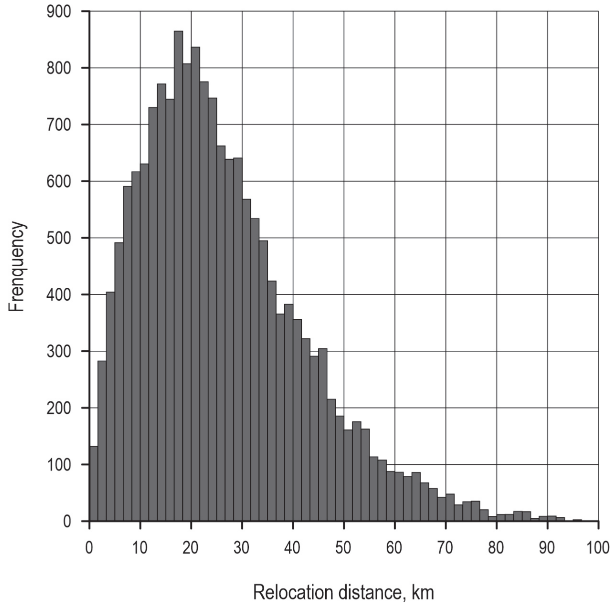

Fig. 5 Distribution of distances of forest machine relocations (n=17,368) in the final relocation data

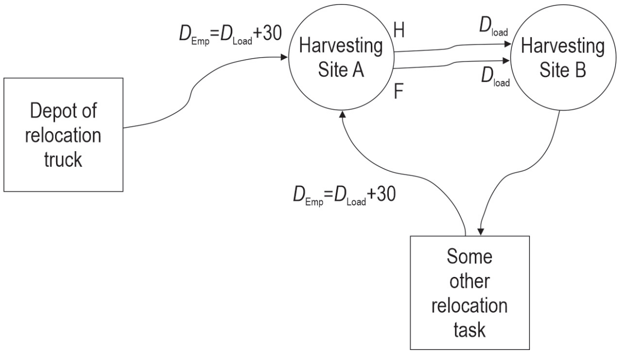

Fig. 6 Procedure for calculating relocation distances to forest machine relocations with relocation trucks. H=harvester, F=forwarder (cf. Eq. 12)

Total calculated driven distance for one relocation of one harvesting chain (i.e. harvester and forwarder) averaged 165.1 km (on average 82.6 km, in total, driving for one forest machine relocation). The calculated distance driven by relocation trucks totalled 2,867,441 km, of which the share with empty trucks was 68.2% and with loaded trucks 31.8%.

2.5 Calculating the Forest Machine Relocation Fuel Consumption and Emissions

The fuel consumption of relocation trucks driving empty and loaded was determined by applying Eq. 13 and Eq. 14. Fuel consumption for each machine relocation was calculated by applying Eq. 15 and Eq. 16.

$$FC_{\mathrm{Emp\_100}} = 47.672 \times D_{\mathrm{Emp}}^{-0.076} \tag{13}$$

Where:

$FC_{\mathrm{Emp_100}}$fuel consumption driving empty, L/100 km.

$$FC_{\mathrm{Load\_100}} = 73.155 \times D_{\mathrm{Load}}^{-0.056} \tag{14}$$

Where:

$FC_{\mathrm{Load_100}}$fuel consumption driving loaded, L/100 km.

$$FC_{\mathrm{Emp\_100}} = FC_{\mathrm{Emp\_100}} \times (D_{\mathrm{Emp}} / 100) \tag{15}$$

Where:

FC_{Emp} fuel consumption driving empty, L/relocation.

$$FC_{\mathrm{Load}} = FC_{\mathrm{Load\_100}} \times (D_{\mathrm{Load}} / 100) \tag{16}$$

Where:

FC_{Load} fuel consumption driving loaded, L/relocation.

The *GHG* emissions of forest machine relocation trucks were calculated by applying the VTT's Lipasto database (2017) of the average emissions (g per kilometre driven; g/km) of an earthmoving truck along densely populated communities in 2016 in Finland because the Lipasto database did not include a specific truck for forest machine relocations or transports (Table 4). The same *GHG* emissions were calculated for harvesters and forwarders (CO_2 eq., CO, HC, CH_4, N_2O, NO_X, SO_2, and PM). The *GHG* emissions were separately determined for the empty and loaded relocation trucks (Table 4).

The cubic-based *GHG* emissions (g per m^3 harvested; g/m^3) for the study relocation trucks were calculated by dividing total *GHG* emissions by trucks with the total roundwood removals harvested in the study stands (Eq. 17).

$$GHG_{\mathrm{C\_Rel}} = GHG_{\mathrm{TOT\_Rel}} / R \tag{17}$$

Where:

$GHG_{\mathrm{C\_Rel}}$ cubic-based *GHG* emissions of machine relocations in each emission category, g/m^3

$GHG_{\mathrm{TOT\_Rel}}$ total *GHG* emissions by relocation trucks in each emission category, g.

