Journal of Cleaner Production 577 (2026) 149500

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Reducing the idle times of forest machines: A scenario analysis with machine big data in Finland

Jarkko Pesonen [a,*], Topi Rantala [a], Robert Prinz [b], Heikki Ovaskainen [c], Asko Poikela [d], Pertti Kauranen [e], Kalle Kärhä [a]

[a] University of Eastern Finland, School of Forest Sciences, P.O. Box 111, Joensuu, FI-80101, Finland
[b] Natural Resources Institute Finland, Yliopistokatu 6, Joensuu, FI-80100, Finland
[c] Lapland University of Applied Sciences, Jokiväylä 11 C, Rovaniemi, FI-96300, Finland
[d] Metsäteho Oy, Vernissakatu 1, Vantaa, FI-01300, Finland
[e] LUT University, School of Energy Systems, P.O. Box 20, Lappeenranta, FI-53851, Finland

HIGHLIGHTS

- Idling times of harvesters were greater than that of forwarders.
- Reducing idles of forest machines can produce major emission and cost savings.
- Transferring idling into productive working time could produce additional income.

ARTICLE INFO

Keywords:
CO_2 emissions
Forest machine data
Fuel consumption
Idling
Non-road mobile machinery
Wood harvesting

ABSTRACT

The idling of forest machines reduces the energy and cost efficiencies of logging operations. This study aimed to estimate the idle times and fuel consumption during idling using automatically collected machine big data. Furthermore, a scenario approach was used to describe the influence of idle times on the volume and price of carbon dioxide (CO_2) emissions. The dataset included monthly data from 2021 to 2024, covering 10 logging enterprises with a total of 28 harvesters and 23 forwarders. The results showed that the proportion of idle time of harvesters and forwarders regarding the total operating hours was 14.0% and 11.1%, respectively. Average fuel consumption during idling was 4.28 L h^{-1} for harvesters and 3.38 L h^{-1} for forwarders. Annual idle-related CO_2 emissions for wood-harvesting machines in Finland were roughly estimated at around 11,000 metric tonnes (t) with costs equivalent to approximately €50 million. Reduction in idling by 25–50% could cut emissions by around 3000–5000 t CO_2 and generate additional revenue roughly up to €55 million when the reduced idle engine hours were transferred into productive hours. This study concluded that understanding, as well as acknowledging, the influence of idling has a positive impact on energy and cost-efficiencies, while also ensuring more environmentally friendly logging operations. While more research is needed regarding the effects of idling in non-road machinery, this study provides a solid foundation for promoting low emissions non-road machinery operations.

1. Introduction

In 2023, global greenhouse gas (GHG) emissions were 37.4 Gt, driven by a 0.5% annual increase in total emissions over the previous decade (International Energy Agency (IEA), 2024). Since climate change remains a major challenge, the European Union aims to reduce GHG emissions by 55% by 2030 and achieve net-zero emissions by 2050 (Ministry of the Environment, 2024). Consequently, further actions are required from the industry, transport, agriculture, and forestry sectors (European Commission, 2023). However, GHG emissions from diesel-powered machinery are decreasing more slowly due to the levelled-out emission levels (Sparrevik et al., 2023).

* Corresponding author.
E-mail addresses: jarkko.pesonen@uef.fi (J. Pesonen), topi.rantala@uef.fi (T. Rantala), robert.prinz@luke.fi (R. Prinz), heikki.ovaskainen@lapinamk.fi (H. Ovaskainen), asko.poikela@metsateho.fi (A. Poikela), pertti.kauranen@lut.fi (P. Kauranen), kalle.karha@uef.fi (K. Kärhä).

https://doi.org/10.1016/j.jclepro.2026.149500
Received 14 October 2025; Received in revised form 11 September 2026; Accepted 13 September 2026
Available online 17 September 2026

One measure to achieve the EU goals is to maximize the energy efficiency of non-road mobile machinery (NRMM) (Ministry of the Environment, 2024), which includes a wide range of sectors, such as agriculture, forestry, construction, mining, and material handling (Antila et al., 2025). In Finland, for instance, NRMM is responsible for approximately 6% of total GHG emissions, of which 14% originate from forestry machinery (i.e., harvesters and forwarders) (Ministry of the Environment, 2024). Although agricultural and construction machinery are the two largest machinery segments in terms of GHG emissions at the EU-level (Söderena et al., 2024), forest machines play a major role in Finland. For example, in 2024, approximately 4500 harvesters and forwarders were operating in Finnish forests (Saarijärvi, 2024). As such, there is strong interest in optimizing logging operations (i.e., cutting and forest haulage) and the current machinery setup to reduce fuel consumption and carbon dioxide (CO_2) emissions (Prinz et al., 2018).

