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Fuel Consumption and CO_2 Emissions in Fully Mechanized Cut-to-Length (CTL) Harvesting Operations of Industrial Roundwood: A Review

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Abstract

Purpose of Review The aim of this literature review was to bring together the most relevant and recent research information on the fuel consumption and CO_2 emissions caused by the fully mechanized cut-to-length (CTL) harvesting machinery when applied to industrial roundwood. A specific aim of this review was to describe the effect of different independent variables on fuel consumption in fully mechanized CTL wood-harvesting operations.

Recent Findings The review showed that the engine power of CTL forest machines accounts for most of the variance in the hourly fuel consumption of both harvesters and forwarders. We underline that the cubic-metre-based fuel consumption of CTL forest machines is correlated to the same factors that affect work productivity. Among all influencing factors, the average stem size, removal intensity and silvicultural treatment have the strongest effect on the fuel consumption per m^3 incurred with felling-processing, whereas forwarding distance, removal intensity and payload size are the main drivers of fuel consumption per m^3 as incurred with extraction. Further influencing factors are soil type (mineral soil or peatland), use of tracks, assortment type and machine size. Together with those factors, the role of the machine operator remains crucial and is dependent on two separate skills: the capacity to achieve high productivity, and that to apply fuel-saving driving techniques.

Summary The easiest way to reduce the carbon footprint of CTL harvesting machines is to increase the productivity of the harvesting work, for example by giving machine operator-specific training to utilize more efficient work methods and economic energy-efficient driving techniques. Furthermore, several other measures to reduce the carbon footprint of CTL harvesting operations were discussed in this review. Finally, we recommend that all essential variables that have a significant impact on the productivity of harvesting work, fuel consumption and CO_2 emissions are reported in study papers in the future.

Keywords Forest operations · Felling-processing · Extraction · Logging · Harvester · Forwarder · Greenhouse gas (GHG) emissions

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Introduction

According to the latest statistics of the International Energy Agency (IEA) [1], global energy-related carbon dioxide (CO_2) emissions grew by 0.9% or 321 Mt in 2022, reaching a new record of over 36.8 Gt. The Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) [2] summarized the state of knowledge of climate change, its widespread impacts and risks, and climate change mitigation and adaptation measures. This report showed that human activities, principally through greenhouse gas (GHG) emissions, mostly CO_2 but also for instance carbon monoxide (CO), nitric oxide (NOx) and hydrocarbon (HC), have unequivocally caused global warming, with global surface temperature reaching 1.1 °C above the level of 1850–1900 in 2011–2020.

Moreover, the IPCC AR6 [2] highlighted that continued GHG emissions will lead to increasing global warming, and deep, rapid and sustained reductions in GHG emissions is needed to induce a discernible slowdown in global warming within two decades. If warming exceeds a specified level such as 1.5 °C, it could gradually be reduced again by achieving and sustaining net negative global CO_2 emissions. The IPCC AR6 [2] emphasized that rapid and far-reaching transitions across all sectors and systems are necessary to achieve deep and sustained emissions reductions and secure a livable and sustainable future for all.

The European Union (EU) plays a very active role in the global fight against climate change. The EU has a target to cut GHG emissions by at least 55% below 1990 level by 2030 [3]. Furthermore, the EU aims to be climate-neutral by 2050 – an economy with net-zero GHG emissions [4]. Several strategy papers, laws, directives and regulations (the European Climate Law, the European Green Deal, the Emissions Trading System (ETS) Directive, the Effort Sharing Regulation (ESR), and the Land Use, Land Use Change and Forestry (LULUCF) Regulation) [5–10] have been set out to support the implementation of the EU's challenging climate targets and to explore pathways for the transition to climate-neutrality in the EU countries. The effort sharing sector (ESS), i.e. sector outside the ETS, except for the land use sector, comprises the emissions from transport, agriculture, residential heating, off-road vehicles, waste management, F-gas emissions, and emissions from industry and energy consumption outside the ETS [11].

The main part of the emissions caused by the ESS comes from transport, agriculture, residential heating, and off-road vehicles. The latter are excavators, wheel loaders, farm tractors, and dedicated forest machines (i.e. harvesters and forwarders). The EU Commission's proposed emissions reduction obligation for the ESS within Finland to 2030 is 50% compared to the 2005 level [11]. For Austria, Italy and Sweden, the EU Commission's proposed emissions reduction obligation for the ESS are 48%, 43.7% and 50%, respectively [12]. In Finland, for example, the VTT Technical Research Centre of Finland calculated that the targets set to the ESS cannot be achieved with the existing measures, and further actions are needed [13]. Among other things, the Ministry of the Environment in Finland [11] presents the following additional actions: more taxes for fossil fuels, higher distribution obligation of biofuel oil, stronger promotion of new low-emission off-road vehicles, introduction of a zero-emissions worksite green deal, development of better calculation models and systems for GHG emission accounting, additional training on energy-saving driving techniques for machine operators, procurement support for electric and biogas-powered off-road vehicles, and development of a new Stage Regulation (2016/1628 [14]) so that it also covers CO_2 emissions.

In recent years, the global removals of industrial roundwood (i.e. logs and pulpwood harvested for forest industries) have averaged 2.3 billion m^3 (over bark [ob]) according to the statistics of the Food and Agriculture Organization (FAO) [15]. Lundbäck et al. [16] calculated that mechanized cut-to-length (CTL) harvesting, including felling and processing a tree on stump with a harvester and the extraction of timber from forest to roadside landing with a forwarder, accounts for almost 40% of the total amount of industrial roundwood harvested globally: that is approximately 850–900 million m^3 of roundwood per year. There is no estimate about the annual fuel consumption and CO_2 emissions caused by fully mechanized CTL machinery, when applied to the harvesting of industrial roundwood at a global level. Almost all engines in CTL harvesting machinery are endothermal and are fueled with diesel oil or light fuel oil. There are only a few hybrid-powered CTL harvesting machines in use, and they all feature a combustion engine in addition to an electric engine [17•].

Fuel consumption and GHG emissions of harvesting machines in fully mechanized CTL wood-harvesting operations have been studied to some extent during the last two decades. However, an extensive global review on the fuel consumption and CO_2 emissions caused by fully mechanized CTL harvesting machinery has not previously been carried out. There are some review papers on the fuel consumption of fully CTL forest machinery and the environmental impact of CTL wood-harvesting operations [18–22, 23•, 24], but their scope is still regional, not global.

When aiming to reduce the fuel consumption and CO_2 emissions of off-road vehicles (including CTL wood-harvesting machinery), it is important that there is aggregated research data on their fuel consumption and CO_2 emissions, and that the key lessons and the conclusions of previous studies are compiled into a synthetic view. Moreover, up-to-date information on the fuel consumption and CO_2 emissions of such machinery are needed for estimating reliable machine cost figures (e.g. [25–31]) and drawing accurate LCA projections (e.g. [32–35, 36•]).