Table 4 Emissions per kilometre driven (g/km) by empty and loaded relocation trucks (Lipasto database 2017)

Emission category	Empty	Loaded
	Emissions, g/km	
CO_2 eq.	838	1384
CO	1.0	1.2
HC	0.20	0.23
CH_4	0.008	0.012
N_2O	0.029	0.034
NO_X	5.8	8.0
SO_2	0.0028	0.0046
PM	0.10	0.13

2.6 Calculating the Energy Efficiency of Harvesting Operations

The energy efficiency (i.e. the efficiency ratio of the renewable wood energy provided and fossil energy consumed) of wood-harvesting operations and forest machine relocations by trucks was calculated applying Eq. 18 (Palander et al. 2020):

$$EE = E_{\mathrm{Pro}} / E_{\mathrm{Con}} \tag{18}$$

Where:

EE energy efficiency, kWh/kWh

E_{Pro} amount of renewable wood energy provided, kWh

E_{Con} amount of fossil energy consumed, kWh.

The amount of renewable wood energy provided was calculated using the following assumptions and Equations: First, the harvested wood volume (m^3) was converted to kilograms applying a green density of 845 kg/m^3 of fresh timber cut (cf. Marjomaa 1992, Kainulainen and Lindblad 2005, Lindblad and Repola 2019). Then, the net calorific value of the fresh wood was produced using Eq. 19 (Alakangas et. al 2016). The moisture content of the wood of 55% was applied and the net calorific value of the dry wood of 19.167 MJ/kg was used in the calculations (cf. Palander et al. 2020).

$$Q_{\mathrm{net,f}} = Q_{\mathrm{net,d}} \times (100 - M_{\mathrm{ar}}) / 100 - c \times M_{\mathrm{f}} \tag{19}$$

Where:

$Q_{\mathrm{net,f}}$ net calorific value of fresh wood, MJ/kg

$Q_{\mathrm{net,d}}$ net calorific value of dry wood, MJ/kg

M_{f} moisture content of fresh wood,%

c a constant of 0.02441 MJ/kg, equivalent to water evaporation rate at a temperature of 25°C

M_{ar} moisture content of wood at the time of arrival, %.

The net calorimetric value of the fresh wood in mega joules was produced when the net calorific value of the fresh wood (7.2826 MJ/kg), calculated by Eq. 19, was multiplied by the mass of the fresh wood. Further, the amount of wood energy provided, expressed in kWh, was calculated applying the factor of 3.6 MJ/kWh.

When calculating the amount of fossil energy consumed, first, the volume of diesel was converted to kilograms using a diesel density of 830 kg/m^3 of a sulphur light fuel oil in the study (cf. ABC 2015, 2017, Neste 2020a, 2020b). Then, the fuel energy quantity was calculated by converting with the net calorific value coefficient of 43 MJ/kg for light fuel oils (Seppänen et al. 2012). The amount of energy consumed expressed in kWh was determined by dividing MJ by 3.6.

3. Results

3.1 Use of Forest Machine Fleet

The results illustrate that the forest machinery researched in the study was not directed at different cutting methods and harvesting sites based on the engine power. For instance, in cutting, the majority (31.6%; more than 220,000 m^3) of the first-thinning wood was cut by harvesters with an engine power of >199 kW (i.e. the largest harvester group of the study) (Fig. 7). Almost an equal proportion (30.9%) of the first-thinning wood was cut by harvesters with the engine power of 140–159 kW (i.e. with middle-sized harvesters). Correspondingly, in later thinnings, the 140–159 kW harvesters were used the most (i.e. 33.0% of the later-thinning wood was cut by these harvesters), while the largest harvesters equipped with an engine power of more than 199 kW cut 30.3% of the later-thinning wood. In final fellings, the largest (>199 kW) harvesters were the most frequently used (39.4%), and the middle-sized (engine power of 140–159 kW) harvesters cut 28.5% of the final-felling wood (Fig. 7).

Investigating the allocation of forwarder resources indicates that forest haulage was mostly (around 50%) executed by the middle-sized (engine power of 140–159 kW) forwarders in all cutting methods (Fig. 7). Furthermore, the so-called lower middle-sized forwarders equipped with an engine power of 120–139 kW conducted the forwarding of timber, with 28.0–30.1% by the cutting method (Fig. 7). The share of forest-hauled timber by the forwarders equipped with an engine power of >199 kW varied between 13.1% and 13.8% by the cutting method (Fig. 7).

Regarding the cutting method proportions in each engine power group (Fig. 8), the same observation as