According to Kärhä et al. (2024), global CO_2 emissions caused by fully mechanized cut-to-length (CTL) forest harvesting are estimated at 4 million metric tonnes (t). Of those, harvesters are responsible for approximately 57% and forwarders for 43% (Kärhä et al., 2024). In 2022, the total harvesting volume of industrial roundwood in Finland was around 68 million cubic meters (m^3) (Natural Resources Institute Finland, 2025), which produced approximately 300,000 t CO_2 (Poikela and Strandström, 2023). This corresponded to a total of 120.7 million liters (L) of fuel used to conduct logging operations (Poikela and Strandström, 2023). Furthermore, the total costs of the logging operations of industrial roundwood in Finland were around €640 million in 2023 (Strandström, 2025). Fuel costs, on the other hand, are responsible for approximately 10% of total logging costs (Statistics Finland, 2023).

According to Ringdahl et al. (2012), idling of forest machines is responsible for approximately 20% of total fuel consumption, which lowers the profitability of the logging operations and also delays the emission reduction goals set by EU (European Commission, 2023). Currently, there are several ways to enhance the energy efficiency of forest machines (Auvinen et al., 2025). Firstly, an increase in the price of fossil fuels would promote low-emission alternative solutions, thereby allowing exploitation of the energy efficiency benefits of such solutions (Söderena et al., 2024). Secondly, improved utilization and resource efficiency would result in cost and emissions savings (Auvinen et al., 2025), which would reduce the need for new machines, since the utilization rate of a single machine would increase. Thirdly, electrification could improve efficiency due to improved power adjustment, although implementation with forest machines is a challenge, especially in Finland (Antila et al., 2025; Pesonen et al., 2025a).

The undergoing development of Fleet Management Systems (FMS) enables accurate data collection from the logging operation and environment (Ovaskainen and Kivilinna-Korhola, 2016). Hence, the setting parameters of forest machines can be optimized (Prinz et al., 2018) or forest machines can be allocated based on the operational environment, such as soil conditions, for greater efficiency (Grigorev et al., 2020; Haavikko et al., 2022). The minimization of idling, which can be described as needless engine running time (Menzies, 2005; Haavikko et al., 2019), is also an option to improve efficiency, while also reducing fuel consumption and CO_2 emissions (Mercier and Makkonen, 2004; Amishev, 2010; Ghaffariyan et al., 2018).

Idling also has other negative effects; it eventually wears out the engine by increasing the engine running hours (Mollenhauer and Tschöke, 2010; Molari et al., 2019). Moreover, the increased operating hours caused by unnecessary idling lowers the exchange value of the machine significantly (Viitamäki et al., 2015). A greater number of operating hours also leads to more frequent maintenance periods (Shancita et al., 2014). In addition, diesel particulate filters, diesel oxidation catalysts, and selective catalytic reduction do not operate optimally during periods of idling due to the lower engine temperature (Michelin et al., 2000; Mollenhauer and Tschöke, 2010; Wihersaari, 2015). Consequently, the forest machine manufacturer Ponsse (2025) has recommended that their forest machines be regularly maintained at intervals of 900 machine hours.

To date, research concerning idling has mainly focused on relatively small machine-generated datasets. For instance, in the example calculation by Viklund (2012), the proportion of idle time of one harvester operating in Sweden was 22%, whereas the follow-up study by Polowy and Molińska-Glura (2023) indicated slightly lower idle times of approximately 15% in two harvesters that operated nearly four months in Poland. Moreover, Molari et al. (2019) found in their two-month follow-up study on an agricultural tractor that around two thirds of all idling was unnecessary. A few previous studies have also examined idling using survey methods. For instance, Pesonen et al. (2025b) recently highlighted that every fourth logging company in Finland is aware of the idle times of their fleet, and more than 50% of logging enterprises would prefer idle times to be $< 5\%$. Moreover, Haavikko et al. (2019) reported that 60% of logging entrepreneurs consider idling as a significant factor in improving the energy-efficiency of logging operations. However, according to Pesonen et al. (2025b), only 5% of logging entrepreneurs have used incentives for operators to promote idle time reduction in their enterprises.

