



Fossil-fuel consumption and CO₂eq emissions of cut-to-length industrial roundwood logging operations in Finland

Kalle Kärhä¹ · Hanna Haavikko¹ · Heikki Kääriäinen¹ · Teijo Palander¹ · Lars Eliasson² · Kimmo Roininen³

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Abstract

The aim of this study was to measure and model the fuel consumption of cut-to-length (CTL) logging machinery in cutting and forwarding under Nordic harvesting conditions, and to clarify which factors had the greatest effect on the fuel consumption. In addition, the total annual fuel consumption and CO₂eq emissions were calculated for CTL logging operations in Finland in 2020. The data were collected during a long-term follow-up study on the fuel consumption of harvesters and forwarders conducted between March 2018 and April 2019. The fuel consumption data were obtained from a total of 16 harvesters and 13 forwarders equipped with digital flow metres featuring an accuracy of $\pm 1\%$ of the fuel volume measured. The engine power of the forest machines explained most of the hour-based fuel consumption. Correspondingly, the harvesting conditions of the forest stand best explained the cubic-metre-based fuel consumption. The fuel consumption of CTL logging operations (cutting and forwarding) averaged 1.4 L m⁻³ in final felling, and 3.1 and 2.2 L m⁻³ in first and later thinning, respectively. There was a large variation in the cubic-metre-based fuel consumption between individual machines, both for harvesters and forwarders. The total calculated fuel consumption in Finnish CTL operations in 2020 was 126.6 million L, with the calculated CO₂eq emissions totalling 334,209 t (i.e. 5.7 kg m⁻³). Several measures to accelerate fuel and energy efficiency and reduce CO₂eq emissions in CTL logging operations are discussed in the paper.

Keywords Fuel efficiency · Energy efficiency · Harvesting · Cutting · Forest haulage · Follow-up study

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✉ Kalle Kärhä
kalle.karha@uef.fi

Hanna Haavikko
hanna.haavikko@gmail.com

Heikki Kääriäinen
heikki868@gmail.com

Teijo Palander
teijo.s.palander@uef.fi

Lars Eliasson
lars.eliasson@skogforsk.se

Kimmo Roininen
kimmo.roininen@storaenso.com

¹ School of Forest Sciences, University of Eastern Finland, P.O. Box 111, 80101 Joensuu, Finland

² Skogforsk, Uppsala Science Park, 75183 Uppsala, Sweden

³ Stora Enso, Forest Division, Forest Finland, Heikinkatu 1, 55100 Imatra, Finland

Introduction

In 2020, a total of 2269 million m³ (Mm³) solid-over-bark of industrial roundwood were harvested globally (Food and Agriculture Organization (FAO), 2021). In Europe, industrial roundwood cuttings totalled 722 Mm³, with the biggest removals of industrial roundwood in Europe being harvested in the Russian Federation (231 Mm³), Sweden (80.7 Mm³), Germany (70.6 Mm³) and Finland (58.7 Mm³) (Food and Agriculture Organization (FAO), 2021). Recently, AFRY Management Consulting (2021) estimated that the global market for forest industry products will have grown by €175 billion by 2035, from €540 billion in 2019 to a forecasted €715 billion in 2035. AFRY Management Consulting (2021) emphasised that market growth is being driven by the replacement of plastic packaging, digitalisation, more packaging for online retail purposes, population growth, urbanisation, the prosperity of a growing middle class, increased environmental awareness by consumers, a reduction in greenhouse gas (GHG) emissions, and targets for carbon neutrality.

Globally, in 2020, energy-related carbon dioxide (CO₂) emissions were at a level of 31.5 Gt, with the European Union (EU27) producing approximately 2.6 Gt of CO₂ emissions (Global Carbon Atlas 2022; International Energy Agency 2022). In Finland, the total GHG emissions corresponded to 48.1 Mt of CO₂ equivalent (CO₂eq) in 2020 (Statistics Finland 2021). The EU's climate and energy framework has set three demanding targets for 2030—firstly, reduce GHG emissions by at least 40%; secondly, increase the share of renewable energy sources by at least 27%; and thirdly, improve energy efficiency by at least 27% from the level of 1990 (European Union 2014). Furthermore, there is an even more exacting aim for 2050—to decrease GHG emissions to 80% below the level of 1990 (European Union 2011). In Finland, there is an ambitious target to become a carbon-neutral country by 2035 (Finnish Government 2020).

The TYKO machinery model, developed and maintained by the VTT Technical Research Centre of Finland, is used to calculate the official annual GHG emissions from machinery (e.g. agricultural tractors, wheel loaders, excavators, harvesters, forklifts, generators and forwarders) and off-road vehicles powered by combustion engines throughout Finland. According to the TYKO model, the GHG emissions from machinery in Finland in 2020 amounted to 2.4 Mt CO₂eq (VTT 2021).

The annual GHG emissions from forest machines (i.e. harvesters and forwarders) were approximately 13% of the total emissions from the work-machine fleet in 2020 (VTT 2021). According to the TYKO model, 121.3 ML of fossil light fuel oil (LFO) is used in forest machines annually. In addition to the fuel consumption by harvesters and forwarders, there is the relocating of cut-to-length (CTL) logging machinery from one harvesting site to another (Berg and Karjalainen 2003; Haavikko et al. 2022), the car travel by harvester and forwarder operators from their homes to the harvesting sites and back, and the car travel by logging managers and service and maintenance staff to the harvesting sites, all of which consume diesel fuel. However, the TYKO model does not take this additional fuel consumption into account (Laurikko and Mäkelä 2019).

Emissions from machinery and how to reduce these have become areas of interest in Finland's current climate and energy policy (Huttunen 2017; Markkanen and Lauhkonen 2021; Paloneva and Takamäki 2021; Ministry of the Environment 2022). Emissions reduction measures for machinery have been proposed, including a change in the obligation to distribute biofuel oil, the use of biogas in machinery, a review of fuel tax increases and investment subsidies, improvements to the energy efficiency of machinery, and the proliferation of electric and hydrogen-powered machinery (Vapaavuori et al. 2014; Huttunen 2017; Paloneva and Takamäki 2021; Ministry of the Environment 2022).

However, electric versions of large machinery (i.e. harvesters and forwarders) that would be out of reach of any charging infrastructure is challenging in terms of both the energy capacity of the batteries and the power required by the machinery, and so these are not expected to gain a significant market share for the next 10 or more years (Lajunen et al. 2018). Consequently, the easiest action towards decreasing fuel consumption and GHG emissions in logging operations is to improve the energy efficiency of the CTL logging-machine fleet.

Calculations and life-cycle assessments and analysis of GHG emissions call for a better understanding of, and up-to-date information on, fuel consumption from industrial roundwood CTL logging operations, including machine relocations and the car travel by operators, managers and service and maintenance staff to and from the harvesting sites (e.g. Handler et al. 2014; Han et al. 2015; de la Fuente et al. 2017; Abbas and Handler 2018; Palander et al. 2018; Haavikko et al. 2019). However, there are few recent long-term follow-up studies on the fuel consumption of CTL logging-machine chains that include both harvesters and forwarders. The latest comprehensive follow-up study on the fuel consumption of CTL logging machines in Finland was carried out in 2003—almost 20 years ago (Rieppo and Örn 2003). Rieppo and Örn (2003) reported an average hour-based fuel consumption of 12.2 L h⁻¹ for a harvester and 10.5 L h⁻¹ for a forwarder, with an average cubic-metre-based LFO consumption of 0.87 L m⁻³ for cutting and 0.65 L m⁻³ for forwarding.

Other comprehensive follow-up studies on the fuel consumption of CTL logging machinery in boreal forests are also quite old, such as Brunberg (2013), who studied the fuel consumption of 230 harvesters and 230 forwarders in Sweden over a two-week period. The study revealed that the total fuel consumption of forest machines had increased, on average, by 9% in 2012 compared to the level of 2006 (Brunberg 2007)—that is, from 1.50 to 1.63 L m⁻³. In addition, Holzleitner et al. (2011) conducted a long-term follow-up fuel-consumption study on CTL logging machinery involving 12 harvesters and 18 forwarders in 2004–2008 in Austria, whereas Ackerman et al. (2017) assessed the fuel consumption of two harvesters and two forwarders in a follow-up study in 2014–2015 in South Africa. Magagnotti et al. (2017) and Spinelli and De Arruda Moura (2019) reported on a follow-up study of purpose-built and excavator-based harvesters using big data.