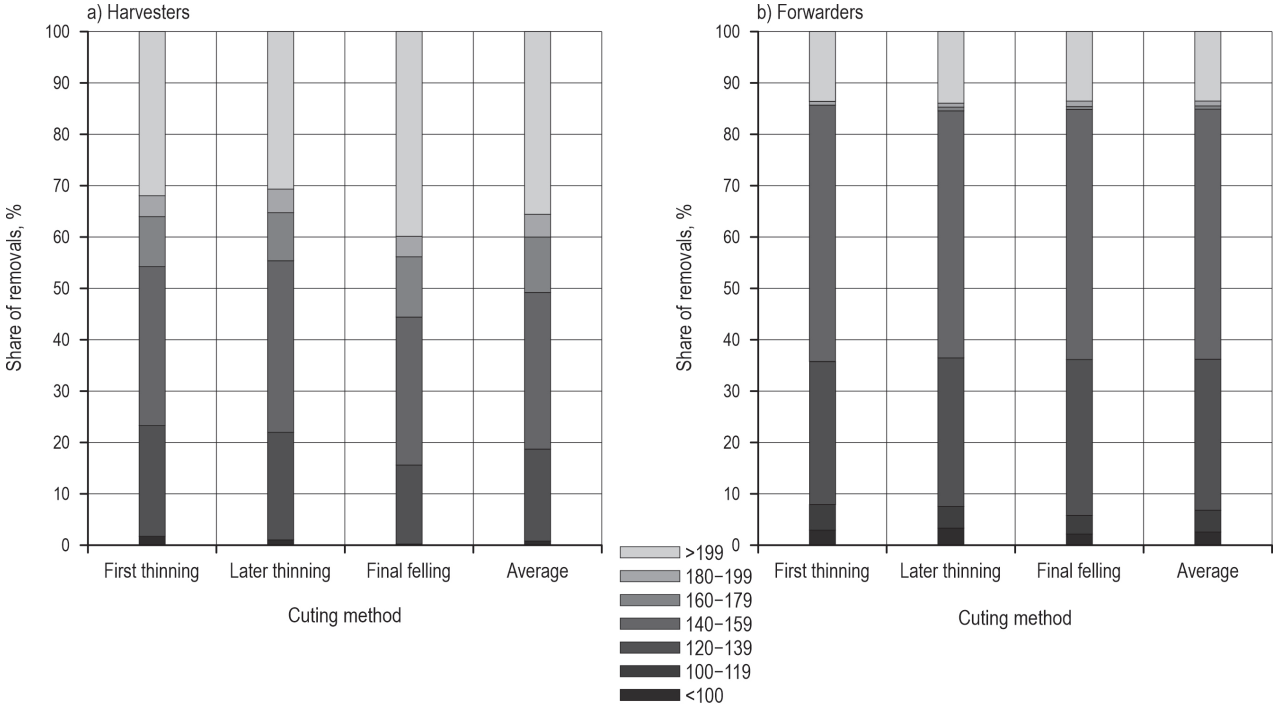

Fig. 7 Distribution of removals by cutting method (cf. Table 1) and by engine power (kW)

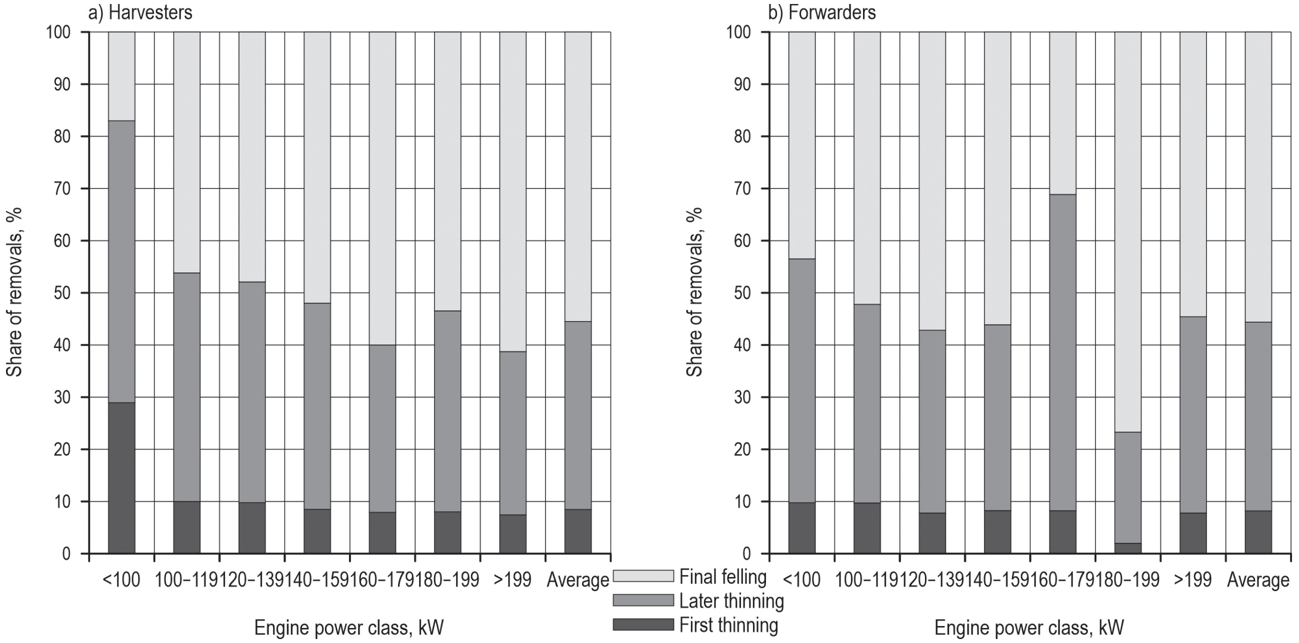

Fig. 8 Distribution of removals harvested by the engine power

earlier can be made (Fig. 7): Directing of the forest machine fleet is not optimal in terms of the machines engine power and further energy efficiency. Nonetheless, the small harvesters equipped with an engine power of less than 100 kW were more frequently allocated to thinnings, and their use in final cuttings was avoided (Fig. 8). Apart from the small harvesters, the other harvester groups were used similarly for the different cutting methods (Fig. 8).