The data obtained from machines is extremely valuable for establishing a baseline and for strengthening the knowledge base required to meet the national and global emissions reduction targets (Ministry of the Environment, 2024). In addition, assessing the broader impacts of idling, such as at the national level, necessitates data collected from dozens of machines. Nowadays, the FMS of forest machines allow accurate and continuous monitoring of various parameters, which include engine running time, fuel consumption, and other factors that influence logging operations (Ovaskainen and Kivilinna-Korhola, 2016). Consequently, the aim of this study was to examine the effects of machinery type (i.e., harvesters and forwarders), logging enterprises, and seasonal variation on idle times, based on machine big data (Fig. 1). Furthermore, we aimed to describe the effect of seasonal variation on the fuel consumption of forest machines during idling. Ultimately, we used a scenario analysis to highlight the effects of idling on CO_2 emissions and the price of CO_2 (€ t CO_2^{-1}).

2. Materials and methods

2.1. Data collection

Data of this study originated from the same machine manufacturer, who aggregated the second-by-second data recorded by forest machines into monthly data. The data were collected from 10 logging enterprises between May 2021 and April 2024. A non-disclosure agreement (NDA) was signed between the authors, machine manufacturer, and enterprises. The data included a total of 28 harvesters and 23 forwarders, and data collection involved machine data from harvesters for a combined 668 months, and from forwarders for a combined 632 months (Table 1). The number of data collection months for each harvester and forwarder are presented in Appendix A. Most enterprises also operated with forest machines from other manufacturers. Appendix B presents the total number of forest machines and the annual volumes of the enterprises included in this study.

During the period of interest, the controller area network (CAN-Bus) of each machine had transmitted up-to-date data from the operation to a cloud server. This data were then downloaded and delivered for this study by machine manufacturer. Data collection months for which the harvesting volumes and number of stems were missing for harvesters as well as months lacking operating hours for machinery at the beginning or at the end of data collection month were excluded from the dataset. Furthermore, each enterprise was contacted via phone in early 2024 for additional information, such as whether the enterprise had previously focused on reducing idling times. A total of six enterprises noted that they had been initiative on examining their idle times based on FMS data, and also giving their operators instructions to avoid unnecessary idling (Table 1).

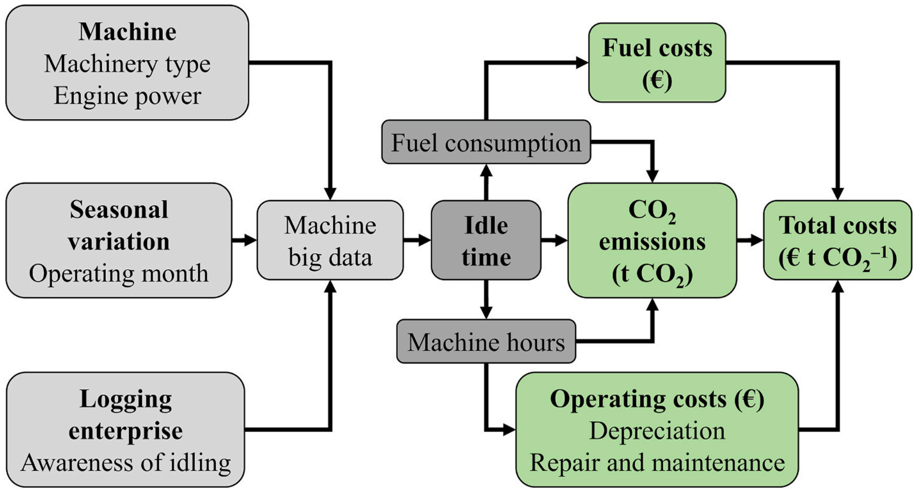

Fig. 1. Effects of different variables on idle times based on machine big data.

Table 1
Number of enterprises (A–J) and forest machines, as well as data collection months in the study. Enterprises marked with an asterisk had previously focused on idling. The total number of forest machines and the annual volumes of the enterprises included in this study are presented in Appendix B.

Enterprise code	Harvesters	Forwarders	Total
	Number of machines [Number of observation months]		
A	1 [29]	1 [30]	2 [59]
B*	1 [30]	1 [36]	2 [66]
C*	3 [89]	4 [81]	7 [170]
D	6 [147]	5 [157]	11 [304]
E*	5 [105]	4 [99]	9 [204]
F	1 [12]	1 [36]	2 [48]
G*	4 [92]	3 [89]	7 [181]
H*	5 [104]	3 [68]	8 [172]
I*	2 [60]	-	2[60]
J	-	1 [36]	1 [36]
Total	28 [668]	23 [632]	51 [1300]

The final data included factors, such as machine model, manufacture date, serial number, engine hours at the beginning and at the end of the data collection period, and the volume of fuel consumed. The operating hours and fuel consumed were automatically classified into four categories: *Idle*, *Low load*, *Medium load*, *High load*, although the specific load thresholds used for this classification remained undisclosed. Furthermore, enterprise code, data collection month, total timber volumes (m^3), and removals (number of stems) were also acquired from the enterprises. The data lacked the volume of timber hauled by forwarders; thus, those values remained undetermined.