Recently, follow-up studies on fuel consumption have been made using data derived from the machines' own data records. This new method simplifies the data collection compared to traditional studies in which fuel refills were measured. However, data from both methods are needed to ensure that the fuel consumption is of comparable magnitude, regardless of method used. In a long-term

follow-up study using machine data, Jylhä et al. (2019) found that the fuel consumption of harvesters in industrial roundwood cutting operations averaged 0.90 L m^{-3} . This is close to the average cubic-metre-based fuel consumption of 0.87 L m^{-3} for cutting reported by Rieppo and Örn (2003). In Sweden, Eliasson (2022) reported a total fuel consumption for cutting and forwarding of 1.48 L m^{-3} based on machine data from 31 harvesters and 42 forwarders, which is also close to the amounts reported by Rieppo and Örn (2003) and Brunberg (2007).

Earlier fuel consumption studies have underlined that the harvesting conditions (e.g. removal stem size, cutting method, number of timber assortments), machine properties (e.g. engine power, type of machine, machine adjustments, use of tracks and wheel-chains) and machine operators (i.e. level of education, skills) have significant effects on the fuel consumption of harvesters (e.g. Rieppo and Örn 2003; Holzleitner et al. 2011; Brunberg 2013; Kenney et al. 2014; Ghaffariyan et al. 2018; Magagnotti et al. 2017; Prinz et al. 2018; Jylhä et al. 2019; Spinelli and De Arruda Moura 2019). The same is valid for forwarders, where the harvesting conditions (e.g. forwarding distance, hectare-based removals [$\text{m}^3 \text{ ha}^{-1}$], number of timber assortments harvested, removal stem size), machine properties (e.g. engine power, use of tracks and wheel-chains, payload) and machine operators (i.e. level of education, skills) have a large influence on fuel consumption (e.g. Nordfjell et al. 2003; Rieppo and Örn 2003; Holzleitner et al. 2011; Brunberg 2013; Kenney et al. 2014; Ghaffariyan et al. 2018; Oyier and Visser 2016; Pandur et al. 2019).

It is evident that up-to-date information on the fuel consumption of CTL harvesters and forwarders is needed, and that studies using both traditional methods and machine data are necessary for validating the latter method. Furthermore, it is essential to understand the effects of different factors on fuel consumption in cutting and forwarding. With a firm understanding of the fuel consumption of forest machines, the fuel and energy efficiency of logging machines can be improved and emissions reduction targets can be met.

Consequently, the target of this study was to measure and model the fuel consumption of CTL harvester and forwarder operations under Nordic harvesting conditions in Finland, and to clarify which factors have the most significant effect on the fuel consumption. In this study, the fuel consumption was examined in terms of the: (1) hour-based fuel consumption (L h^{-1}); and (2) fuel consumption per cubic metre (L m^{-3}) harvested. In addition, we calculated the total annual fuel consumption and CO_2eq emissions caused by: (1) the harvesters and forwarders in the forests; (2) relocation of the CTL logging machinery; and (3) the car travel by harvester and forwarder operators, logging managers and service and maintenance staff to and from the harvesting sites.

Materials and methods

Long-term follow-up study

This long-term follow-up study of the fuel consumption of harvesters and forwarders ran from March 2018 to April 2019. Data was collected from the machines working for Stora Enso Wood Supply Finland (WSF) under different harvesting conditions in southern, eastern and central Finland (Fig. 1). The fuel consumption data were collected at a total of 510 harvesting sites during cutting and 306 harvesting sites during forwarding.

Fuel consumption data were obtained from a total of 16 harvesters and 13 forwarders manufactured by Ponsse plc, John Deere Forestry Oy, Komatsu Forest AB and Logset Oy (Table 1). Entire logging chains consisting of a harvester and a forwarder were expected to take part in the study. However, forwarding data from all the chains and harvesting sites were not received. In total, 32 different harvester operators and 37 different forwarder operators participated in the study. The number of operators varied from one to five per machine studied, with the most common number being one or two.

Digital Piusi K24 flow metres (Piusi 2022) with a flow rate of $7\text{--}120 \text{ L min}^{-1}$ and a maximum operating pressure of 20 bar were installed in the refuelling hoses of the fuel tanks of each forest machine in order to measure the amount of fuel used at each harvesting site. The manufacturer guarantees an accuracy of $\pm 1\%$ of the fuel volume measured for the Piusi K24 flow metre (Piusi 2022).

During the study, a total of 306,791 L of LFO was consumed during cutting and 136,979 L during forwarding (Table 2), and a total of 308,113 m^3 of wood was cut and 201,174 m^3 was hauled from the forests to the roadside landings. The production time (i.e. all the time at the harvesting sites, excluding long delays due to repairs in workshops and machine relocations) (Magagnotti et al. 2012; Jylhä et al. 2019) was 20,148 h for the harvesters and 12,202 h for the forwarders (Table 2).

At the start of this follow-up study, background information on the machine operators (age, work experience in mechanised logging [in years], training in energy-efficient operations [yes/no]) and data about the machines (model, harvester head model, year of manufacture, operating hours at the start of the study, engine brand, engine power [kW], number of wheels and whether the machine had been regularly serviced [yes/no]) were collected. Fuel consumption, working time and harvesting data from each harvesting site were collected by work shift. Each machine at the harvesting site started with a full tank. At each refuelling, the machine operator added the number of litres and fuel grade (summer/winter) to a monitoring form kept in the cabin of the machine.

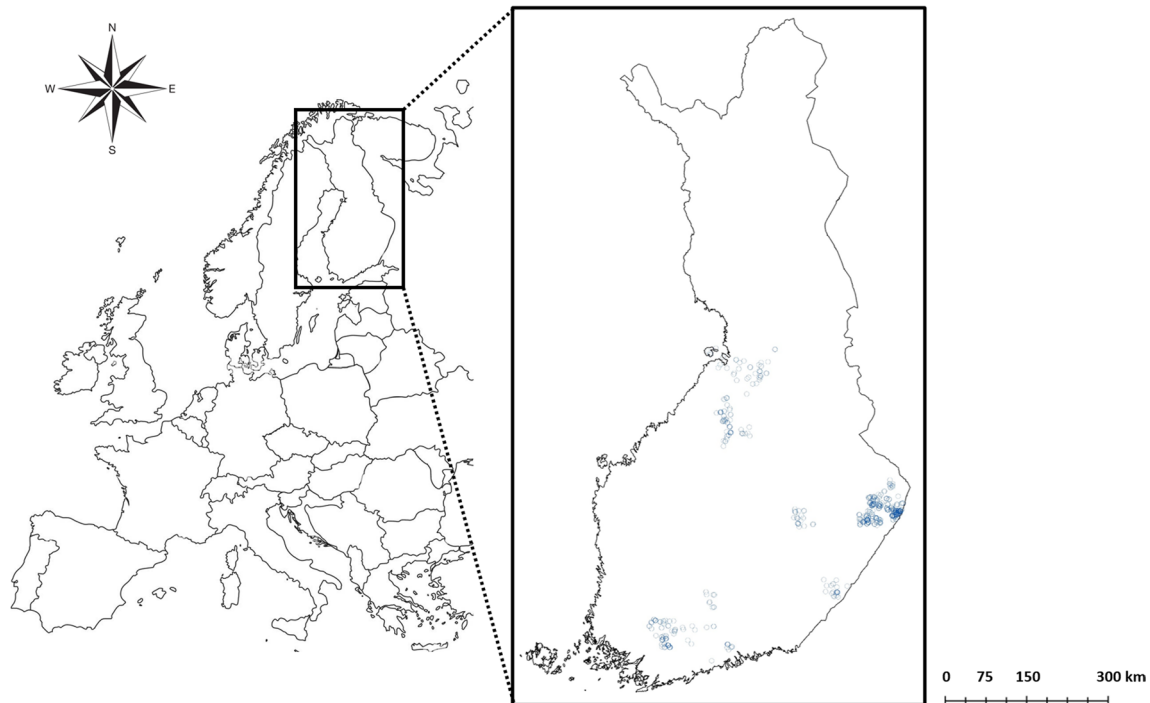


Fig. 1 Map showing the locations (blue dots) of the studied harvesting sites during cutting ($n=510$)

When a machine operator started a work shift, they noted the starting time of the shift (to within 1 min), as well as the air temperature ($^{\circ}\text{C}$) and the depth of any snow cover (cm) on the monitoring form. At the end of the work shift, they noted the ending time on the form, as well as the equipment used on the machine (which tracks or wheel-chains were used on the front and rear bogies), the type of soil (mineral/peatland) and any other important observations (e.g. soft, rocky or hilly terrain, hindering and dense undergrowth). If there were delays (i.e. machine repairs in workshops, machine relocations) during the work shift, the operators were asked to add these to the monitoring form as well. For each harvesting site, the site number and cutting method (first thinning, later thinning, final felling, other cutting method) were also documented.