Fig. 8 depicts the same trend with the forwarders in forest haulage as with the harvesters: There was no intentional forest machine allocation related to the engine power of the machines in the 2016 study data. However, the share of final cuttings with the forwarders equipped with an engine power of 160–179 kW, as well as the proportion of thinnings with the forwarders of an engine power of 180–199 kW, was smaller than that of the forwarders of other engine power groups (Fig. 8). Nevertheless, it is important to note that the number of these forwarder groups (160–179 kW and 180–199 kW) was quite small (Fig. 3), as was the forwarding volume, which was only around 50,000 m^3 (160–179 kW) and 95,000 m^3 (180–199 kW).

3.2 Fuel Consumption of Forest Machine Fleet

The calculated fuel consumption totalled 14.2 million litres (ML) for wood harvesting of the removals of 8.9 million m^3 in 2016. The share of cutting work was 57.1% (8.1 ML) of the total calculated fuel consumption. The biggest calculated total fuel consumption by the cutting method was in later thinnings (6.4 ML), which was 45.1% of the total fuel consumption in wood-harvesting operations in the forests. The share of first thinnings was 14.0% (2.0 ML) of the total calculated fuel consumption, and the proportion of final fellings was 40.9% (5.8 ML). In first thinnings, the proportion of cutting work from the total fuel consumption was the highest (64.9%), and in later thinnings it was lower (59.9%) than that of first thinnings. On the contrary, when harvesting wood from final fellings, the share of cutting from the total calculated fuel consumption was the lowest, at 51.3% of the total calculated fuel consumption due to wood-harvesting operations in the forests.

The calculated cubic-based fuel consumption of wood harvesting averaged 1.6 L/m^3 in the study (Table 5). In final fellings, the average cubic-based fuel consumption of wood harvesting was the lowest (1.2 L/m^3).

Table 5 Calculated average cubic-based fuel consumption in cutting and forwarding by cutting method in 2016

	First thinning	Later thinning	Final felling	Total harvesting
	Fuel consumption, L/m^3			
Cutting	1.78	1.18	0.60	0.91
Forwarding	0.96	0.79	0.57	0.68
Total harvesting	2.75	1.97	1.17	1.59

On the other hand, in first thinnings, the average fuel consumption was the highest, on average, 2.8 L/m^3 of fuel. Surveying the calculated cubic-based fuel consumption by the cutting method, it can be observed that cutting work consumed more fuel than forwarding in all cutting methods (Table 5).

3.3 *GHG* Emissions of Forest Machine Fleet

The calculated CO_2 eq. emissions of the harvesting operations of 8.9 million m^3 in the forests totalled 37,971 tonnes of CO_2 eq., of which 21,676 tonnes were from cutting work and 16,295 tonnes were from forwarding (Table 6). The calculated total CO emissions were 94 tonnes, total HC emissions were 12 tonnes, total CH_4 emissions were 2 tonnes, total N_2O emissions were 0.6 tonne, total SO_2 emissions were 0.1 tonne, total PM emissions were 2 tonnes and the emissions of NO_X totalled 68 tonnes. The cutting work proportions by emission category ranged between 35.1% and 57.1% in the calculated *GHG* emission data (Table 6).

Table 6 Calculated total *GHG* emissions in cutting and forwarding by cutting method with the removals harvested (8,916,024 m^3)

	First thinning	Later thinning	Final felling	Total harvesting
	CO_2 eq. emissions, kg			
Cutting	3,448,021	10,262,855	7,964,988	21,675,864
Forwarding	1,864,927	6,878,490	7,551,527	16,294,944
Total harvesting	5,312,947	17,141,346	15,516,515	37,970,808
	CO emissions, kg			
Cutting	7350	21,877	16,978	46,205
Forwarding	5512	20,329	22,318	48,159
Total harvesting	12,862	42,206	39,297	94,364
	HC emissions, kg			
Cutting	928	2763	2145	5836
Forwarding	656	2419	2656	5730
Total harvesting	1584	5182	4800	11,567
	CH_4 emissions, kg			
Cutting	193	576	447	1216
Forwarding	105	386	424	914
Total harvesting	298	962	871	2130
	N_2O emissions, kg			
Cutting	54	161	125	340
Forwarding	29	108	119	256
Total harvesting	83	269	244	596
	NO_X emissions, kg			
Cutting	5029	14,968	11,617	31,614
Forwarding	4186	15,440	16,951	36,577
Total harvesting	9215	30,408	28,568	68,191
	SO_2 emissions, kg			
Cutting	10	31	24	66
Forwarding	6	21	23	49
Total harvesting	16	52	47	115
	PM emissions, kg			
Cutting	106	315	244	665
Forwarding	140	515	565	1219
Total harvesting	245	829	809	1884

The calculated cubic-based CO_2 eq. emissions averaged 4259 g/m^3 harvested in the study (Table 7). By cutting method, the highest CO_2 eq. emissions were recorded in first-thinning stands (7340 g CO_2 eq./m^3), and the lowest in final fellings (3140 g CO_2 eq./m^3), which represented only 43% of the corresponding CO_2 eq. emissions from first-thinning stands. The calculated CO emissions were, on average, 10.6 g CO/m^3, and the NO_X emissions averaged 7.6 g NO_X/m^3. The average cubic-based HC and CH_4 emissions were 1.30 and 0.24 g/m^3 harvested, respectively (Table 7).