Fuel consumption data for CTL harvesting machines have traditionally been collected in either short-term time studies or long-term follow-up studies: typically, time studies include few machines (e.g. [37–41].), while follow-up studies often cover multiple machines, up to several dozen (e.g. [42–45, 46••, 47••]). Regardless of study type, fuel consumption data is generally collected with flow meters installed on the machines or on the fuel bowser, and in the latter case fuel records are generally noted on the respective machine logs (e.g. [41, 47••, 48, 49•]). Recently, fuel consumption is also being recorded through the machines' on-board computers, which store that information in StanForD-based files (mom/drf) or the manufacturers' cloud services and fleet management systems (FMSs) (e.g. [44, 45, 46••, 50, 51, 52••, 53••]). Data collection forms, logbooks and questionnaires have also been used to gather information on the fuel consumption of CTL forest machines (e.g. [44, 54–56]). In addition to the measured fuel consumption data, the fuel consumption of CTL forest machinery has also been modeled [57].

The CO_2 emissions caused by the CTL wood-harvesting machines of industrial roundwood have mostly been derived from fuel consumption through suitable conversion coefficients (e.g. [38, 45, 47••, 51]). The coefficient of 2.684 kg CO_2 L^{-1} by the Environmental Protection Agency (EPA) of the United States of America [58] has been a very commonly used coefficient in determining CO_2 emissions (e.g. [38, 45, 51, 59]). Furthermore, some other conversion coefficients have been used when determining CO_2 emissions (Nakano et al. 2018 [35]: 2.920 kg CO_2 L^{-1}; Rodrigues et al. 2019 [60]: 2.431 kg CO_2 L^{-1}; Bacescu et al. 2022 [52••]: 2.610 kg CO_2 L^{-1}; Haavikko et al. 2022 and Kärhä et al. 2023 [47••, 57]: 2.673/2.674 kg CO_2 L^{-1}). One of the reasons for differences in conversion coefficients are differences in diesel fuel quality. However, CO_2 emissions can also be measured directly through suitable gauges [59]. Direct measurement has also been used to determine CO, NOx and HC emissions [59, 61, 62].

Consequently, the aim of this literature review was to bring together the most relevant and recent research information on the fuel consumption (L h^{-1} & L m^{-3}) and GHG emissions caused by the fully mechanized CTL harvesting machinery when applied to industrial roundwood. For that reason, the search was limited to papers published from the year 2000 onwards. Furthermore, the review concentrated on CO_2 emissions, as the main and most studied component of the larger family of GHG emissions. A specific aim of this review was to describe the effect of different independent variables (e.g. harvesting conditions, harvesting machine fleet and forest machine operator) on fuel consumption in fully mechanized CTL wood-harvesting operations (Fig. 1). Finally, this review was geared to determine the annual fuel consumption and CO_2 emissions for the fully mechanized CTL harvesting operations of industrial roundwood globally, using the average values found in the literature.

Literature Review

Data Collection

At the beginning of this work, a systematic literature review was conducted to obtain an overview of the fuel consumption and CO_2 emissions caused by fully mechanized CTL wood-harvesting operations deployed for industrial roundwood procurement. The focus of the review was on study papers published between January 2000 and June 2023 in English, Finnish, German, Italian and Swedish. The literature databases of Scopus, Google Scholar and Web of

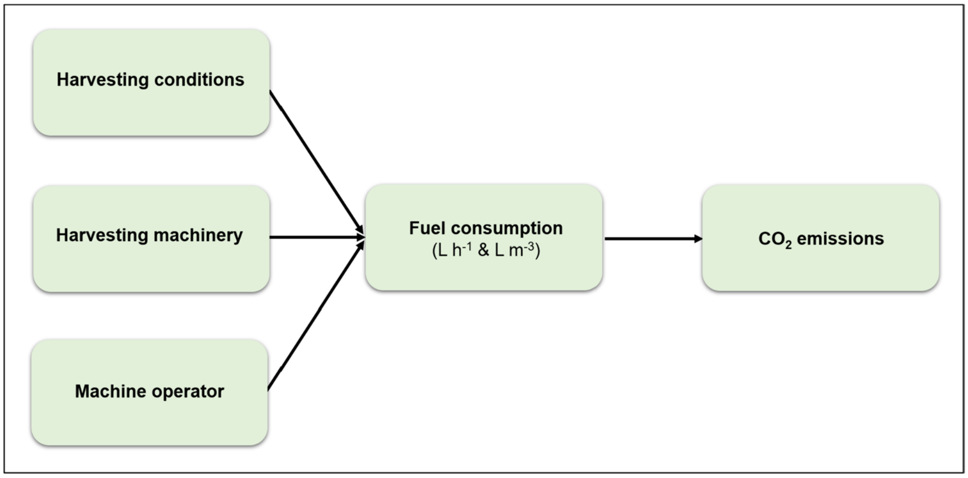

Fig. 1 The effects of different independent variables on the fuel consumption (L h^{-1} and L m^{-3}) caused by the fully mechanized CTL harvesting machinery of industrial roundwood that were depicted in this review

Science were used to find suitable studies. The following keywords and the combination of these words were specifically searched for: forest machine, harvester, forwarder, cutting, felling, processing, extraction, forwarding, forest haulage, primary transportation, harvesting, logging, forest operations, fuel consumption, emissions, carbon dioxide, CO_2, LCA, life cycle assessment, life cycle analysis, energy efficiency, timber, roundwood, and forest industry. Search terms and their various combinations using Boolean operators (AND OR) were used to perform the search. In addition, publications were also sourced from the reference list of previous partial reviews on the same subject [23•, 63, 64, 65•].

The database CO2FORMEC by Cavalli et al. [63] allowed retrieval of many relevant scientific publications dealing with CO_2 emissions in forest operations, including primary and secondary transportation, over the years 1994–2014. The master thesis by Argnani [64] was also searched for suitable studies. The thesis had done excellent preparatory work, pre-sorting many studies and compiling them in a structured list. Due to the specific goals set for the present study, however, a critical examination of those studies had to be carried out as well. Furthermore, Grünberg [23•] and Zeh [65•] had also collected relevant studies dealing with fuel consumption of harvesters and forwarders. Those Authors used the LCA approach to calculate the GHG emissions and the environmental impacts of CTL harvesting operations.

All selected studies were assigned an ID number and compiled in a Microsoft Excel file (Database on *Fuel Consumption and* CO_2 *Emissions Caused by Fully Mechanized CTL Harvesting Operations of Industrial Roundwood*). Table 1 describes which parameters from each study paper were collected for the review. The Study type categories in the review were:

- Time study: short-term (e.g. 2–3 work days, mostly less than one week) collection of research material in the field for the study paper,
- Follow-up study: longer-term (e.g. 2–3 weeks or even more than 12 months) collection of research data in the field for the study,
- Survey: no collection of field research data but data collection with e.g. questionnaire forms,
- LCA study: no collection of field research data but a case study was the LCA study, and
- Modeling: no collection of field research data but other modeling study than the LCA study.