The majority of the harvesting site properties were obtained from the enterprise resource planning system of Stora Enso WSF. The harvesting site properties used in the study included the identification number of the site, cutting method, area of the site (ha), total removals from the site by tree species (Scots pine [*Pinus sylvestris* L.], Norway spruce [*Picea abies* L.], birch [*Betula* spp.] and other broadleaves), in terms of number of stems removed and their volume (m^3), number of timber assortments harvested and forwarding distance (m). The average stem size of the removal was calculated by dividing the total cut volume by the number of stems removed.

The data collected during the work shift were summarised by harvesting site. The hour-based fuel consumption (L h^{-1}) was calculated by dividing the total refilled fuel by the total production hours at the harvesting site, with the cubic-metre-based fuel consumption (L m^{-3}) being defined by dividing the total refilled fuel by the total volume cut or forwarded at the harvesting site. In turn, a value for the mode of utilisation of tracks and wheel-chains was determined for each harvesting site.

Data analysis

The variables relating to the forest machinery, machine operators, harvesting conditions and fuel consumption were analysed using percentage shares, mean values (average and mode) and standard deviations. The data were initially tested for the assumption of a normal distribution using a Kolmogorov–Smirnov test. This indicated that the data did not correspond to a normal distribution. Therefore, a non-parametrical Mann–Whitney U test and a Kruskal–Wallis one-way analysis of variance test (χ^2) were used for statistical analysis.

The fuel consumption (in L h^{-1} and L m^{-3}) of the harvesters and forwarders was modelled by applying regression analysis using the different attributes of “forest machine”, “machine operator” and “harvesting site” as the independent variables. Different transformations were tested in order

Table 1 Description of the harvesters and forwarders used in this study

| Study | Manufacturer | Model | Harvester head | Year of manufacture | Machine hours ¹ (1000 h) | Engine power (kW) | Number of wheels |
|------------|--------------|---------------|----------------|---------------------|-------------------------------------|-------------------|------------------|
| Cutting | | | | | | | |
| | John Deere | 1170E | H414 | 2016 | 5.0 | 145 | 6 |
| | John Deere | 1270E | H414 | 2012 | 17.0 | 190 | 8 |
| | Komatsu | 931XC | C123 | 2017 | 4.0 | 185 | 6 |
| | Komatsu | 951 | C144 | 2016 | 4.5 | 210 | 8 |
| | Logset | 6HP GT | TH55 | 2013 | 15.0 | 170 | 6 |
| | Ponsse | Beaver | H6 | 2013 | 11.0 | 129 | 6 |
| | Ponsse | Beaver | H6 | 2018 | 2.8 | 150 | 6 |
| | Ponsse | Ergo | H7 | 2013 | 9.5 | 210 | 6 |
| | Ponsse | Ergo | H6 | 2014 | 13.0 | 210 | 8 |
| | Ponsse | Ergo | H7 | 2015 | 8.5 | 210 | 6 |
| | Ponsse | Ergo | H6 | 2016 | 7.5 | 210 | 8 |
| | Ponsse | Scorpion | H6 | 2016 | 7.0 | 210 | 8 |
| | Ponsse | Scorpion | H6 | 2016 | 5.0 | 210 | 8 |
| | Ponsse | Scorpion King | H6 | 2017 | 3.5 | 210 | 8 |
| | Ponsse | Scorpion King | H6 | 2018 | 1.0 | 210 | 8 |
| | Ponsse | Scorpion King | H6 | 2018 | 0.2 | 210 | 8 |
| Forwarding | | | | | | | |
| | John Deere | 1210G | | 2018 | 0.5 | 156 | 8 |
| | Komatsu | 855 | | 2012 | 13.0 | 150 | 8 |
| | Komatsu | 855 | | 2017 | 3.0 | 170 | 8 |
| | Komatsu | 890 | | 2011 | 20.0 | 150 | 8 |
| | Logset | 5F | | 2014 | 12.0 | 127 | 8 |
| | Logset | 6F | | 2012 | 15.5 | 170 | 8 |
| | Ponsse | Elk | | 2011 | 16.0 | 129 | 8 |
| | Ponsse | Elk | | 2013 | 9.0 | 129 | 8 |
| | Ponsse | Elk | | 2014 | 12.5 | 129 | 6 |
| | Ponsse | Elk | | 2016 | 5.0 | 150 | 8 |
| | Ponsse | Elk | | 2016 | 5.5 | 150 | 8 |
| | Ponsse | Elk | | 2017 | 3.6 | 150 | 8 |
| | Ponsse | Buffalo | | 2007 | 27.0 | 205 | 8 |

¹At the beginning of the study

to achieve symmetrical residuals for the regression models and to ensure the statistical significance of the model coefficients. The suitability of the models with respect to the data was numerically assessed based on the adjusted degree of explanation (adjusted R^2) and statistical significance ($p < 0.05$).

When analysing the machine-specific cubic-metre-based fuel consumption ($L m^{-3}$), firstly, for each harvester and forwarder, cubic-metre-based fuel consumption regression models were produced, where the removal stem size was the independent variable for the harvesters and the forwarding distance was the independent variable for the forwarders. There were no models for one of the harvesters and one of the forwarders because they had been

used on fewer than five harvesting sites. Secondly, two harvester groups were constructed for stands with a harvested stem size of 0.1–0.6 m^3 : (1) the four harvesters that had the lowest cubic-metre-based fuel consumption; and (2) the four harvesters that had the highest cubic-metre-based fuel consumption. The lowest cubic-metre-based fuel consumption harvesters were considered to be “*fuel-saving harvesters*” and the highest were regarded as “*fuel-wasting harvesters*”. The same procedure was conducted with the forwarders for stands with forwarding distances of between 100 and 500 m, with the three forwarders with the lowest cubic-metre-based fuel consumption being regarded as “*fuel-saving forwarders*” and the three that had the highest as “*fuel-wasting forwarders*”.

Table 2 Data on the cutting and forwarding by cutting method. “Other fellings” consisted of removing hold-overs, strips, seed trees and shelter trees, and some other special cuttings. Harvesting sites where data could not be allocated to one particular cutting method were placed in the “Several cutting methods” category

| Study Cutting method | Number of harvesting sites | Production time (h) | Refuelled fuel (L) | Industrial roundwood removal (m ³) |
|-------------------------|----------------------------|---------------------|--------------------|--|
| Cutting | | | | |
| First thinning | 29 | 1470 | 20,148 | 10,000 |
| Later thinning | 170 | 6646 | 21,187 | 68,397 |
| Final felling | 216 | 8331 | 95,164 | 173,527 |
| Other fellings | 54 | 965 | 132,930 | 13,771 |
| Several cutting methods | 41 | 2736 | 14,975 | 42,417 |
| Total | 510 | 20,148 | 306,791 | 308,113 |
| Forwarding | | | | |
| First thinning | 7 | 309 | 3235 | 3459 |
| Later thinning | 86 | 3583 | 39,188 | 46,523 |
| Final felling | 120 | 4636 | 52,578 | 89,554 |
| Other fellings | 30 | 614 | 7000 | 9788 |
| Several cutting methods | 63 | 3060 | 34,975 | 51,850 |
| Total | 306 | 12,202 | 136,976 | 201,174 |

Description of the data

The age of the harvester operators varied from 19 to 63 years. Their work experience in mechanised CTL logging operations was 1 to 34 years, with an average of 14.4 years. Of the harvester operators, 61% had taken part in training in energy-efficient operations. For the forwarder operators, their ages ranged between 17 and 64 years and their work experience varied between 1 and 40 years, with an average of 12.3 years. Around half (56%) of the forwarder operators had been given energy-efficient operations training.