3.4 Fuel Consumption and *GHG* Emissions of Forest Machine Relocations

The calculated fuel consumption of relocation trucks totalled 1,234,605 litres, of which the share of driving a loaded relocation truck was 44.6%, and more than half (55.4%) of the calculated fuel consumption was caused by driving empty relocation trucks. For the relocation of one harvesting chain, the calculated fuel consumption averaged 71.1 L/relocation/harvesting chain, in total. The calculated total CO_2 eq. emissions of relocation trucks were 2901 tonnes when the annual wood-harvesting volume was 8.9 million m^3 (Table 8). The calculated NO_X and CO emissions totalled 18.6 and 3.1 tonnes, respectively.

The cubic-based fuel consumption averaged 0.13 L/m^3 harvested, and the average calculated fuel

Table 7 Calculated average cubic-based *GHG* emissions in wood harvesting (including cutting and forwarding) in the forests by cutting method with the removals harvested (8,916,024 m^3)

Emission category	First thinning	Later thinning	Final felling	Average
	Emissions, g/m^3			
CO_2 eq.	7340	5274	3140	4259
CO	17.8	13.0	8.0	10.6
HC	2.19	1.60	0.97	1.30
CH_4	0.176	0.239	0.412	0.239
N_2O	0.049	0.067	0.115	0.067
NO_X	12.7	9.4	5.8	7.6
SO_2	0.010	0.013	0.022	0.013
PM	0.339	0.255	0.164	0.211

Table 8 Calculated total *GHG* emissions caused by driving empty and loaded relocation trucks when the total removals harvested were 8,916,024 m^3

Emission category	Empty	Loaded	Total relocations
	Emissions, kg		
CO_2 eq.	1,638,089	1,263,150	2,901,239
CO	1955	1095	3050
HC	391	210	601
CH_4	16	11	27
N_2O	57	31	88
NO_X	11,338	7301	18,639
SO_2	6	4	10
PM	195	119	314

Table 9 Calculated average cubic-based *GHG* emissions caused by driving empty and loaded relocation trucks when the total removals harvested were 8,916,024 m^3

Emission category	Empty	Loaded	Total relocations
	Emissions, g/m^3		
CO_2 eq.	184	142	325
CO	0.219	0.123	0.342
HC	0.044	0.024	0.067
CH_4	0.022	0.001	0.003
N_2O	0.006	0.003	0.010
NO_X	1.27	0.82	2.09
SO_2	0.001	0.000	0.001
PM	0.022	0.013	0.035

consumption of relocation trucks was 43.1 L/100 km. Correspondingly, the cubic-based CO_2 eq. emissions in the forest machine relocations of the study averaged 325 g CO_2 eq./m^3 (Table 9). The calculated cubic-based NO_X and CO emissions averaged 2.09 g NO_X/m^3 and 0.34 g CO/m^3.

3.5 Energy Efficiency of Wood-Harvesting Operations

The energy-efficiency calculations illustrated that the energy-efficiency of the wood-harvesting operations including relocation by trucks is at a very good level (Table 10). The energy-efficiency ratios were more than 50 in all options calculated. As in thinning the productivity of cutting and forwarding is lower and fuel consumption is higher than that in final fellings, the energy efficiency was lower in thinnings (Table 10). For instance, in thinnings the energy efficiency of the total harvesting ranged from 63 to 87, and in final fellings it was 147 (Table 10). The forest machine relocations lowered the energy-efficiency ratio of the total wood-harvesting operations by 4.8–10.5% by cutting method (Table 10).

Table 10 Energy efficiencies of wood-harvesting operations by cutting method. The energy-efficiency figures of the total wood-harvesting operations also include the relocation of forest machinery on the roads

Wood-harvesting operation	First thinning	Later thinning	Final felling	Total harvesting
	Energy efficiency, kWh/kWh			
Cutting (harvester)	96.8	146.0	286.1	189.6
Forwarding (forwarder)	178.9	217.8	301.6	252.2
Total harvesting	62.8	87.4	146.8	108.2
Total wood-harvesting operation (including machine relocations)	59.8	81.7	131.3	99.6

4. Discussion

The Energy Efficiency Directive and energy efficiency agreements were launched to implement the targets of the EU's climate and energy framework, which guides European governments and companies to improve their energy efficiency and even reach carbon-neutrality targets with increased use of RESs. In this respect, this research on the energy efficiency of wood-harvesting operations is not only important from the environmental point of view, but higher energy efficiency can also improve the profitability of wood-harvesting contractors and the whole forestry sector (cf. Brunberg 2013, Haavikko et al. 2019, Palander et al. 2020). Several studies have confirmed that fuel costs are one of the most essential cost components for logging contractors. For instance, Nordfjell et al. (2003) and Greene et al. (2014) and the latest forestry sector statistics in Finland (Metsäalan kone- ja… 2018) underlined that the share of fuel costs is around 12–20% of the total wood-harvesting costs of logging contractors. Consequently, fuel cost deviations play a decisive role in the business of logging contractors, and in the future, the trend seems to be strengthening (Brunberg 2013, Haavikko et al. 2019).