2.2. Data description

The manufacture year of harvesters varied between 2014 and 2024 (median: 2021) and of forwarders between 2012 and 2024 (median: 2020) (Appendix A). The average engine hours at the beginning of the data collection period for harvesters were 6872 h, and the engine power varied between 145 kW and 200 kW (median: 163 kW). For forwarders, the average engine hours at the beginning of data collection were 6796 h, and the engine power was between 131 kW and 200 kW (median: 156 kW).

The total harvesting volume was 2.4 million m^3 and the number of stems was around 12.5 million (average stem size: 0.191 m^3). Annual fuel consumption averaged 834,786 L by harvesters (30,135 L harvester^{-1}) and 583,511 L by forwarders (25,370 L forwarder^{-1}). The total annual engine running times of harvesters and forwarders were 51,022 h and 45,240 h, respectively. Machine-specific harvesting volume, fuel consumption, and engine running hours are presented in Appendix A.

2.3. Scenario analysis

According to de Ruijter (2014) and Chermack et al. (2026), scenarios are tools for navigating future visions in terms of decision-making and strategies amidst uncertainties, without trying to predict the future. In this study, the impacts of idling on CO_2 emissions and operating costs were examined by comparing current CO_2 emissions and operating costs (i.e., business as usual) (Scenario 1: BAU) to four alternative scenarios. In Scenario 2, idle times were reduced by 25% (Scenario 2: −25) and in Scenario 3 by 50% (Scenario 3: −50), while the productive hours were assumed to remain the same in both scenarios. In Scenarios 4 and 5, it was assumed that all reduced idle times would transfer into productive hours, thus increasing the productive hourly rates. In Scenario 4, idle times decreased by 25% (Scenario 4: −25_PH) and in Scenario 5 by 50% (Scenario 5: −50_PH) (Table 2).

When determining CO_2 emissions, a coefficient of 2.44 kg CO_2 L^{-1} was applied (Statistics Finland, 2025a). Furthermore, the average annual cutting volume in Finland (66.8 million m^3) was used for the CO_2 emission calculations, which was based on reported annual volumes during the past five years (Natural Resources Institute Finland, 2025).

For the machine cost calculations, the machine cost model automatically calculated annual harvesting volumes, which were based on the operating hours and level of productivity used (Appendix C). It was assumed that 60% of the total harvesting volume originated from final fellings, and the remaining 40% from thinnings. Total operating hours, idling times, annual harvesting volumes, depreciation (i.e., decrement of the exchange value of the machine), and total operating costs within the different scenarios are presented in Appendix D. A detailed description of the other machine cost calculation parameters is presented in Appendix C. The operating hours and idle engine hours within the

Table 2
Proportional changes (%) of idling times within each alternative scenario compared to the business as usual (BAU) scenario. In Scenarios 2 and 3, the productive hours were assumed to be the same as in BAU. In Scenarios 4 and 5, the reduced idle times were assumed to transfer into productive working hours.

	Idling time reduction (%)	Increment of productive hours
Scenario 1: (BAU)	0	No
Scenario 2: (−25)	−25	No
Scenario 3: (−50)	−50	No
Scenario 4: (−25_PH)	−25	By reduced idle times
Scenario 5: (−50_PH)	−50	By reduced idle times

different scenarios were calculated with Equations (1) and (2):

$$H_{Idle} = H_{BAU} \times P_{Idle} \times P_{Reduction} \quad (1)$$

where H_{Idle} is the number of idle engine hours, H_{BAU} is the total operating hours in the BAU scenario, P_{Idle} is the proportion of idling time, and $P_{Reduction}$ is the proportion of reduced idling time.

$$H_{Scenario} = H_{BAU} + H_{Idle} \quad (2)$$

where $H_{Scenario}$ is the operating hours of each scenario, H_{BAU} is the operating hours in the BAU scenario, and H_{Idle} is the number of idle engine hours.

2.4. Data analysis

The data were not normally distributed ($p < 0.05$), Kolmogorov-Smirnov (K-S) test). Therefore, non-parametrical tests, such as Kruskal-Wallis (K-W) one-way ANOVA and Mann-Whitney (M-W) U tests were used for statistical analyses. The significance of statistical values was evaluated at the 95% confidence level ($p < 0.05$).