The average engine power of the harvesters was 192 kW and of the forwarders 151 kW (Table 1). According to the forest-machine owners (contractors), all the machines had been serviced regularly. Most commonly, the sites were harvested using machines equipped with tracks, with 82% of the harvesting sites being cut by harvesters equipped with tracks on the front bogie and 78% with tracks on the rear bogie/axle. The corresponding values for the forwarders were 79 and 95%, respectively.

Summer-grade LFO was utilised at 58% of the harvesting sites in the harvesters and at 69% of the sites in the forwarders. The air temperature varied from −19 °C to +28 °C from the cutting data, with 28% of the harvesting sites being cut when the average air temperature was below 0 °C. From the forwarding data, the air temperature by site varied from −16 °C to +32 °C. Of the forwarding sites, 23% were hauled when the average air temperature was below 0 °C. Of the total number of sites, the share with snow cover (depth ≥ 1 cm) during cutting operations totalled 33%, and during forwarding, 25%. The proportion of operations on mineral soils was 88% during cutting and 83% during forwarding (Table 3). The share of softwood (Scots pine and

Norway spruce) of the total removals harvested was 82% from the cutting data and 84% from the forwarding data.

Calculating the total annual fuel consumption and CO₂eq emissions of CTL loggings

When calculating the total annual fuel consumption and CO₂eq emissions involved in industrial roundwood removals in Finland—including the actual logging (cutting and forest haulage), the relocation of forest machines from one harvesting site to another, and the car travel of the machine operators, logging managers, and service and maintenance staff from their homes/offices to the harvesting sites and back—certain assumptions were applied: The annual removals of industrial roundwood in Finland were 58.668 Mm³ in 2020 (Sauvula-Seppälä and Torvelainen 2021). Of these annual removals, the distribution of different cutting methods was as follows: first thinnings 6.952 Mm³, later thinnings 19.899 Mm³, final fellings 30.076 Mm³ and other fellings 1.741 Mm³ (cf. Peltola and Vaahtera 2021; Sauvula-Seppälä and Torvelainen 2021). The fuel consumed in the CTL loggings was the average cubic-metre-based fuel consumption from cutting and forwarding determined in this study (see Fig. 3). The CO₂eq emissions of the harvesters and forwarders were calculated using the VTT’s Lipasto (2021) database of forest machinery in Finland—harvesters 2674 g CO₂eq L⁻¹ and forwarders 2673 g CO₂eq L⁻¹.

The fuel consumption and CO₂eq emissions from the forest-machine relocations were determined by applying the values provided by Haavikko et al. (2022), which resulted in the harvested cubic-metre-based fuel consumption being 0.130 L m⁻³ and the harvested CO₂eq emissions from the forest-machine-fleet relocations between harvesting sites being 325 g CO₂eq m⁻³.

Table 3 Description of the data from the cutting and forwarding by cutting method

| Study Cutting method | Removal stem size (m ³) | Hectare-based removal (m ³ ha ⁻¹) | Forwarding distance (m) | Number of timber assortments | Share of mineral-soil harvesting sites (%) |
|-------------------------|-------------------------------------|--|-------------------------|------------------------------|--|
| Cutting | | | | | |
| First thinning | 0.077 | 60 | 244 | 5.6 | 97 |
| Later thinning | 0.144 | 66 | 271 | 7.5 | 87 |
| Final felling | 0.321 | 214 | 275 | 8.1 | 88 |
| Other fellings | 0.221 | 81 | 313 | 6.9 | 83 |
| Several cutting methods | 0.187 | 106 | 261 | 8.0 | 90 |
| Average | 0.215 | 119 | 275 | 7.6 | 88 |
| Forwarding | | | | | |
| First thinning | 0.113 | 46 | 280 | 6.0 | 100 |
| Later thinning | 0.161 | 63 | 311 | 7.9 | 78 |
| Final felling | 0.340 | 214 | 245 | 8.4 | 86 |
| Other fellings | 0.222 | 117 | 365 | 7.0 | 73 |
| Several cutting methods | 0.205 | 115 | 285 | 8.4 | 86 |
| Average | 0.229 | 114 | 284 | 8.1 | 83 |

When estimating the fuel consumption and CO₂eq emissions from the car travel undertaken by the forest machine operators, logging managers and service and maintenance staff (in pickups or small van) to and from the harvesting sites, it was assumed that one logging chain would harvest 35,000 m³ per year and the total kilometres driven per logging chain were 64,500 km (Statistics Finland 2022). This, the car travel totalled 109 Mkm (1.843 km m⁻³). In addition, it was assumed that the fuel consumption of the cars driven by the operators, managers and service and maintenance staff would average 8.59 L 100 km⁻¹ with an average driving distance of 45 km (cf. VTT 2021). Furthermore, the CO₂eq emissions of the cars used were calculated by applying an emissions rate of 202 g CO₂eq km⁻¹ (VTT 2021). Thus, the calculated fuel consumption of the car travel by the operators, managers and service and maintenance staff was

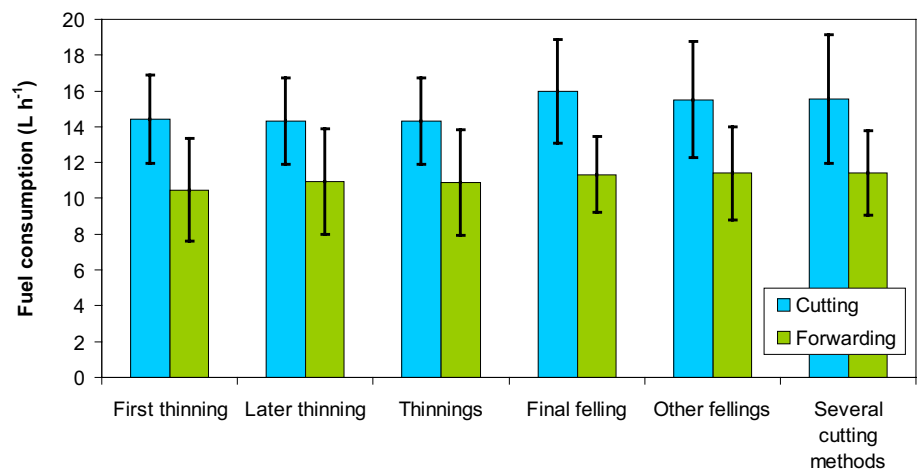
0.158 L m⁻³, with the CO₂ emissions from these journeys being 372 g CO₂eq m⁻³ harvested.

Results

Average fuel consumption and CO₂eq emissions

The fuel consumption involved in the first thinning averaged 14.4 L h⁻¹ during cutting and 10.5 L h⁻¹ during forwarding, whereas, in the final felling, the fuel consumption averaged 16.0 L h⁻¹ during cutting and 11.3 L h⁻¹ during forest haulage (Fig. 2). For the cutting, there was a statistically significant difference between the cutting methods in the hour-based fuel consumption ($\chi^2 = 33.0$, $p < 0.001$). For the forwarding, there was no statistically significant difference

Fig. 2 Hour-based fuel consumption by cutting method from the cutting and forwarding data from the study. Bars illustrate average values and black lines the standard deviation



between the cutting methods used in the fuel consumption ($\chi^2 = 5.3$, $p = 0.383$).

The cubic-metre-based fuel consumption from logging, including both during the cutting and forest haulage, averaged 3.06 L m^{-3} harvested (cutting 2.12 L m^{-3} and forwarding 0.94 L m^{-3}) during the first thinnings and, during the later thinnings, 2.23 L m^{-3} (1.39 and 0.84 L m^{-3} , respectively) (Fig. 3). For all the thinnings, the fuel consumption for the logging operations averaged 2.33 L m^{-3} (1.48 and 0.85 L m^{-3} , respectively). The fuel consumption from CTL logging operations during the final fellings was 1.36 L m^{-3} , on average (0.77 and 0.59 L m^{-3} , respectively), and during other fellings, it was 1.81 L m^{-3} (1.09 and 0.72 L m^{-3} , respectively) (Fig. 3). There were statistically significant differences in fuel consumption between the cutting methods used during both cutting ($\chi^2 = 175.8$, $p < 0.001$) and forwarding ($\chi^2 = 43.3$, $p < 0.001$).