Study methodology included the following categories:

- Flow meter: collection of fuel consumption data with flow meters,

Table 1 Parameters to describe and classify the collected data in the review

ID number of the study	
Author(s)	
Title of publication	
Year of publication	
Study type	Time study, Follow-up study, Survey, LCA survey, Modeling
Study methodology	Flow meter, Exhaust gas gauge, Machine data, Re-filling, Daily logbook, Accounting data, Questionnaire, Calculations
Data collection year in the study	
Data collection country in the study	
CTL system	Harvester, Forwarder, Harvesting chain
Type of silvicultural treatment	First thinning/Later thinning/Thinning, Final felling, All operations, Other cutting method
Tree species (%)	
Stem volume (m^3 ob)	
Terrain conditions	e.g. flat or steep terrain, slope in %
Forwarding distance (m)	
Machine type	
Weight of machine (t)	
Engine power (kW)	
Productivity (m^3 ob h^{-1})	
Fuel consumption (L h^{-1})	
Fuel consumption (L m^{-3} ob)	
CO_2 emissions (kg m^{-3} ob)	
Remarks	

- Exhaust gas gauge: measurement of the CO_2 emissions with gas gauge,
- Machine data: collection of fuel consumption data using data produced by CTL forest machines,
- Re-filling: collection of fuel consumption data when refueling the forest machine without flow meters,
- Daily logbook: bookkeeping by the machine operator of fuel consumption in the cabin of machine,
- Accounting data: accounting data on the CTL forest machine's fuel consumption,
- Questionnaire: fuel consumption data reported by forest machine contractors using a questionnaire on the fuel consumption of CTL machine fleet, and
- Calculations: calculations prepared by the research scientist about the fuel consumption and/or CO_2 emissions of the CTL forest machine fleet.

In the review, particular attention was placed on recording the Type of silvicultural treatment as accurately as possible in an Excel Database. The "All operations" category was used if the Type of silvicultural treatment could not be clearly recorded as a treatment of Thinnings or Final felling in the review.

Data Analysis

The following data conversions were made in the review, when needed:

- Cubic metres, under bark (ub) were converted into cubic metres, over bark (ob) with a factor of 1.14 [66]
- Oven dry tonnes (odt) were converted into cubic metres (ob) with a factor of 2.5 [67]
- Loose cubic metres were converted into cubic metres (ob) with a factor of 0.4 [68]
- The weights of the tree species of *Pinus radiata* and *Populus* were converted into cubic metres (ob) with the green densities of 870 and 770 kg m^{-3}, respectively [69–71].

Data analysis started with estimating the descriptive statistics for the Microsoft Excel Database on *Fuel Consumption and CO_2 Emissions Caused by Fully Mechanized CTL Harvesting Operations of Industrial Roundwood.* In particular, the mean fuel consumption and CO_2 emissions were estimated separately for thinning and final-felling operations, and then also separately for felling-processing, extraction and the entire CTL harvesting chain (sum of the two). The calculation of average values for our defined processes was conducted when the separate mean values were presented in the published study papers. On the contrary, if only the variation range was presented in the study paper, they were excluded from the calculation of the average value for the review. The average values and functions calculated were not weighted based on the quantity of data collected in the studies reviewed, but each study and observation in the review had the same weight. The figures were not weighted because the size of datasets was not reported in all the studies reviewed.

The correlations between the main explanatory variables and the selected dependent variable (e.g. fuel consumption per hour and m^3, and CO_2 emissions) were tested with the Spearman's rank technique (ρ). Finally, the fuel consumption (in L h^{-1} and L m^{-3}) of the felling-processing and extraction was modeled by applying regression analysis. The hourly fuel consumption was formulated with the engine power of the harvester and forwarder machinery and fuel consumption per m^3 using stem size (felling-processing) and forwarding distance (extraction) as independent variables. The inverse transformation of stem size was applied to fit the model of fuel consumption per m^3 for felling-processing. The suitability of the fuel consumption models related to the data produced by the study papers was assessed based on the symmetrical residuals for the regression models, the adjusted degree of the explanation (adjusted R^2) of the models, and the statistical significance of the model coefficients. All statistical analyses were conducted with IBM SPSS Statistics 27.

An overall global estimate of fuel consumption and emissions derived from fully mechanized CTL harvesting as applied to industrial roundwood procurement was estimated on the assumption that thinning operations account for 20% of the total production. The mean fuel consumption per product unit found in this review for felling-processing and extraction in thinning and final-felling operations were used. The total calculated fuel consumption was converted into CO_2 emissions using the EPA [58] coefficient (2.684 kg CO_2 L^{-1}).

Data of the Review

The final review included 83 study papers and the Excel Database contained a total of 283 data lines (i.e. study observations), including the combinations of Study type, Study methodology, CTL system, Type of silvicultural treatment, Machine type, Weight of machine, and Engine power. There were 1–15 data lines from each study paper in the Excel Database. There was a general increase over time in publications and 2019 and 2022 were the years that had the highest number of papers used within the timeframe considered (Fig. 2).

Of the review's study papers, 39% were classified as Time studies, 31% were classified as Follow-up studies and 14% as LCA studies. On the other hand, Calculations was the most commonly used study methodology (n = 30) among the study papers reviewed. Forest machine data were used in 17 study papers, Re-filling data in 13 studies and Flow

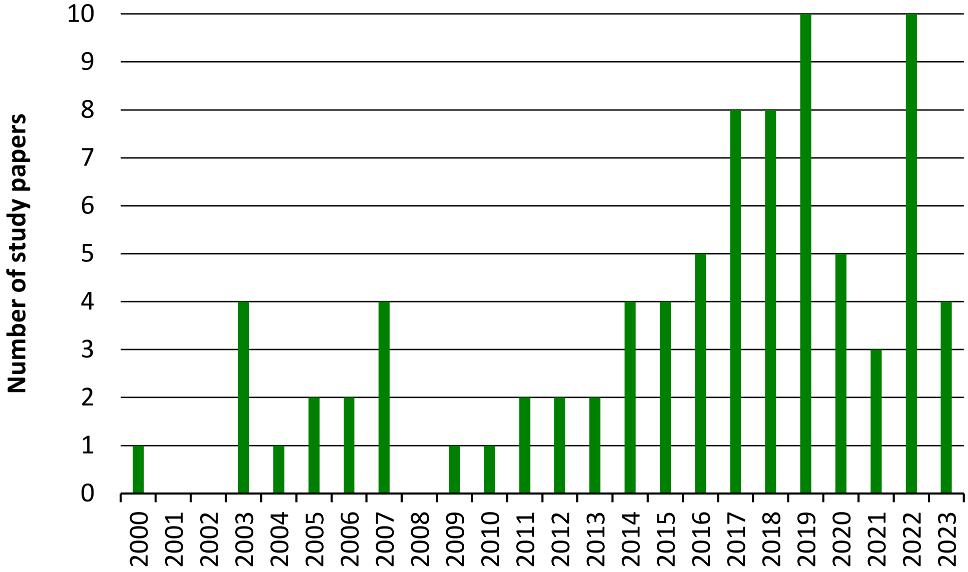

Fig. 2 Publication years of the study papers (n = 83) used within the review

meter data in 12 study papers. The data of the study papers had been collected mostly (more than three quarters of the studies) from Europe; of which data for 12 studies had been collected in Sweden and 11 studies in Finland. Furthermore, there were study papers from all continents in the review. There were a total of 121 data lines from felling-processing (43%) and 120 lines from extraction (42%) and the rest of the data lines (42 lines, 15%) from the entire harvesting chain in the review.