Monthly, enterprise and machine type-specific proportion of idling times were calculated by first summing the idle times of all machines in each enterprise and then dividing the sum by the total operating hours of all machines in each enterprise during the period of interest. The data also allowed us to calculate the total and idle-related average hourly and cubic meter-based fuel consumption values: hourly fuel consumption was calculated by dividing the amount of fuel consumed (L) by the engine running hours (h). Moreover, cubic meter-based fuel consumption was calculated by dividing fuel consumption (L) by the total harvested volume (m^3).

For CO_2 emissions and cost assessment, machine-specific CO_2 emissions, fuel costs, repair and service costs, and depreciation were estimated for both harvesters and forwarders within the BAU scenario. The values observed in this scenario were then compared to other scenarios by estimating the emissions, fuel and cost savings with either a 25% or 50% reduction in idling time. In Scenarios 4 and 5, (Table 2), possible revenues (i.e., income from increased productive hours compared to the costs of the remaining proportion of idling) were also mapped by multiplying the increment of harvesting volume by the cubic meter-based operating cost.

To illustrate the country-wide impact of idling on CO_2 emissions, costs, and revenues, we used the latest published statistics by Natural Resources Institute Finland (2026) to describe the number of forest machines operating in Finland and rounded those values to the nearest hundred; on average, a total of 1937 harvesters (std: 83.2) and 1914 forwarders (std: 77.2) were operating in Finland during 2020–2024. Therefore, machine-specific values obtained in this study were multiplied by 1900 for both machinery types, a value with statistical uncertainties that roughly represents the total number of harvesters and forwarders operating in Finland (Koneyrittäjät, 2025).

3. Results

3.1. Proportion of idle times

The average annual idle time of a single harvester was 253 h, which represented 14.0% of the total engine running hours. The average annual idle time of each forwarder was 223 h, which accounted for 11.1% of the total engine running hours. The standard deviation (std) was higher with harvesters (std: 5.5%) than with forwarders (std: 3.2%). A statistically significant difference was observed between harvesters and forwarders with regard to idle times (M-W, $p < 0.001$).

3.2. Enterprise-specific idle times

The greatest proportion of harvester idle times was observed with enterprise A (18.8%) (std: 2.8%) and the lowest with enterprise B (5.5%) (std: 1.1%) (Fig. 2). For forwarders, the greatest proportion of idle times occurred with enterprise J (13.3%) (std: 2.5%) and the lowest with enterprise B (7.6%) (std: 1.2%). Statistically significant differences were observed between enterprises in the idle times of harvesters and forwarders (K-W, $p < 0.001$).

For the six enterprises that had previously focused on idling, average idle times of harvesters and forwarders were 13.1% and 9.9%, respectively. In contrast, average idling times of harvesters and forwarders were 13.5% and 12.1% for the remaining four enterprises, who had not focused on idling. A statistically significant difference occurred between the enterprises that had focused on idling and those that had not (harvesters: M-W, $p < 0.05$, forwarders: M-W, $p < 0.001$).

3.2.1. Seasonal variation

The monthly idling times of harvesters and forwarders varied approximately by 3–4% units during the year. The greatest proportions of idling times were observed during the winter months (November–February) for both harvesters and forwarders (std: 3.1–5.8% units) (Fig. 3). Statistically significant differences between operational months were found between the idle times of harvesters and forwarders (K-W, $p < 0.001$).

3.2.2. Idling fuel consumption

On average, total annual fuel consumption during idling was 1093 L and 734 L for each harvester and forwarder, respectively. The proportion of fuel consumed during idling (of the total amount of fuel consumed) was 3.6% by harvesters and 2.9% by forwarders. The average hourly fuel consumption of harvesters during idling was 4.28 L h^{-1} (std: 0.92) and 3.38 L h^{-1} (std: 0.61) for forwarders (Fig. 4). A statistically significant difference was observed between the hourly idling fuel consumption of harvesters and forwarders (M-W, $p < 0.001$). The variation in the engine power of the machines within different months was non-significant (K-W, $p = 0.250$). The highest hourly idling fuel consumption was recorded in December for both harvesters (4.36 L h^{-1}) and forwarders (3.51 L h^{-1}). The lowest hourly idling fuel consumption was observed in May for harvesters (4.19 L h^{-1}; std: 0.96) and in June for forwarders (3.22 L h^{-1}; std: 0.61). No statistically significant differences were found between the operational months (harvesters: K-W, $p = 0.975$, forwarders: K-W, $p = 0.161$).