The calculated CO_2eq emissions are presented in Table 4. The calculations indicate that the emissions from logging operations were the lowest during the final felling at $3.64 \text{ kg CO}_2\text{eq m}^{-3}$ harvested. In comparing the CO_2eq emissions from the final fellings to those from the thinnings, it was found that the calculated CO_2eq emissions from logging during the first thinnings were 2.2 times higher, and 1.6 times higher during the later thinnings (Table 4).

Modelling hour-based fuel consumption

Both during the cutting and forest haulage, the engine power of the forest machine most significantly explained the hour-based fuel consumption (Tables 5, 6, Figs. 4, 5). With an increase in engine power of 10 kW , the fuel consumption increased by 0.25 L h^{-1} for the harvesters and 0.58 L h^{-1} for the forwarders (Tables 5, 6). The operating hours of the forest machines also had a significant association with fuel consumption, with the harvesters and forwarders with more operating hours at the beginning of the study having lower

Table 4 Calculated average CO_2eq emissions based on cubic-metre-based fuel consumption from the study (Fig. 3) by cutting method during cutting, forwarding and CTL logging operations from forests to roadside landings

| Cutting method | Cutting | Forwarding | Total logging |
|-------------------------|---------|------------|---------------|
| | | | |
| First thinning | 5.67 | 2.51 | 8.18 |
| Later thinning | 3.72 | 2.25 | 5.96 |
| Thinnings | 3.96 | 2.27 | 6.23 |
| Final felling | 2.06 | 1.58 | 3.64 |
| Other fellings | 2.91 | 1.92 | 4.84 |
| Several cutting methods | 2.67 | 1.79 | 4.46 |

hour-based fuel consumption (Tables 5, 6). When modelling the hour-based fuel consumption of the harvesters, the cutting method (thinning dummy) and air temperature at the harvesting site also explained the fuel consumption during cutting—with thinning, the fuel consumption of the harvesters was 1.19 L h^{-1} lower (Table 5). By contrast, when the air temperature increased, the fuel consumption of the harvesters increased.

In addition to the engine power and operating machine hours of the forwarders, the equipment used (tracks on the front bogie) and the type of soil (peatland vs. mineral) explained their fuel consumption (Table 6). The use of tracks on the front bogie increased their fuel consumption by 1.82 L h^{-1} . On the other hand, when forwarding wood over peatlands, the fuel consumption was 1.38 L h^{-1} higher than that used over mineral soils (Table 6).

Modelling the cubic-metre-based fuel consumption

During cutting, the cubic-metre-based fuel consumption was explained by the removal stem size in the stand, the hectare-based removal and the cutting method (thinning dummy) (Table 7). The removal stem size significantly explained

Fig. 3 Cubic-metre-based fuel consumption by cutting method from the cutting and forwarding data from the study. Bars illustrate average values and black lines the standard deviation

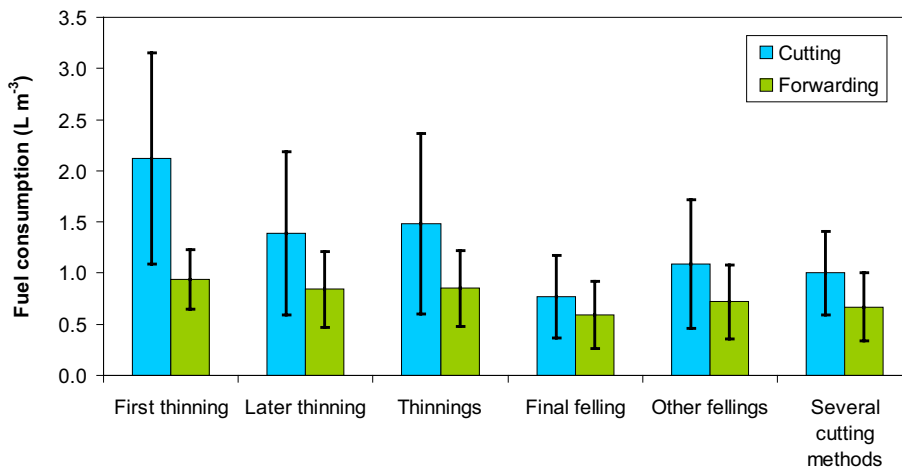


Table 5 Regression model for predicting the hour-based fuel consumption during cutting

$$y = a + bx_1 + cx_2 + dx_3 + ex_4$$

Where
 y = fuel consumption (L h⁻¹)
 x₁ = engine power (kW)
 x₂ = machine hours (1000 h)
 x₃ = thinning dummy (1 if thinning site, 0 if some other cutting method)
 x₄ = air temperature (°C)
 a = constant
 b, c, d, e = coefficients of the variables

| Coefficient | Estimate of coefficient | Standard error of estimate | t-value |
|-------------|-------------------------|----------------------------|-----------|
| a | 11.759 | 0.814 | 14.452*** |
| b | 0.025 | 0.004 | 6.232*** |
| c | -0.138 | 0.031 | -4.506*** |
| d | -1.189 | 0.241 | -4.927*** |
| e | 0.026 | 0.012 | 2.137* |

Adjusted R² = 0.171; F = 27.159***; standard error of the estimate of the model = 2.640

* p < 0.05

*** p < 0.001

Table 6 Regression model for predicting the hour-based fuel consumption during forwarding

$$y = a + bx_1 + cx_2 + dx_3 + ex_4$$

Where
 y = fuel consumption (L h⁻¹)
 x₁ = engine power (kW)
 x₂ = machine hours (1000 h)
 x₃ = tracks on the front bogie of the forwarder (1 if tracks, 0 if no tracks)
 x₄ = peatland dummy (1 if peatland, 0 if no peatland)
 a = constant
 b, c, d, e = coefficients of the variables

| Coefficient | Estimate of coefficient | Standard error of estimate | t-value |
|-------------|-------------------------|----------------------------|-----------|
| a | 1.751 | 0.739 | 2.369* |
| b | 0.058 | 0.005 | 11.367*** |
| c | -0.047 | 0.018 | -2.597** |
| d | 1.816 | 0.291 | 6.244*** |
| e | 1.378 | 0.406 | 3.392*** |

Adjusted R² = 0.395; F-value = 50.776***; standard error of the estimate of the model = 1.934

* p < 0.05

** p < 0.01

*** p < 0.001

the cubic-metre-based fuel consumption of the harvester (Table 7, Fig. 6). When the harvesting site was a thinning stand, the fuel consumption was 0.15 L m⁻³ higher than that during other cuttings (Table 7).

During forest haulage, the cubic-metre-based fuel consumption was best explained by the hectare-based removal, forwarding distance and type of soil (mineral-soil dummy)

(Table 8). A decrease in removals and lengthening of the forwarding distances increased the cubic-metre-based fuel consumption. With an increase in forwarding distance of 100 m, the fuel consumption increased by 0.05 L m⁻³ for the forwarders (Table 8, Fig. 7). On the other hand, operating on mineral soils reduced the fuel consumption by 0.11 L m⁻³ compared to forest haulage over peatlands (Table 8).

The regression model created using hour-based fuel consumption for the forwarder can be considered quite good because the explanation rate (adjusted R^2) of the model was 39.5% (Table 6). By contrast, the hour-based fuel consumption model for the harvester explained only 17.1% of the total variation, which is relatively low. Correspondingly, when the cubic-metre-based fuel consumption of the forest machinery was explained, the fuel consumption of the harvesters was better explained (42.4%) than that of the forwarders (23.1%) (Tables 7, 8).

Detecting fuel-saving and fuel-wasting machine units

There was a significant variation between the harvesters and forwarders in terms of cubic-metre-based fuel consumption. The difference in fuel consumption between low-consumption (i.e. fuel-saving) and high-consumption (i.e. fuel-wasting) harvesters averaged about 0.23–0.72 L m⁻³ when the removal stem size was 0.1–0.6 m³ in the stand (Fig. 8). The relative cubic-metre-based fuel consumption averaged 38–58% higher for the fuel-wasting harvesters than their fuel-saving counterparts, and 12–17% higher than average compared with all the harvesters for a removal stem size of 0.1–0.6 m³ (Fig. 8).

During forest haulage, the absolute differences in fuel consumption between the fuel-saving and fuel-wasting machine units were smaller at around 0.3 L m⁻³ for forwarding distances of 100–500 m (Fig. 9). However, the relative differences in fuel consumption between the fuel-saving and fuel-wasting forwarders were greater than those of the harvesters. The cubic-metre-based fuel consumption of the fuel-wasting machines was 60–68% higher than that of the fuel-saving machines, and 21–23% higher than

the average for the forwarders for forwarding distances of 100–500 m.