Correspondingly, there were a total of 100 data lines from thinnings and 95 data lines from final fellings. The stem size in thinnings averaged 0.261 m^3 and 0.685 m^3 in final fellings with harvesters and with forwarders a forwarding distance averaged 529 m. The productivity of harvesters for thinnings and final fellings averaged 13.4 and 35.4 m^3 h^{-1}, respectively, in the review Database. For forwarders the corresponding figures were 10.6 and 23.2 m^3 h^{-1}, respectively. The average weight of harvesters in the review Database was 16.8 t and that of forwarders 13.5 t. The engine power of harvesters was 162 kW, on average, and that of forwarders 137 kW.

Results

Table 2 shows the number of study papers which have reported the fuel consumption (L h^{-1} & L m^{-3}) of felling-processing (harvesters), extraction (forwarders) and the entire harvesting chain. By far the most study papers have reported fuel consumption in either felling-processing or extraction. On the other hand, the measurement and reporting of the fuel consumption of the entire harvesting chain has been substantially at the lower level (Table 2). Table 2 also demonstrates that the study papers of the review have

Table 2 Total 83 study papers of the review which have reported the fuel consumption and CO_2 emissions of harvesters, forwarders and entire harvesting chain in 2000–2023

	Fuel consumption		CO_2 emissions
	L h^{-1}	L m^{-3}	kg m^{-3}
	ID number of study paper		
Harvester / Felling-processing	[25–27, 29–34, 37, 42, 43, 45, 47••, 48, 51, 52••, 53••, 55, 56, 60, 72, 73, 75–77, 79–89, 99]	[17•, 37, 38, 43–45, 46••, 47••, 48, 49•, 51, 52••, 53••, 55–57, 59, 62, 73, 77, 80–88, 90–97]	[21, 33, 34, 36•, 38, 45, 47••, 49•, 51, 52••, 59, 75, 84–86, 88, 90, 92, 93]
Forwarder / Extraction	[26–34, 37, 39–42, 47••, 48, 50, 51, 52••, 54–56, 60, 72–78, 80–82, 84, 85, 88, 98, 100–107]	[39–41, 46••, 47••, 48, 49•, 51, 52••, 54–57, 59, 73, 77, 78, 80–82, 84, 85, 88, 90–93, 95–97, 100–102, 104–106, 108, 109]	[21, 33, 34, 36•, 47••, 49•, 51, 52••, 59, 75, 84, 85, 88, 90, 92, 93, 104, 106–108]
Entire harvesting chain	[51, 110]	[24, 46••, 51, 52••, 55–57, 90, 96, 111]	[21, 24, 32, 35, 47••, 51, 52••, 57, 72, 88, 90, 92, 93, 95, 110, 112–115]

reported considerably less CO_2 emissions than fuel consumption in felling-processing and extraction.

Fuel Consumption

Felling-Processing

Fuel Consumption Per Hour

From this review, the average fuel consumption was estimated at 13.8 L h^{-1} for thinnings and 19.5 L h^{-1} for final fellings. In fact, several studies have reported that the characteristics of the harvester, and especially its engine power, have a strong effect on hourly fuel consumption [42, 47••, 55, 56, 92] (Fig. 3). When engine power is 100 kW, fuel consumption averages 11.0 L h^{-1}. Larger, more efficient harvesters with an engine power of 150–200 kW incur an average fuel consumption between 14.2 and 17.3 L h^{-1} (Fig. 3).

Santos et al. [86] studied the fuel consumption (L h^{-1} and L m^{-3}) of an excavator-based harvester in Brazil. They found that engine speed and hydraulic pump flow rate have a linear, positive and significant effect on hourly fuel consumption for a range of stem volumes (0.08 and 0.16 m^3). Furthermore, they reported that keeping the pump flow rate fixed and decreasing the engine speed to a set and moderate level (i.e. ca. 1900–2000 rpm) resulted in a mean reduction of fuel consumption of 0.78 and 0.27 L h^{-1} for stem volumes of 0.08 and 0.16 m^3, respectively.

In general, there is a sharp difference between dedicated harvesters and excavator-based harvesters: the former is favored by a better integration between the head and the carrier, which allows functional optimization and results in a much lower fuel consumption per hour (approximately –33%) [43]. Dedicated optimization kits have been developed in order to improve the hydraulic and fuel efficiency of excavators, but they cannot fill the gap entirely [45]. Finally, Kärhä et al. [47••] showed that the harvester wear (i.e. accumulated work hours) has a significant effect on hourly fuel consumption: old harvesters had lower hourly fuel consumption than new ones. As for work conditions, Kärhä et al. [47••] showed that silvicultural treatment and air temperature had a notable effect on hourly fuel consumption: fuel consumption was 1.2 L h^{-1} lower in thinning operations than in other treatments, while hourly fuel consumption increased alongside with air temperature.

Fuel Consumption Per m^3

While harvester characteristics (especially engine power) have a dominant effect on its hourly fuel consumption, work conditions have the strongest impact on fuel consumption per product unit (m^3). Among them, stem size is by far the most important driver of fuel consumption per m^3. This is expected, because machine productivity increases very rapidly with stem size, while fuel consumption per hour is relatively constant for any given machine power class. Many studies report about such relationship, such as Rieppo and Örn [48], who demonstrated the strong and inverse correlation between cutting productivity and fuel consumption per product unit. Our Excel Database confirmed such a relationship and allowed estimation of the strong and significant correlation ($\rho = -0.775$; $p < 0.001$) between harvester productivity and fuel consumption per product unit.

Fuel consumption per product unit (m^3) averaged 1.43 L m^{-3} for thinning and 0.86 L m^{-3} for final felling. Figure 4 depicts the fuel consumption per m^3 as a function of the average stem size: as stem size increased from 0.1 m^3 to