3.2.3. CO_2 emissions

Based on the assumption that the annual total harvesting volume in Finland is 66.8 million m^3 (Natural Resources Institute Finland, 2025), an illustrative national-level extrapolation estimated the total annual CO_2 emissions caused by idling approximately 11,000 t (0.16 kg CO_2 m^{-3}) (Scenario 1: BAU). If idling were reduced by 25% for both harvesters and forwarders (Scenario 2: −25), exemplifying emission savings could be around 3000 t CO_2 (0.04 kg CO_2 m^{-3}). Correspondingly, reduction of idling by 50% (Scenario 3: −50) could reduce CO_2 emissions by approximately 5000 t CO_2 (0.08 kg CO_2 m^{-3}) compared to BAU. If the reduced idle time was transferred into productive working time (Scenario 4: −25_PH; Scenario 5: −50_PH), CO_2 emissions from harvesters and forwarders could roughly increase by 8000 and 15,000 t CO_2 (0.11–0.23 kg CO_2 m^{-3}), respectively.

3.2.4. Costs and revenues

When assuming that the total number of both harvesters and forwarders is 1900 in Finland, the total annual costs caused by idling in the BAU scenario were approximately €50 million. Of these illustrative costs, service and maintenance accounted for 28% (€15 million), depreciation for 62% (€30 million), and fuel costs for 10% (€5 million) (Fig. 5). Consequently, an idle time reduction of 25% (Scenario 2: −25) could yield cost savings of approximately €10 million, and a reduction of 50% (Scenario 3: −50) could produce approximately €25 million in cost savings compared to BAU. Within Scenarios 4 (−25_PH) and 5

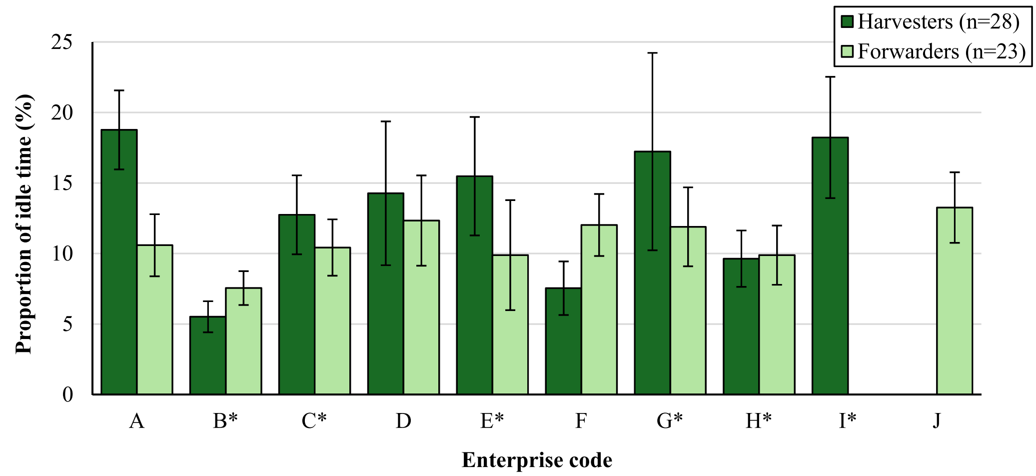

Fig. 2. Enterprise-specific idle times of harvesters and forwarders. Error bars represent the standard deviation of monthly idle times within different enterprises. The values are weighted by total operating hours of the month under review. Enterprises marked with an asterisk had previously focused on idling.

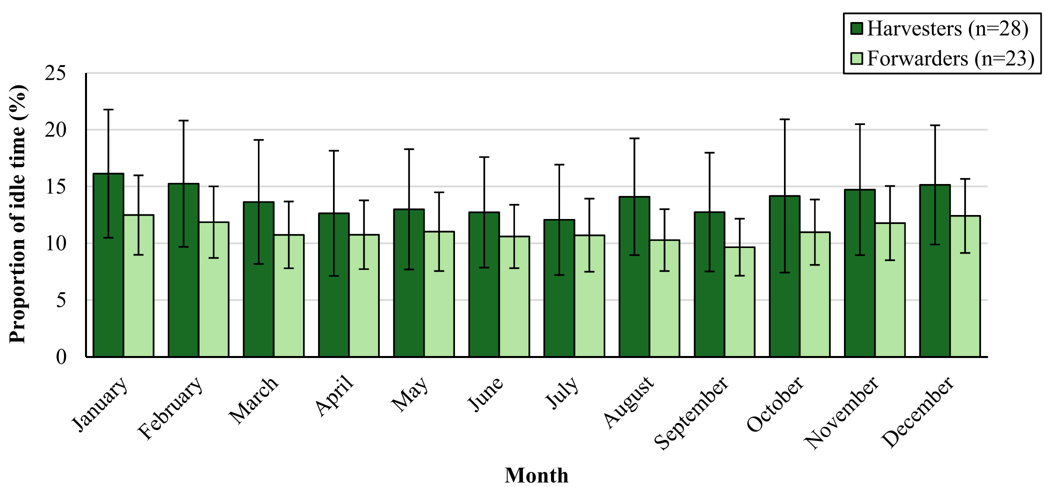

Fig. 3. Monthly average idle times of harvesters and forwarders. Error bars represent the standard deviation. The values are weighted by total operating hours of the month under review.