Total annual fuel consumption and CO₂eq emissions of total industrial roundwood loggings in Finland

The calculations drawn up illustrate that, when 58.7 Mm³ of timber was harvested in Finland in 2020, the fuel consumption totalled 126.6 ML or 2.16 L m⁻³ harvested (Table 9). The calculated fuel consumption of CTL logging operations totalled 109.7 ML, of which cutting accounted for 67.5 ML and forwarding for 42.2 ML. In total, CTL logging operations accounted for 86.6% of the total calculated fuel consumption. In addition, the calculated fuel consumption of the machine relocations was 7.6 ML and of the car travel by all workers 9.3 ML. Machine relocations and car travel accounted for 6.0 and 7.3% of the total fuel consumption calculated, respectively (Table 9).

Correspondingly, the calculated CO₂eq emissions totalled 334,209 t when a total of 58.7 Mm³ (5.70 kg m⁻³) of industrial roundwood was harvested in Finland (Table 9). Of the total CO₂eq emissions, logging operations accounted for 87.8%, the relocation of forest machines accounted for 5.7% and the car travel by all the workers accounted for 6.5% (Table 9).

Discussion

Evaluation of the study data and methods

The values from this study are relatively large, with the timber volume and fuel consumption during cutting being more than 0.3 Mm³ and 0.3 ML of LFO, and during forwarding, over 0.2 Mm³ and 0.13 ML, respectively, for different

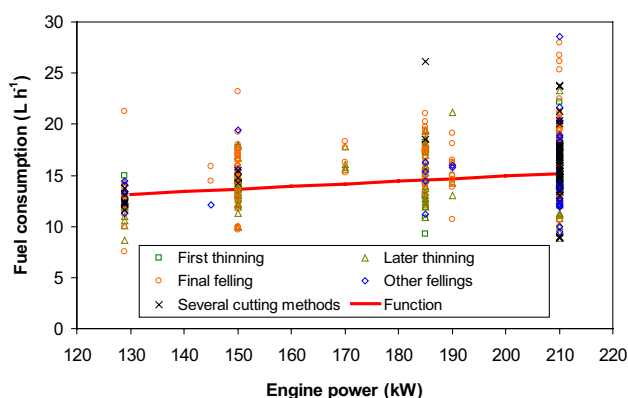


Fig. 4 Hour-based fuel consumption during cutting as a function of the engine power of the studied harvesters. The function assumptions used were 6000 machine hours, thinning harvesting site and 6.4°C average air temperature (Table 5)

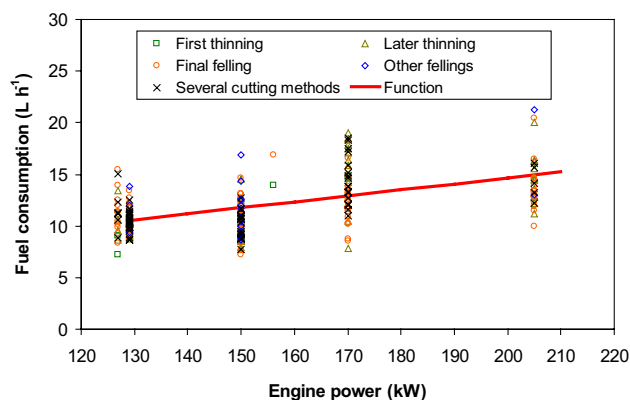


Fig. 5 Hour-based fuel consumption during forwarding as a function of the engine power of the studied forwarders. The function assumptions used were 11,000 machine hours, use of tracks on the front bogie of the forwarder and mineral soil at the site (Table 6)

Table 7 Regression model for predicting the cubic-metre-based fuel consumption during cutting

$$y = a + bx_1^{-1} + cx_2^{-1} + dx_3$$

Where

y = fuel consumption ($L\ m^{-3}$)

x_1 = stem size of removal in stand (m^3)

x_2 = hectare-based removal ($m^3\ ha^{-1}$)

x_3 = thinning dummy (1 if thinning site, 0 if some other cutting method)

a = constant

b, c, d = coefficients of the variables

| Coefficient | Estimate of coefficient | Standard error of estimate | t-value |
|-------------|-------------------------|----------------------------|-----------|
| a | 0.494 | 0.047 | 10.483*** |
| b | 0.105 | 0.008 | 12.359*** |
| c | 9.501 | 2.793 | 3.402*** |
| d | 0.149 | 0.065 | 2.282* |

Adjusted $R^2 = 0.424$; F-value = 119.399***; standard error of the estimate of the model = 0.563

* $p < 0.05$

*** $p < 0.001$

harvesting conditions (e.g. summertime and wintertime [freeze, snow] CTL logging operations, thinnings and final fellings, on mineral soils and peatlands). However, when evaluating the data by cutting method (Table 2), it can be seen that the values from the first-thinning stands were relatively small. The main reason for this is that the first-thinning sites were frequently cut together with another main cutting method (later thinnings and final fellings). Thus, these kinds of first-thinning sites were included in the “Several cutting methods” category.

Fuel- and time-consumption data, as well as notes on some properties of the harvesting sites and the equipment used on the machinery, were collected by the machine operators via monitoring forms. Flow metres were used to measure refilled fuel to an accuracy of $\pm 1\%$ of the fuel volume measured, with no problems encountered. This was an advantage over the advanced modern method of estimating the fuel consumption of CTL logging operations from machine-gathered data, where the amount of fuel is estimated, not measured. In the latter method, data are collected from standardised mom files that include the fuel and time used and the cubic metres harvested by the machine (Liski et al. 2020; Skogforsk 2021; Eliasson 2022); this provides easy access to large datasets. However, it should be noted that some properties of the harvesting sites—depth of snow cover, air temperature, low bearing capacity of the ground, dense and hindering undergrowth in the stand—and additional machine equipment used (tracks, wheel-chains) cannot be obtained from these mom files. As a result, these factors have to be collected in another way—for example, through traditional monitoring forms.

Some machines included in the study reported data from only a few harvesting sites, whereas, by contrast, there were

nine harvesters that covered more than 20 harvesting sites and seven forwarders that covered over 20 sites. The forest machines covering a small (≤ 5) number of harvesting sites in the study were excluded when determining the fuel-saving and fuel-wasting machine units. More than 30 different harvester operators and 30 different forwarder operators were included in the study, which is a lot, and which is to be expected in a long-term follow-up study running for more than twelve months and incorporating several machines. A large number of different machine operators is essential to a study like this because the forest-machine operator has a significant effect on productivity (Sirén 1998; Kärhä et al. 2004, 2018; Ovaskainen 2009; Purfürst and Erler 2011) and fuel consumption (Makkonen 2004; Kenney et al. 2014; Ghafariyan et al. 2018) during logging operations.

To sum up, the dataset from this study was large enough to be representative of Nordic harvesting conditions. The data collection methods used were suitable for producing comprehensive long-term follow-up data and reliable results on fuel consumption under Nordic harvesting conditions.

Discussion of the results

It was found that engine power and machine hours (i.e. age of machine unit) had the greatest and most significant effect on the hour-based fuel consumption in both harvesters and forwarders. Cutting method and air temperature affected the hour-based fuel consumption in harvesters, whereas utilisation of tracks on the front bogie and forest haulage over peatland increased the hour-based fuel consumption in forwarders. These results are in line with those from earlier studies, such as Brunberg (2007, 2013) and Holzleitner et al.

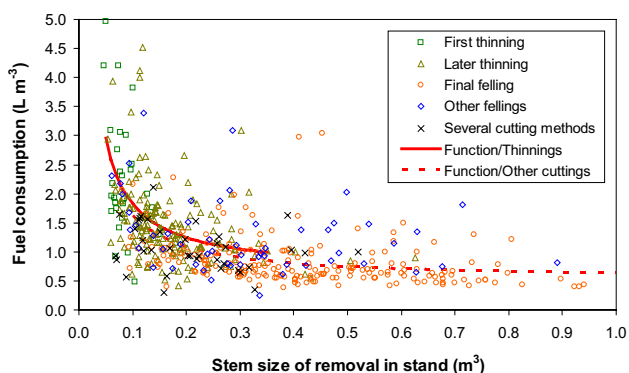


Fig. 6 Cubic-metre-based fuel consumption during cutting as a function of the removal stem size in the studied stands. The function assumptions used included removals from 43 m³ ha⁻¹ (0.05 m³) to 193 m³ ha⁻¹ (0.35 m³) in thinnings, and from 104 m³ ha⁻¹ (0.1 m³) to 347 m³ ha⁻¹ (1.0 m³) in other cuttings (Table 7)

(2011) who reported that engine power was a significant factor affecting the hour-based fuel consumption of forest machinery.