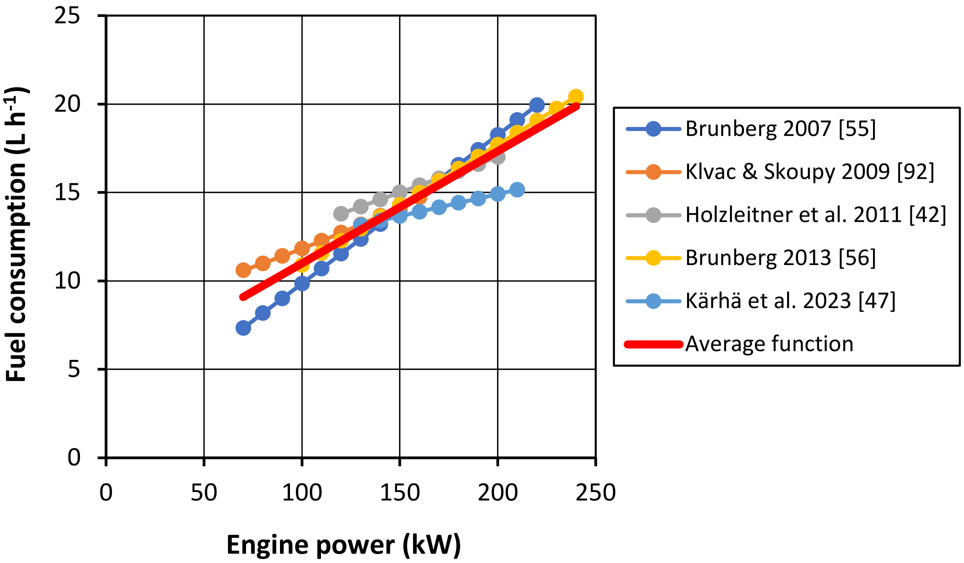

Fig. 3 Fuel consumption in felling-processing as a function of the engine power of harvester in those study papers where hourly fuel consumption has been reported in relation to the engine power of harvester. Also shown is the calculated average fuel consumption function from the review dataset: Fuel consumption (L h^{-1}) = 4.6409 + 0.0635 × Engine power (kW) (Adj. $R^2 = 0.89$; Standard error of the estimate of the model = 0.963; F value = 456, $p < 0.001$)

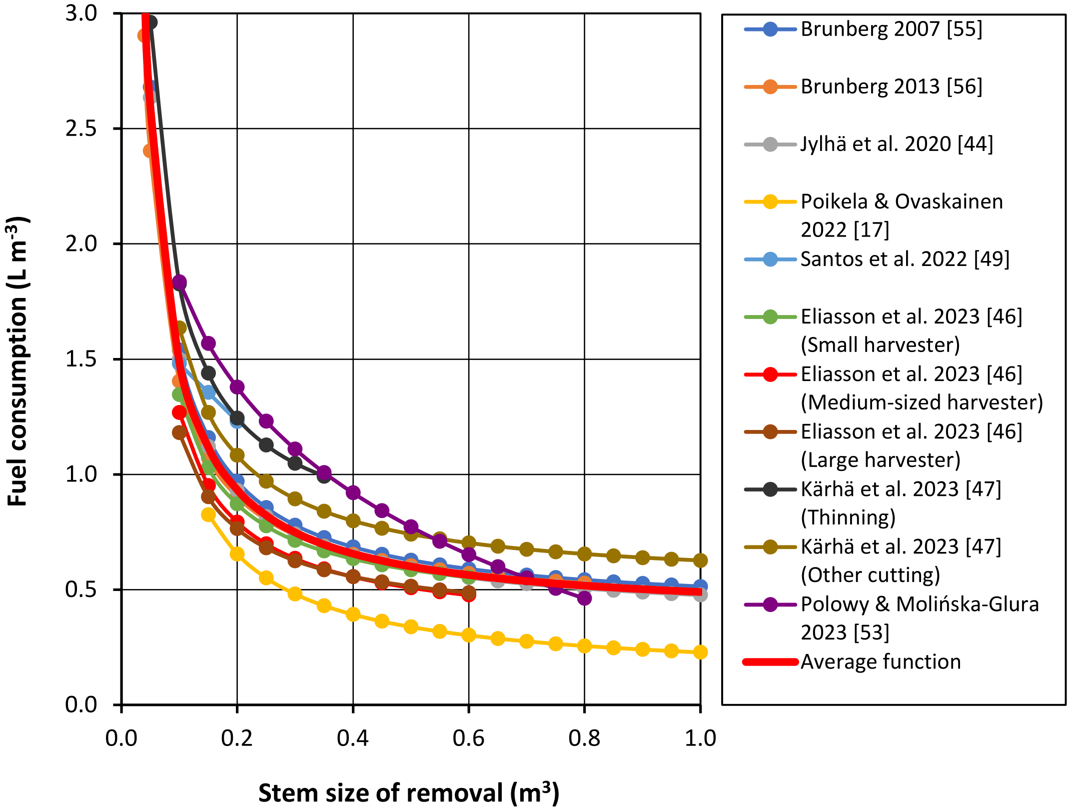

Fig. 4 Fuel consumption in felling-processing as a function of the removed stem size in those study papers where cubic-metre-based fuel consumption has been reported in relation to the stem size of removal. Also shown is the calculated average fuel consumption function from the review dataset: Fuel consumption (L m^{-3}) = 0.3789 + 0.1108 × Stem size of removal (m^3) $^{-1}$ (Adj. R^2 = 0.86; Standard error of the estimate of the model = 0.168; F value = 4356, $p < 0.001$)

0.3, 0.5 and 0.7 m^3, fuel consumption decreases from 1.49 L m^{-3} to 0.75, 0.60 and 0.54 L m^{-3}, respectively (Fig. 4).

In addition to stem size, removal intensity (m^3 ha^{-1}) and silvicultural prescription have been found to have a significant effect on fuel consumption. As removal intensity increases, fuel consumption decreases [47••]. Due to the low removal intensity and small tree size, thinning operations generally incur a higher fuel consumption, which can be estimated at 0.15 L m^{-3} above that of the other silvicultural prescriptions [47••]. Similar conclusions were reached recently by Eliasson et al. [46••]. Furthermore, machine type has a strong impact on fuel consumption: in particular, the higher hourly fuel consumption incurred by excavator-based harvesters compounds with their lower productivity and results in a fuel consumption per m^3 that is 2.4 times greater than recorded for dedicated harvesters [43]. However, such a dramatic difference must be placed within context: The excavator-based machines included in that study were all detached to assist cable-yarders, and their lower productivity was partly dependent on operational limitations and not entirely due to machine factors.

Santos et al. [86] reported that engine speed and hydraulic pump pressures had a significant quadratic effect on cubic-metre-based fuel consumption in felling-processing in all scenarios studied. With an engine speed of 1900 rpm and a hydraulic pump flow rate of 290 L min^{-1}, the lowest fuel consumption (1.22 L m^{-3}) was obtained with the stem volume of 0.08 m^3. In the high stem volume (0.16 m^3) scenario, the lowest fuel consumption (0.95 L m^{-3}) was achieved with an engine speed of 2060 rpm and a pump flow rate of 300 L min^{-1}. Similarly, Prinz et al. [38] studied harvester adjustments and found that they have a substantial effect on the cubic-metre-based fuel consumption of harvesters.

Moreover, operator proficiency has been found to have a major impact on fuel consumption per m^3. For example, Kärhä et al. [47••] reported that the difference in fuel consumption between low-consumption (i.e. fuel-saving) and high-consumption (i.e. fuel-wasting) harvester-operator combinations averaged about 0.23–0.72 L m^{-3} for a stem size of 0.1–0.6 m^3, respectively. Kärhä et al. [47••] also found that operator technique accounted for a difference in fuel consumption per m^3 between 38 and 58%. Poor operating technique can result in an increase of fuel consumption between 12 and 17% over the general average, for a stem size of 0.1m^3 and 0.6 m^3, respectively.