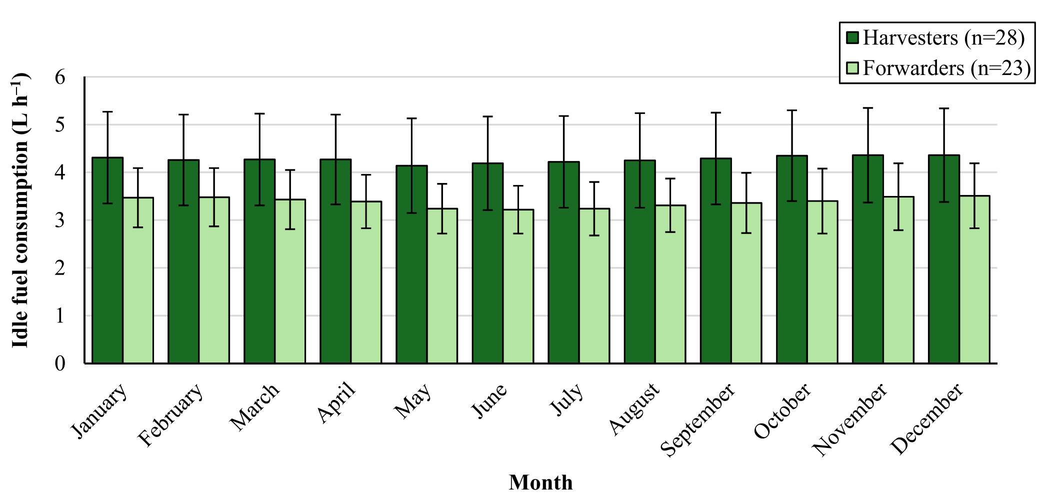

Fig. 4. Monthly average idle fuel consumption (L h^{-1}) of harvesters and forwarders. Error bars represent the standard deviation.

(−50_PH), converting idle time into productive working hours could generate substantial revenues; reduction in idling by 25–50% could

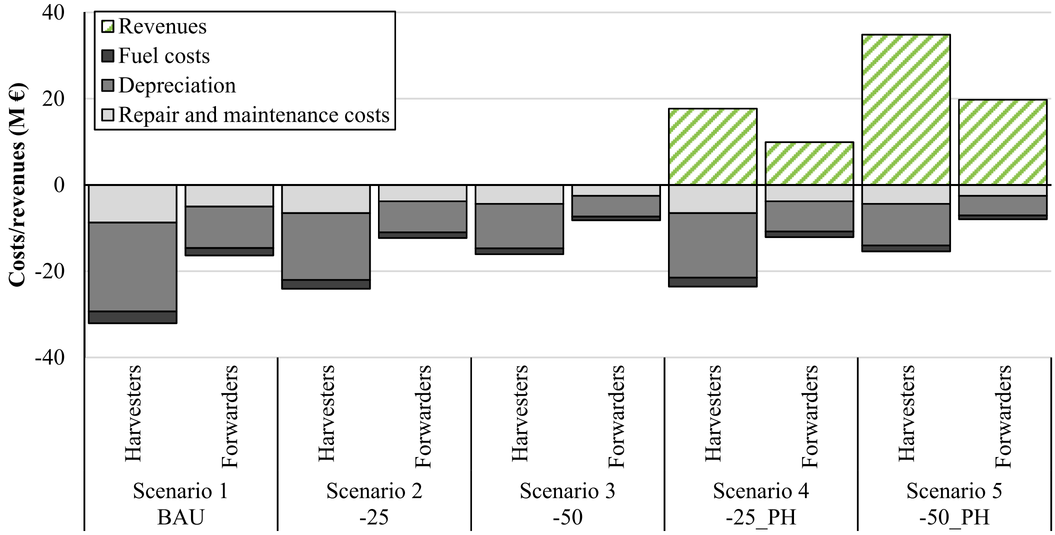

Fig. 5. Depicted estimates of the costs and revenues (million €) caused by idling in the scenario analysis. The values presented are only illustrative due to statistical uncertainties in national extrapolation. Within Scenarios 4 (−25_PH) and 5 (−50_PH), reduced idling was assumed to transfer into productive working hours.

result in annual revenues of roughly €30–55 million (Fig. 5).