This study developed and tested the comprehensive energy-efficiency calculation procedure for industrial use of the forestry sector. Generally, as the results of the study are computational, the used functions have a great impact on the results calculated. In fact, the productivity modelling for the harvesters and forwarders was conducted by applying the functions by Eriksson and Lindroos (2014), which are based on the largest Nordic CTL wood-harvesting data ever. Furthermore, the functions by Brunberg (2013), which are based on a wide and extensive follow-up study in Sweden, were used to determine the fuel consumption of forest machines according to their engine power. Moreover, VTT's Lipasto database (2017) of average emissions was applied for *GHG* emissions calculations. These Lipasto emission factors are commonly used in Finland and were updated in 2017. In comparison with the emission factors used in several other studies (e.g. Ackerman et al. 2017, Prinz at al. 2018, Hudiburg et al. 2019, Spinelli and de Arruda Moura 2019, Domke et al. 2020), such as EPA (2016), the factors are almost the same and hence the results and conclusions of the study are comparable to them. In addition, the emission factors are applicable to calculating *GHG* emissions and energy efficiencies in future emissions investigations.

The results illustrated that small and medium-sized harvesters (engine power <160 kW) cut almost half of final-felling removals, while larger machines (engine power >160 kW) cut more than a third of first thinnings. This situation is non-optimal with respect to use of the machine fleet. In cutting, the machine size has a significant impact on machine productivity, as Klvac and Skoupy (2009) suggested, because the most powerful (kW) harvesters are designed for felling trees with the largest stem diameters, which in practice means final fellings. Correspondingly, small and medium-sized harvesters are most suitable for cutting small-diameter trees (i.e. for thinnings) (Jylhä et al. 2019). It is concluded that it is more productive to cut the final fellings with bigger harvesters (e.g. John Deere 1270E, Ponsse Scorpion, and Ponsse Scorpion King), but in the case of thinnings, total relative productivity is better with medium-sized harvesters (e.g. Komatsu 901.4 and Ponsse Beaver). The distribution of forwarders by engine power (kW) was relatively equal to that of harvesters. Some studies have pointed out that large forwarders should be mainly used for final fellings because of their higher productivity (Jiroušek et al. 2007). However, there was no difference in the distribution of machine use between thinnings and final fellings in this study. Forwarders equipped with an engine power of 100–160 kW forwarded most timber (first thinning 74%, later thinning 73%, and final felling 75%). Comparing the harvesting stand data to that of other Finnish studies, it can be noticed that, for example, the average stem size of removals was almost the same. In this study, the average stem size of removals was 305 dm^3, while Jylhä et al. (2019) found 327 dm^3 and Kuitto et al. (1994) found 309 dm^3 in the case of final fellings. Thus, the results are comparable.

In this study, the share of calculated total fuel consumption of wood-harvesting operations including fuel consumption by relocation trucks were as follows: 52% for harvesters, 40% for forwarders, and 8% for relocation trucks. Total calculated fuel consumption was the highest for later thinnings (47%), but only just over a third (37%) of the removals were harvested from later thinnings. Final fellings accounted for more than half (55%) of the total harvesting volume, but only accounted for just over a third (37%) of the total calculated fuel consumption. The relative share of first thinnings was very small (8%) in the wood-harvesting volumes, and their total fuel consumption remained the lowest (16%). However, when looking at the cubic-based fuel consumption, harvesting first thinnings consumed relatively a lot of fuel compared to later harvesting operations.

The average calculated fuel consumption of cutting by harvesters was 0.91 L/m^3 and 0.68 L/m^3 in forest haulage by forwarders. Harvesters average fuel consumption was higher in first thinnings (1.78 L/m^3) than in later thinnings (1.18 L/m^3) and final fellings (0.60 L/m^3). These results are consistent with other studies in Nordic countries on CTL harvesting operations. Rieppo and Örn (2003) found that cubic-based fuel consumption was higher in first thinnings (1.76 L/m^3) than in later thinnings (1.42 L/m^3) and final fellings (0.70 L/m^3). These fuel consumption figures are slightly lower than the figures reported in this study. According to Jylhä et al. (2019), fuel consumption was 1.18 L/m^3 for forest thinnings (including first thinnings and later thinnings) and 0.69 L/m^3 for final fellings. Brunberg (2013) reported the same levels in his research: The fuel consumption of harvesters was 1.41 L/m^3 (over the bark) in forest thinnings (including first thinnings and later thinnings) and 0.73 L/m^3 in final fellings.