Extraction

Fuel Consumption Per Hour

Based on the reviewed studies, hourly fuel consumption incurred during extraction averaged 9.1 L h^{-1} for thinning and 13.0 L h^{-1} for final felling. As for felling-processing, engine power was the main driver of the hourly fuel consumption incurred by forwarders. Fuel consumption averaged 10.1 L h^{-1} for an engine power of 100 kW, and between 12.9 and 15.7 L h^{-1} for an engine power between 150 and 200 kW, respectively (Fig. 5). The hourly fuel consumption of forwarders was remarkably lower (–0.9 to –1.7 L h^{-1}) than that of harvesters, for the same engine power levels (cf. Figures 3 and 5).

As with harvesters, forwarder wear (i.e. accumulated operational hours) resulted in a reduction in fuel consumption [47••]. Furthermore, the installation of boogie/wheel tracks resulted in a marked increase in fuel consumption [56, 116], which was estimated at + 1.82 L h^{-1} by Kärhä et al. [47••]. Regarding work conditions, it has been shown that fuel consumption is higher on peatland than on mineral soils (+ 1.38 L h^{-1}, [47••]), and it generally increases with driving intensity (i.e. number of passes on the same track [117]).

Fuel Consumption Per m^3

Expressed on a per-product basis, fuel consumption averaged 0.88 L m^{-3} for thinning and 0.69 L m^{-3} for final felling. That exactly matched Brunberg's findings [56] about fuel consumption being 0.2 L m^{-3} lower in final felling than in thinning (Fig. 6). Obviously, fuel consumption per m^3 increased with forwarding distance, and averaged 0.72 L m^{-3}, 0.84 L m^{-3} and 1.00 L m^{-3} for distances of 100 m, 400 m and 800 m, respectively (Fig. 6). Fuel consumption per m^3 also decreased with removal intensity and on mineral soil, where it was 0.11 L m^{-3} lower than on peatlands [47••].

In fact, most of the variables that affect productivity will also impact fuel consumption accordingly: Rukomojnikov et al. [109] reported that harvest tree diameter has a significant effect on fuel consumption in extraction; Nordfjell et al. [54] and Gagliardi et al. [40] showed that fuel consumption is lower when long sawlogs are extracted rather than shorter logs (pulpwood and bolts). Finally, Danilović et al. [100] demonstrated that when payload size increases during extraction, the cubic-metre-based fuel consumption of the forwarder decreases significantly. Eliasson et al. [46••] came to similar conclusions when they demonstrated fuel consumption per cubic meter incurred by large forwarders with payloads of 13–16 t is lower than that of medium-sized forwarders with payloads of 10–13 t. Again, fuel consumption per m^3 was found to increase with forwarding distance, as expected.

Machine settings also have an impact on fuel consumption per m^3 during extraction. Santos et al. [108] found that engine speed had a significant and linear effect on fuel consumption per m^3, for a range of tree volumes between 0.10 and 0.29 m^3, while the effect of pump pressure was significant only for the larger volumes in that range. As for felling-processing, operator technique has a marked effect on fuel consumption and can account for variations in the order of 0.3 L m^{-3}, over distances of between 100 and 500 m [47••]. Over the same range of distances, the maximum variation between the worst and the best operators can reach 60% to

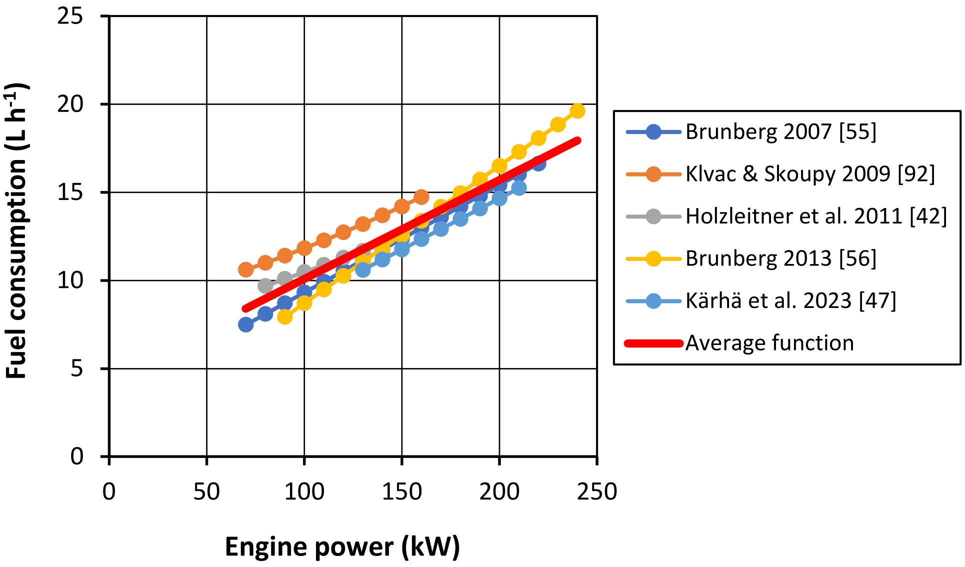

Fig. 5 Fuel consumption in extraction as a function of the engine power of forwarder in those study papers where hourly fuel consumption has been reported in relation to the engine power of forwarder. Also shown is the calculated average fuel consumption function from the review dataset: Fuel consumption (L h^{-1}) = 4.4539 + 0.0562 × Engine power (kW) (Adj. $R^2 = 0.85$; Standard error of the estimate of the model = 1.041; F value = 334, $p < 0.001$)