When comparing the values from this study with those from other large follow-up studies conducted under Nordic harvesting conditions (Rieppo and Örn 2003; Brunberg 2007, 2013), it was noted that the hour-based fuel consumption of forest machines, and especially of harvesters, has increased over the last 15–20 years. Brunberg (2013) obtained similar results when comparing the average hour-based fuel consumption values between studies conducted in 2006 and 2012. Brunberg (2013) thought this resulted from the increasing power of forest-machine engines and the increasing utilisation of tracks on forest machines.

While the results show that both forest-machine properties and harvesting conditions had the most significant influence on the hour-based fuel consumption, the machine properties were found to have no significant effect on the cubic-metre-based fuel consumption. In fact, the harvesting conditions—removal stem size in the stand, hectare-based removal, cutting method used, forwarding distance and soil type—had the greatest effect on both harvesters and forwarders (George et al. 2022). From this study, it was determined that the CTL logging operations averaged 1.4 L m⁻³ during final fellings and 3.1 and 2.2 L m⁻³, respectively, during first and later thinnings.

Again, when comparing the cubic-metre-based fuel consumption of CTL logging operations from this study with that of the 2000s under Nordic harvesting conditions (Rieppo and Örn 2003; Brunberg 2007, 2013; Eliasson 2022), it can be seen that the values have remained almost at the same level. This can be explained by the fact that, although more fuel is consumed per hour worked now, the productivity of logging work has increased significantly, with larger quantities of wood being cut and hauled to the roadside storage per hour than previously (Brunberg 2013).

In this study, the CO₂eq emissions from CTL logging operations (Table 4) were calculated based on the fuel consumed and the coefficients for CO₂eq emissions per litre of LFO. During thinning, the calculated CO₂eq emissions averaged 6.6 kg m⁻³, whereas, in final felling, this value was 3.6 kg m⁻³. Haavikko et al. (2022) determined that the average CO₂eq emissions from first and later thinnings were 7.3 and 5.3 kg m⁻³, respectively, and 3.1 kg m⁻³ from final felling. Karjalainen and Asikainen (1996) calculated that the average CO₂ emissions of CTL logging operations as

Table 8 Regression model for predicting the cubic-metre-based fuel consumption during forwarding

$$y = a + bx_1 + cx_2^{-1} + dx_3$$

Where
 y = fuel consumption (L m⁻³)
 x₁ = forwarding distance (100 m)
 x₂ = hectare-based removal (m³ ha⁻¹)
 x₃ = mineral-soil dummy (1 if mineral soil, 0 if no mineral soil)
 a = constant
 b, c, d = coefficients of the variables

| Coefficient | Estimate of coefficient | Standard error of estimate | t-value |
|-------------|-------------------------|----------------------------|----------|
| a | 0.516 | 0.062 | 8.372*** |
| b | 0.049 | 0.009 | 5.408*** |
| c | 17.033 | 2.698 | 6.314*** |
| d | -0.106 | 0.049 | -2.161* |

Adjusted R² = 0.231; F-value = 31.523***; standard error of the estimate of the model = 0.315

* p < 0.05

*** p < 0.001

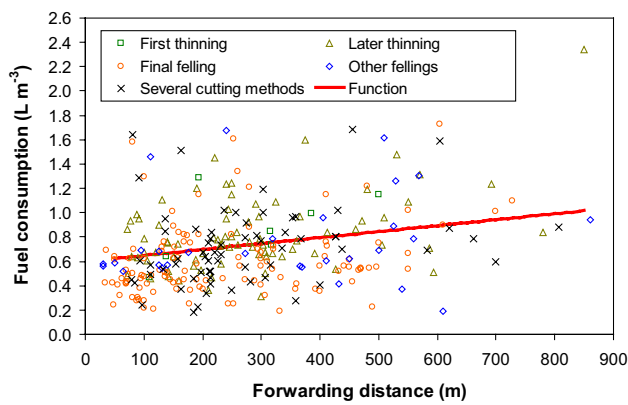


Fig. 7 Cubic-metre-based fuel consumption during forwarding as a function of the forwarding distance in the studied stands. The function assumptions used were hectare-based removals of 114 m³ ha⁻¹ and forwarding on mineral soils (Table 8)

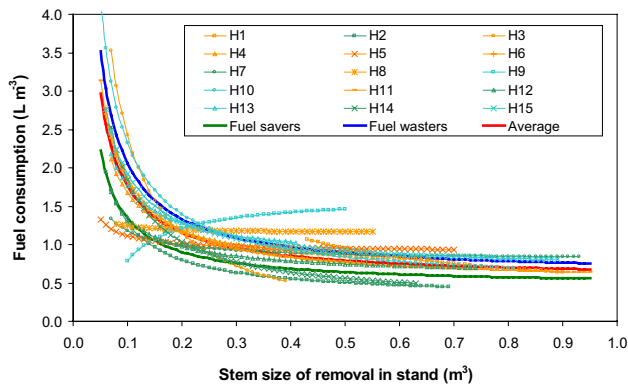


Fig. 8 Cubic-metre-based fuel consumption by harvester (H1–H15), and by the fuel-saving and fuel-wasting harvesters, as a function of the removal stem size in the stand

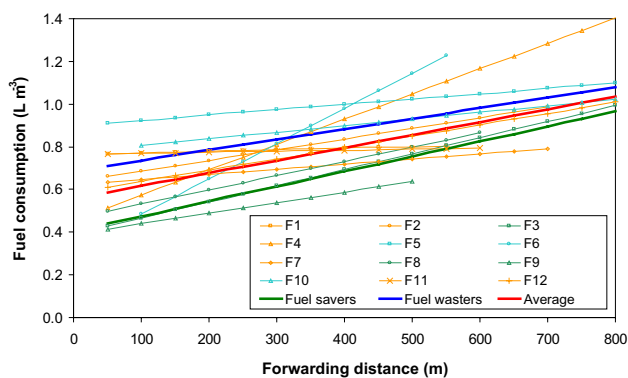


Fig. 9 Cubic-metre-based fuel consumption by forwarder (F1–F12), and the fuel-saving and fuel-wasting forwarders, as a function of forwarding distance

being 5.8 kg m⁻³ from thinnings and 3.4 kg m⁻³ from final fellings. Berg and Karjalainen (2003) determined that, in Finland, CO₂ emissions averaged 3.2 kg m⁻³ in CTL logging operations moving timber to roadside landings. In addition, Berg and Lindholm (2005) estimated that, in Sweden, the average CO₂eq emissions from logging were 4.5 kg m⁻³. Correspondingly, Lijewski et al. (2017) reported CO₂eq emissions from fully mechanised CTL logging operations of 3.6 kg m⁻³ during final fellings in Poland. In South Africa, Ackerman et al. (2017) found the CO₂eq emissions of pine clear-felling CTL logging operations to be 2.7 kg m⁻³, on average. Dias et al. (2007) calculated that CO₂ emissions caused by the CTL logging operations during final cuts in Portugal averaged 5.6 kg m⁻³ in eucalyptus forests and 4.7 kg m⁻³ in maritime pine stands.

For this study, the total CO₂eq emissions from CTL logging operations were determined at the national level for 2020. This is the first time all CO₂eq emissions were included, encompassing those from: (1) cutting and forest haulage operations in forests; (2) CTL logging-machinery relocations; and 3) to-and-from car travel by forest-machine operators, logging managers and service and maintenance staff. It was interesting to learn that cutting and forwarding operations in forests accounted for approximately 90% of the total calculated CO₂eq emissions (Table 9). Although the contributions from logging-machinery relocations and car travel by all workers was minor, it was still relevant, at around 10% of the total calculated CO₂eq emissions. The calculated CO₂eq emissions totalled 334,209 t for a total of 58.7 Mm³ of harvested industrial roundwood in Finland. The results illustrated that, at the country level, the TYKO machinery model produces smaller CO₂eq emissions for CTL logging operations (319,958 t CO₂eq). This is because it does not take all the components (2 and 3) of Table 9 into account (see Laurikko and Mäkelä 2019). Therefore, a more modern and up-to-date TYKO machinery model—or some other platform—is required in order to produce real-time data that shows reductions in fuel consumption and to provide transparent reporting of CO₂eq and other GHG emissions from the logging operations of the near future.