Forwarders fuel consumption was higher in first thinnings (0.96 L/m^3) than in later thinnings (0.79 L/m^3) and final fellings (0.57 L/m^3). Rieppo and Örn (2003) studied forwarders fuel consumption with different cutting methods, and their results are parallel to those of this study. They found that fuel consumption was 0.98 L/m^3 for first thinnings, 0.80 L/m^3 for later thinnings, and 0.62 L/m^3 for final fellings. In the study by Brunberg (2013), the fuel consumption of forwarders was slightly higher for final fellings (0.63 L/m^3 [over the bark]), whereas they reported the same consumption for forest thinnings (0.86 L/m^3). The difference in the relative fuel consumption per m^3 between forwarders and harvesters is not remarkable with final fellings, but during first thinnings, harvesters consume 46% more fuel per m^3 than forwarders do. This same relative increase in fuel consumption per m^3 can also been seen in Rieppo and Örn's (2003) results for forest haulage by forwarders.

In addition to the above-discussed characteristics of wood harvesting, many other specific factors have been found to influence fuel consumption. Brunberg (2013) revealed that the fuel consumption of wood-harvesting machines increased, on average, by 9% between 2006 and 2012. Brunberg (2013) explained his findings by the fact that the engine power of forest machines increased, but the utilization rate of machines also increased. In this respect, Smidt and Gallagher (2013) and Prinz et al. (2018) underscored the effect of the machine operator, machine type, harvesting conditions, and machine and device settings. With harvesters in particular, the average size of a tree has a significant impact on the machine productivity and fuel consumption (Jiroušek et al. 2007, Smidt and Gallagher 2013, Prinz et al. 2018). In other words, harvesters fuel consumption increases with the growth in a tree's diameter, but the productivity increases relatively more per unit m^3 at the same time. Therefore, fuel consumption per m^3 decreases (Rieppo and Örn 2003). In forwarding, the haulage distance and forwarder payload volume affect most productivity and fuel consumption (Jiroušek et al. 2007, Manner et al. 2016, Berg et al. 2019). There are also other important factors that impact fuel consumption in wood harvesting: forest stand location, cutting technique, and forest stand area and removals (Smidt and Gallagher 2013). Furthermore, the skills and education of harvester operators have been found to significantly impact productivity and fuel consumption (Nordfjell et al. 2003, Kärhä et al. 2004, Ovaskainen et al. 2004, Klvac and Skoupy 2009, Ghaffariyan et al. 2018). However, based on the aims of this study and consequently the research data, it was not possible or necessary to investigate and determine the impacts of such specific factors on fuel consumption.

In a recent energy-efficiency study, wood-harvesting contractors evaluated that, from the energy-efficiency point of view, machine relocation distance (km) between harvesting stands is among the ten most significant factors (Haavikko et al. 2019). The average relocation distance of a machine between two forest harvesting stands was 26.3 km. This result is consistent with the results of other studies. Kuitto et al. (1994) found that the average relocation distance was 28 km. Recently, according to Haavikko et al. (2019), contractors determined that the average relocation distance was 26.2 km. In contrast, according to a study comparing Finnish and Swedish wood harvesting by Berg and Karjalainen (2003), the average distance between forest stands of wood harvesting in Sweden was considerably shorter, only 12 km (cf. Wildmark 2014).

The environmental analysis showed that there was a prominent difference in CO_2 eq. emissions between the cutting methods. CO_2 eq. emissions from the final fellings (3.8 kg/m^3) were only half of the later thinnings emissions (6.3 kg/m^3). In addition, the emissions from the first thinnings (8.1 kg/m^3) were more than double the emissions caused by final fellings. Klvac and Skoupy (2009) investigated harvesters and forwarders *GHG* emissions in Ireland. The average CO_2 figures measured for diesel (harvester 4.97 kg/m^3 and forwarder 4.04 kg/m^3) are near the results of this study. In addition, Berg and Karjalainen (2003) studied emissions in Finland and Sweden in the late 1980s and early 1990s. Since then, in two decades, the calculated CO_2 emissions have substantially decreased per cubic meter, by 90% (including cutting, forwarding, and machine relocation). The main reasons for the reduction in emissions are certainly the same as the reasons for the reduction in fuel consumption (i.e., technological development of harvesters and forwarders to make them more productive and advances in engine technology of machines, but also the development of working methods and habits), not least the holistic transformation of wood harvesting into a fully mechanized process. According to Ackerman et al. (2017), CO_2 emissions from harvesters are 1.71 kg/m^3 and from forwarders 1.02 kg/m^3, which is considerably lower than the results of previous studies. These results are examples of the effects of good harvesting conditions. Recently, Venäläinen et al. (2019) studied CO_2 eq. emissions from wood procurement. The same calculation database (VTT's Lipasto) was used in this study to calculate CO_2 eq. emissions. The results are therefore comparable in this respect. CO_2 eq. emissions between the cutting methods were relatively the same compared to these study findings, but there were small differences in the absolute values (0.8–1.0 kg CO_2 eq./m^3), which were caused by the trucks used to relocate forest machinery and harvester operators when they travelled between the harvesting sites.