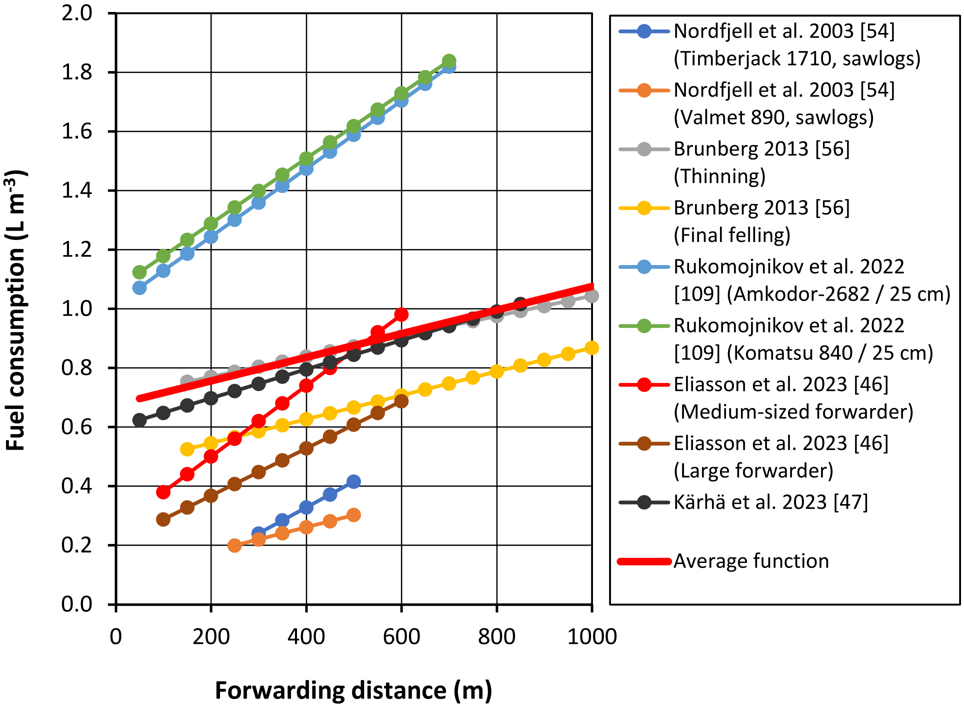

Fig. 6 Fuel consumption in extraction as a function of forwarding distance in those study papers where cubic-metre-based fuel consumption has been reported in relation to forwarding distance. Also shown is the calculated average fuel consumption function from the review dataset: Fuel consumption (L m^{-3}) = 0.6759 + 0.0004 × Forwarding distance (m) (Adj. R^2 = 0.06; Standard error of the estimate of the model = 0.397; F value = 7.8, $p < 0.01$)

68%, while that between those extremes and the general average is estimated at between 21 and 23% [47••].

Entire Wood-Harvesting Chain

The review found only 11 studies where fuel consumption had been estimated for the entire harvesting chain, i.e. fully mechanized felling-processing and extraction (Table 2). Based on those studies, the range of fuel consumption for the entire harvesting chain varied from 1.97–2.75 L m^{-3} for thinning operations, and 1.02–3.04 L m^{-3} for final fellings. The average figures were respectively 2.26 L m^{-3} and 1.57 L m^{-3}.

Labelle and Lemmer [95] reported that fully mechanized CTL harvesting incurs a higher fuel consumption (around 1.11 L m^{-3}) than motor-manual and semi-mechanized harvesting (about 0.91 and 0.85 L m^{-3}, respectively). Oyier and Visser [111] reported an average fuel consumption for ground-based wood-harvesting operations of 2.22 L m^{-3} (ranging from 1.43 to 2.91 L m^{-3}); consumption increased sharply on steep terrain, where it averaged 3.18 L m^{-3} (ranging from 2.35 to 3.98 L m^{-3}).

GHG Emissions

Based on our review of past studies, the CO$_2$ emissions produced during fully mechanized felling-processing averaged 3.62 kg m^{-3} (range from 1.25 to 5.67 kg m^{-3}) in thinning, and 2.56 kg m^{-3} (range from 1.71 to 3.33 kg m^{-3}) in final felling. Zeh [65•] reported similar results with average CO$_2$ emissions for harvester operations of 3.47 kg m^{-3} for thinning and 1.95 kg m^{-3} for final felling. Emissions were lower for extraction and averaged 2.26 kg m^{-3} (ranging from 0.65 to 4.12 kg m^{-3}) for thinning, and 1.95 kg m^{-3} (1.02 to 2.73 kg m^{-3}) for final felling. That matches quite well Grünberg's study [23•], which reports the average CO$_2$ emissions incurred during extraction as 2.60 kg m^{-3} in thinning and 1.81 kg m^{-3} in final felling.

CO$_2$ emissions for the entire harvesting chain averaged 5.71 kg m^{-3} (ranging from 1.89 to 9.30 kg m^{-3}) for thinnings and 4.36 kg m^{-3} (ranging from 1.60 to 10.0 kg m^{-3}) for final fellings. Cosola et al. [21] indicated that the CO$_2$ emissions incurred by fully mechanized CTL harvesting chains were lower in plantation forests (averaged 4.23 kg m^{-3}) than in close-to-nature forests (averaged 6.64 kg m^{-3}). Concerning close-to-nature forestry, Labelle and Lemmer [95] found that CO$_2$ emissions in final fellings were lower for fully mechanized CTL harvesting than for motor-manual and semi-mechanized harvesting (1.60 kg m^{-3} vs. 3.41 and 2.94 kg m^{-3}, respectively), while the contrary is true in thinning operations (3.96 kg m^{-3} vs. 5.17 and 1.64 kg m^{-3}, respectively). In Japan, Nakano et al. [35] found that CO$_2$ emissions in harvesting chain increased linearly with the degree of mechanization. Grünberg [23•] and Zeh [65•] reported that CO$_2$ emissions decreased with increasing machine size, due to the higher productivity of the larger machines.

Global Fuel Consumption and CO_2 Emissions by Fully Mechanized Wood-Harvesting Operations

Considering that the annual amount of industrial roundwood harvested globally with the fully mechanized CTL harvesting method is estimated at 850–900 million m^3, the corresponding fuel consumption and CO_2 emissions can be assessed at about 1.45–1.53 billion L and 3.88–4.11 million t per year, respectively. In those figures, felling and processing accounts for approximately 57% while extraction accounts for the remaining 43%.

Discussion

Data and Methods

The review mapped fuel consumption and CO_2 emissions in the fully mechanized CTL harvesting of industrial roundwood. The review covered 83 scientific papers, reports and articles published in 2000–2023. Among those, 78 documents (94%) determined and/or modeled the fuel consumption incurred by CTL forest machinery. Nine study papers did not determine nor model fuel consumption, but presented expert assumptions used for estimating machine cost. The CO_2 emissions for CTL wood-harvesting operations were directly defined in 33 documents (40%) within the total pool. 32 documents (39%) had been published within the last five years. Thus, the review contained many new papers on fuel consumption and CO_2 emissions, although older ones (2000–2018) were also included. Only study papers published in English, Finnish, German and Swedish were selected for the review. Naturally, there are also articles published in other languages about the fuel consumption and emissions caused by fully mechanized CTL forest machinery, which could not be included in the review because their content was inaccessible to the authors.

The review identified the main drivers of fuel consumption in the fully mechanized CTL harvesting operations of industrial roundwood. The hourly and cubic-metre-based fuel consumption values were successfully estimated, based on the large and comprehensive pool of documents collected with the review. However, it must be stated that not all studies offered a thorough analysis of all the factors affecting fuel consumption, since several documents lacked a detailed description of work conditions and machine characteristics. Therefore, the first lesson learned from this review is that future research should strive to include a comprehensive and accurate description of work conditions and machine characteristics. That would not only facilitate the interpretation of results, but also support replication and meta-analysis. Several good guidelines have been presented for reporting studies on forest operations (e.g. [118, 119]).

All studies that met the criteria following, as set from the start: – 1) the study paper in which the fuel consumption or CO_2 emissions of CTL forest machines were reported and 2) the paper was published in 2000–2023 – were included in the review. It should be noted that the review also included duplicates, i.e. studies that used fuel consumption reported in previously published study papers already included in the review. Duplicate studies were either harvesting cost studies, in which the forest machine cost calculations of industrial roundwood were prepared using a fuel consumption (L h^{-1}) assumption or LCA studies that used a fuel consumption assumption, which was used to calculate CO_2 emissions caused by CTL harvesting operations.