A large variation in fuel consumption between machines was identified (Figs. 8, 9). With the fuel-wasting harvesters, the relative cubic-metre-based fuel consumption averaged 38–58% higher than that of the fuel-saving machines, and 12–17% higher than the average for all harvesters. During forwarding, the cubic-metre-based fuel consumption of the fuel-wasting machines was 60–68% higher than that of the fuel-saving machines, and 21–23% higher than the average for all forwarders. It is clear that this indicates a large variation in fuel consumption between forest-machine operators, but also highlights a great potential to reduce fuel consumption. To improve the fuel and energy efficiency of cutting and forwarding operations, it is obvious that investments in

Table 9 Fuel consumption and CO₂eq emissions calculated for logging the total 58.7 Mm³ of industrial roundwood in Finland in 2020. The calculations involved the fuel consumption and CO₂eq emissions caused by 1) cutting and forest haulage operations in the forests; 2) logging-machinery relocations; and 3) car travel by all the workers

| Cutting method | Fuel consumption (L) | CO ₂ eq emissions (t) |
|---|----------------------|----------------------------------|
| (1) Logging operations | | |
| First thinning | 21,273,120 | 56,878 |
| Later thinning | 44,374,770 | 118,641 |
| Final felling | 40,903,632 | 109,359 |
| Other fellings | 3,150,849 | 8,424 |
| Total | 109,702,371 | 293,302 |
| (2) Machine relocations | | |
| First thinning | 903,760 | 2,259 |
| Later thinning | 2,586,870 | 6,467 |
| Final felling | 3,909,906 | 9,775 |
| Other fellings | 226,304 | 566 |
| Total | 7,626,840 | 19,067 |
| (3) Car travel by machine operators, logging managers and service and maintenance staff | | |
| First thinning | 1,100,512 | 2,588 |
| Later thinning | 3,150,040 | 7,408 |
| Final felling | 4,761,105 | 11,196 |
| Other fellings | 275,571 | 648 |
| Total | 9,287,228 | 21,840 |
| Grand total (including the components of 1, 2 and 3) | | |
| First thinning | 23,277,392 | 61,725 |
| Later thinning | 50,111,680 | 132,516 |
| Final felling | 49,574,643 | 130,329 |
| Other fellings | 3,652,724 | 9,638 |
| Total | 126,616,439 | 334,209 |

forest-machine-operator training and education are needed. Only around half of the machine operators (61% of the harvester operators and 56% of the forwarder operators) had participated in energy-efficiency education prior to this study. Based on the results, this means there is potential for at least a 10–15% improvement in fuel efficiency during CTL logging operations in Finland just from training operators in effective working methods and eco-driving models (Makkonen 2004; Kenney et al. 2014; Ghaffariyan et al. 2018). Advanced forest-machine-operator assistant systems and applications can also support machine operators to work more efficiently during CTL loggings in the future (Kärhä et al. 2021).

Possibilities for improving the fuel and energy efficiency of CTL logging operations

In addition to machine-operator training, there are several other possibilities—both technical and work related—that can enhance the fuel and energy efficiency of the forest-machine fleet. As suggested by Ghaffariyan et al. (2018) and Haavikko et al. (2022), it is essential to allocate CTL logging machinery to the most suitable harvesting sites, given the

properties of the machines (i.e. machine size, engine power, carrying capacity and other properties). Furthermore, fuel consumption can be reduced and energy efficiency enhanced by equipping forest machinery with the attachments most suited to the given harvesting conditions. For instance, Makkonen (2004), Suvinen (2006) and Brunberg (2013) emphasised that using tracks increases fuel consumption and so the unnecessary deployment of tracks should be avoided. In this study, it was found that the forest machines were frequently equipped with tracks. In addition, the good maintenance (e.g. sharp delimiting knives, clean radiators and oil coolers) of forest machinery provides for the possibility of achieving good fuel efficiency. Prinz et al. (2018) showed that optimised operational setups and adjustments of forest machinery can greatly influence fuel consumption. Furthermore, needless idling times of forest machinery and other vehicles should be minimised (Makkonen 2004; Ghaffariyan et al. 2018). For this study, we asked whether the machines had regularly been serviced, but idling times, machine setups and the allocation of the fleet were not clarified. It is possible that these factors had an effect on the variation in fuel consumption among the machines.

The comprehensive planning of the work and tasks of the harvesters and forwarders at the harvesting site affects the

logging work. Through appropriate working methods, the harvester operator can improve the working conditions of the forwarder operator—for instance, by concentrating the wood and carefully piling the logs along the strip roads. In addition, planning the locations of the roadside landings and the main strip road network to take into account the bearing capacity of the ground at the harvesting site, as well as minimising the amount of driving with a loaded forwarder in the stand, would lead to better fuel efficiency (Makkonen 2004). This planning can be enhanced by decision-support systems and tools that recommend where roadside landings and main strip roads should be placed in order to minimise soil damage and forwarding distances on the harvesting site (Mohtashami et al. 2012; Flisberg et al. 2022). Good planning and the chaining of harvesting sites could also reduce the need to relocate the forest machines or the distances between relocations (Haavikko et al. 2022).

To a minor extent, harvesting conditions can be improved to promote greater fuel efficiency in CTL logging operations. Good harvesting conditions, including relatively large removal stem sizes, large hectare-based removals, short forwarding distances and the preclearance of dense and hindering undergrowth, can increase productivity in logging operations (e.g. Kärhä 2006; Eriksson and Lindroos 2014; Manner et al. 2016; Kärhä and Bergström 2020) and can have a strong influence on fuel consumption and efficiency (see Figs. 3, 6–9). However, with the exception of preclearing the undergrowth, these changes can take a long time and can only be achieved through long-term forest management and silvicultural decisions.

Last but not least, car travel, especially by the forest-machine operators, consumes quite a lot of fuel annually (see Table 9), and perhaps the machine operators could be encouraged to increase their co-travel to the harvesting sites and back, thereby helping to improve the fuel efficiency of the entire CTL logging operation.

Conclusions

In this study, we described the fuel consumption of CTL logging machinery during cutting and forwarding operations in Finland and clarified which factors had the greatest impact on fuel consumption. In addition, we calculated the total annual fuel consumption and CO₂eq emissions from the harvesters and forwarders, the relocation of logging machinery and the car travel by the machine operators, logging managers and service and maintenance staff to and from the harvesting sites. This allowed us to generate the total annual fuel consumption and CO₂eq emissions based on all components consuming fuel during CTL logging operations.

We have produced novel and up-to-date information on fuel consumption and CO₂eq emissions from CTL

logging operations under Nordic harvesting conditions. It was revealed that there is great variation—tens of percentages—in fuel consumption between the most and least efficient machines, both in harvesters and forwarders. Because this is probably an effect of the operator, the operators must receive education and training in efficient working methods and eco-driving models. In addition, several other measures for accelerating fuel efficiency and further decreasing CO₂eq emissions can be implemented to increase energy efficiency in CTL logging operations. These include tracks not being used unless needed, machinery being allocated to forest stands that are being harvested optimally, machines receiving proper maintenance, and main strip roads being well planned. Furthermore, harvesting conditions can be improved by putting more effort into good silvicultural practices and tending to young stands, as well as preclearing dense undergrowth, if needed. This will lead to sites that can be harvested with greater fuel and energy efficiency and lower carbon footprints in the future.

Author contributions KK, HK, KR, TP, and HH conceptualized the study. HK, KK, and KR collected field data. KK and HK performed statistical analyses. KK and LE were responsible for the interpretation of the results and wrote the manuscript. All authors commented the manuscript.

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Data availability The raw data are proprietary, but can be disclosed by sending a motivated request to the corresponding author.

Declarations

Competing interests The authors declare no competing interests.

Conflicts of interest The authors declare they have no conflicts of interest.

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