The energy-efficiency model of wood harvesting was tested for improving the energy efficiency of operations and even reach the carbon-neutrality target with use of RESs in the forest industry. The indicator revealed that wood-harvesting operations (cutting, forwarding, and relocation) were carbon neutral (total harvesting including machine relocations: 100 and total harvesting excluding relocations: 108) (cf. Table 10). The results depicted that wood harvesting is fully carbon neutral. The calculations also compared the energy efficiency of the final-felling method of forests to the thinning methods, as it is important to investigate how much the different permissible methods of wood harvesting affect energy efficiency. The use of the final-felling method increased the average energy efficiency most effectively. The most efficient machines operated in the final fellings and produced an energy-efficiency value of 131 in wood harvesting in 2016. If the wood-harvesting machines are discussed separately, their energy efficiency increases with efficient cutting methods. For example, the energy efficiency of the load of the forwarder was 1.7-fold greater when the cutting method changed from first thinning to final felling. However, there were clear and quite large ranges in energy efficiencies between the wood-harvesting machines and supply chains of the different cutting methods. Consequently, the indicator revealed that the energy efficiency of the wood-harvesting chain is also dependent on the machines used. For instance, the differences in machine size provide a possibility to select operation alternatives. When considering the research conducted in the disciplines of fuel consumption and work productivity, it can be seen that there are also great differences in the harvesting conditions of forest stands. Together, these conditions affect vehicle optimization and scheduling alternatives of harvesting machine fleets. In this respect, the indicator gives harvesting contractors the possibility to plan and manage their vehicles in the wood-procurement area in the most energy-efficient way.

Based on the results of this study, practical solutions can be suggested to climate policy makers. With respect to the energy efficiency of wood harvesting, the goal to create a 100% carbon-neutral base can be achieved in the forest industry by utilizing renewable forest resources. Unfortunately, problems can occur if wood harvesting is limited for the sake of short-term benefits of a carbon sink policy. Many trees might die due to the lack of harvesting or due to forest fires pumping carbon into the climate, which are also warming the climate, accelerating climate change, and causing a shorter rotation of forest life. Therefore, intensive wood harvesting and silvicultural operations should be increased to secure the vital carbon sink of forests, for example, in Finnish conditions, for the 50-year rotation of balanced forestry towards a sustainable forest industry (Palander et al. 2020). As forests are the main absorber of carbon, sustainable forestry is undoubtedly necessary to achieving climate goals and adapting them to the current national economy.

5. Conclusions

This research provides a starting point for the development of energy-efficient wood procurement at Stora Enso WSF. The results give valuable information about the current use of harvesters and forwarders, as well as the allocation of forest machinery in practice. Furthermore, these results underline that it is important not only to focus on the fuel consumption and emissions of harvesters and forwarders, but also to understand the whole value chain, for example, including trucks that are used for machine relocations. More energy-efficient utilization of harvesters and forwarders by cutting method will be emphasized in the future. As the fuel consumption and productivity of forest machines are highly dependent on machine size, there is a need for information about how forest machines should be optimized to different stand types. To decrease fuel consumption and at the same time increase productivity and energy efficiency, it is necessary to investigate how harvesters and forwarders are currently used in wood-harvesting operations. Furthermore, the challenge for optimal use of harvesters is that often the same stand contains forest compartments or plots that require different treatments. In this case, even from the point of view of energy efficiency, it might not make sense to bring a separate harvester for each plot to be cut, which would be the most optimal for the dimensions of the trees in each plot. In addition, logging contractors operate in a limited operational area, making it financially possible for few contractors to maintain forest machines of many capacities. Thus, more contractors very commonly have the so-called general-purpose harvesters suitable for both thinning and final felling.

During past decades, Berg (1997) and Venäläinen et al. (2019), for example, have studied fuel consumption in wood harvesting, but all these studies are based on calculations. Therefore, on the contrary, it is essential to research fuel consumption of wood-harvesting machines based on real data. There is a need for more detailed research about the factors affecting the fuel consumption of harvesters and forwarders. To reduce fuel consumption and emissions and at the same time increase productivity, more research is needed on the factors that affect them and the significance of their impact. There are no large-scale long-term studies on fuel consumption and energy efficiency in the whole wood-harvesting system. Such a follow-up study would make it possible to deepen the issues raised in this study and to get a closer look at the variables that affect fuel consumption through different cutting methods. Furthermore, with further study, it would be possible to investigate the impact of harvesting conditions or forest machine operators on fuel consumption. In addition, a follow-up study on relocation trucks would give more detailed information on actual relocation distances, possible delays, and actual routes. Moreover, it would be useful to expand research to fuel consumption and *GHG* emissions of cars, which forest machine operators use for daily travel to harvesting stands. Furthermore, *GHG* emissions could be based on actual data measured. With development, the productivity of harvesters has increased, and emissions have decreased, but at the same time, the use of AdBlue has come to reduce *GHG* emissions. According to a study by Björheden (2019), AdBlue's share of harvesters fuel consumption was determined in Sweden, depending on the harvester model and type. In the future, we should also research AdBlue's total *GHG* emissions.

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