In the review, some LCA study papers did not report accurate CO_2 emissions for CTL harvesting operations but the bars of global warming potential (GWP) or climate change (CC) impact were presented. In the case of these study papers, the share of CO_2 emissions caused by CTL harvesting operations was estimated from the bars presented.

Results

The review produced the average fuel consumption (L h^{-1} & L m^{-3}) and CO_2 emissions for felling-processing and extraction, as well as for the entire harvesting chain in the fully mechanized CTL harvesting operations of industrial roundwood. The review also defined the average fuel consumption functions based on the reported study papers. The review showed that the engine power of CTL forest machines accounts for most of the variance in the hourly fuel consumption of both harvesters and forwarders. Among the machinery-specific independent variables, some other factors (i.e. type of machine, engine speed, hydraulic pump flow rate, use of tracks, operational hours) have also been found to influence the fuel consumption of CTL forest machines. Moreover, the review presented that work technique and conditions (i.e. cutting method, soil type, air temperature) have a significant impact on the hourly fuel consumption of CTL forest machines.

On the basis of the review, it can be underlined that the cubic-metre-based fuel consumption of CTL forest machines is correlated to the same factors that affect work productivity (m^3 h^{-1}). This is logical, because productivity incurs larger variations than hourly fuel consumption, and therefore it becomes a main driver of fuel consumption per product unit. This was also documented by Grünberg [23•] and Zeh [65•]. Among all influencing factors, the average stem size, removal intensity and silvicultural treatment have the strongest effect on the fuel consumption per m^3 incurred with felling-processing, whereas forwarding distance, removal intensity and payload size are the main drivers of fuel consumption per m^3 as incurred with extraction. Further influencing factors are soil type (mineral soil or peatland), use of bogie/wheel tracks, assortment type and machine size. Together with those factors, the role of the machine operator remains crucial and is dependent on two separate skills: the capacity to achieve high productivity, and that to apply fuel-saving driving techniques.

The fuel consumption or CO_2 emissions caused by the fully mechanized CTL harvesting of industrial roundwood have not been previously calculated on a global scale. Our review offered suitable data for such exercise: assuming an annual global harvest of 850–900 million m^3 of industrial roundwood, the fuel consumption of fully mechanized CTL harvesting can be estimated around 1.5 billion L, while the annual CO_2 emissions were estimated at approximately 4.0 million t. However, those figures exclude machine relocation and machine operators' commute to and from harvesting sites, which may have a significant impact, too [47••, 57, 120].

Measures to Reduce Fuel Consumption and CO_2 Emissions in CTL Harvesting Operations

How can the fuel consumption and carbon footprint caused by the fully mechanized CTL harvesting operations of industrial roundwood be reduced in the future? Obviously, there are many possibilities for that. One possibility is to switch CTL forest machines to renewable fuels (biodiesel, biogas) or to electrify them (e.g. [24, 121]). Automation could also make the operations more efficient, thereby saving energy and reducing emissions [65•]. However, Lajunen et al. [122] predicted that forest machines, which require a lot of power and are beyond the reach of fixed charging infrastructure in the forests, will not be electrified within the next few years. Furthermore, Poikela and Ovaskainen [17•] measured that the energy efficiency of a hybrid harvester is not significantly better than that of a traditional harvester equipped with a combustion engine. However, there are possibilities to make the machines more energy efficient by reducing losses in the hydraulic systems and by using hybrid technology [123].

The easiest way to reduce the carbon footprint of CTL harvesting machines is to increase the productivity of the harvesting work, for example by giving machine operator-specific training to utilize more efficient work methods and economic energy-efficient driving techniques [11, 22, 47••, 124]. The positive attitude of forest machine contractors and operators towards fuel and energy efficiency also plays an important role [125]. Several measures can be taken when trying to reduce the carbon footprint of CTL harvesting operations, and a partial list is given below:

- Organizing sufficiently large harvesting sites, with enough standing stock, possibly clustering small lots into larger sales in order to optimize logistics. A large enough sale size allows the use of efficient harvesting machines, while a good standing stock provides for efficient chaining of harvesting sites, which shortens machine relocation distances and reduces relocation time [57].
- Good planning and implementation of the harvesting site. For instance, design and placement of the strip road network and roadside landing areas, landing areas on the lower slope, cutting gentle curves, turning gradually, optimizing payloads during extraction, and minimizing the amount of driving with a loaded forwarder in the stand [19, 22, 47••, 126].
- Improving the forest road network layout. Shorter distances for extracting wood from the harvesting site to the roadside landing area would reduce fuel consumption and emissions [36•, 87, 124, 127].
- Efficient allocation of machinery according to harvesting conditions, i.e. large-sized machines for final felling and smaller-sized machines for thinning [22, 57, 124].
- Improving the harvesting conditions, e.g. if there is dense undergrowth, the stand should be cleaned before harvesting [47••, 128, 129].
- Using suitable machines and equipping machines according to harvesting conditions, e.g. using tracks when needed, and avoiding their use when there is no need for them [19, 47••, 56, 116, 126].
- Good machine maintenance, e.g. greasing, cleaning of radiators and oil cooler, sharpening of delimbing knives etc. [19, 47••, 126].
- Good adjustments in machinery and optimized use of machines, e.g. optimal pressures in the feed rollers of harvester head [38]. Moreover, for instance Santos et al. [86] determined that with the stem volume of 0.16 m^3, the best cutting performance is obtained with an engine speed of 2000 rpm and a hydraulic pump pressure of 300 L min^{-1}.
- Minimizing idling time [19, 22, 124, 126]. For example, Nordfjell et al. [54] reported that fuel consumption at idling is 1.75–2.25 L h^{-1} with forwarders.

Conclusions

This review covered the fuel consumption and CO_2 emissions caused by fully mechanized CTL harvesting operations of industrial roundwood, describing the mean and variation, and the main factors that affect the performance of these variables. In doing so, this study provides insight into the environmental impacts of CTL harvesting operations. In addition, the study scaled these values up and provided a global estimate of fuel consumption and CO_2 emissions from fully mechanized CTL harvesting.

The review showed that the environmental impacts of CTL harvesting operations may be lower than those caused by semi-mechanized harvesting methods or by other industries. Nevertheless, there are still many ways to reduce the carbon footprint of CTL wood-harvesting operations. In order to reduce the carbon footprint of CTL wood-harvesting operations, all actors should play their role, including harvesting machine contractors and operators, forest industries, forest machine manufacturers, forest landowners, and research scientists. More research into the latest CTL harvesting methods and machines' productivity, fuel consumption and GHG emissions will continue to be needed. Digitization and forest machine data with mom/drf files and FMSs offer great opportunities for the collection of big data to support future investigations. On the basis of this review, we recommend that all essential variables that have a significant impact on the productivity of harvesting work, fuel consumption and GHG emissions are reported in study papers in the future.

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Data Availability Data are available from the corresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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- •• Of major importance

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