4. Discussion

4.1. Interpretation of materials and methods

Previously, idling times have been in the scope of the research less exhaustively, although Pesonen et al. (2025b) recently investigated idling times of forest machines and timber trucks based on survey data. Furthermore, no such extensive long-term follow-up study focusing on the idling times of forest machines has been conducted based on automatically collected data. Consequently, the dataset of this study was sufficient for illustrating the overall effects of idling on CO_2 emissions and operating costs at the Finnish level.

Given the relatively long-term data collection period in this study, we were able to include information from a wide range of working conditions and operators, thereby improving the credibility of the dataset (Eriksson and Lindroos, 2014). Regional differences with regard to idling, however, were difficult to detect given the number of logging enterprises involved in this study. Nevertheless, the entrepreneurs that participated in this study had fleet sizes that varied from one to eleven machines (Table 1). It could be assumed that the overall benefits of reduced idling periods are greater for large enterprises than for small enterprises, since the costs of idling accumulate with the number of machines and operators. However, in this study, the proportions of idling times were almost at the same level regardless of the number of machines (Fig. 6). Nevertheless, none of the operators were aware of this study and thus, the influence of their attitudes (i.e., Hawthorne effect) on idle times can be disregarded (Magagnotti et al., 2012).

The dataset used in this study was relatively large compared to previous studies. For instance, Jylhä et al. (2019) examined the productivity of logging operations with 23 harvesters, while Rieppo and Örn (2003) examined the fuel consumption of 20 harvesters and 14 forwarders. Kärhä et al. (2023) explored the fuel consumption of 16 harvesters and 13 forwarders, while Polowy and Molińska-Glura (2023) studied the idle times of two harvesters operating in Poland. However,

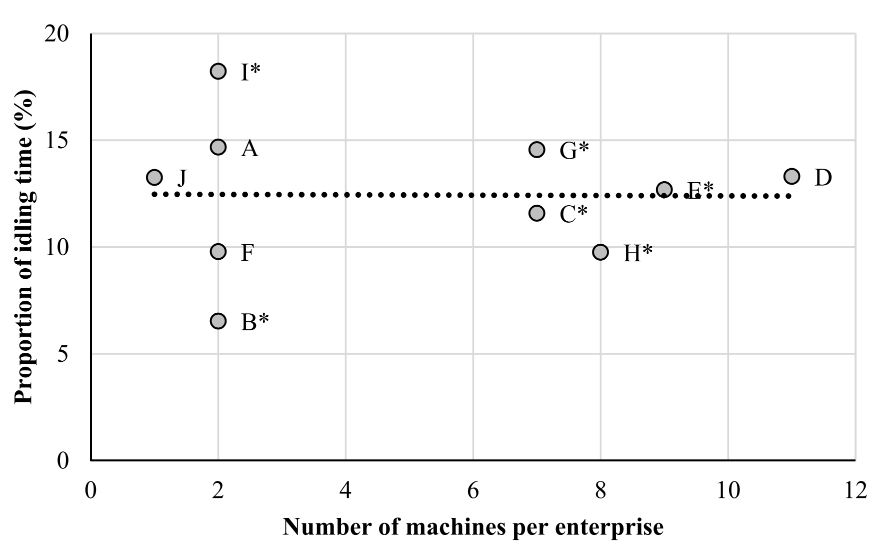

Fig. 6. Scatterplot of the proportion of idling time in different enterprises based on the number of machines. The values are weighted by total operating hours of the month under review. Enterprises marked with an asterisk had previously focused on idling.

idling studies based on automatically collected machine data have been studied less and with limited data. Small datasets could expose measurement errors in the data, which Giechaskiel et al. (2018) reported to be around ±10%. However, we believe that the FMS of novel forest machines (i.e., less than five years old), which comprised most of our data, provide more precise and relevant data, especially concerning fuel consumption.

The scenario analysis, which is usually used for building future visions (de Ruijter, 2014; Chermack et al., 2026), allowed us to highlight potential emissions and cost savings under a range of idling levels (cf. Table 2). According to Pesonen et al. (2025b), logging entrepreneurs consider an idle time reduction in the range of 25–50% as possible. In the scenario analysis of this study, similar range of idling time reduction were focused. It should be noted that the cost calculations were based on predefined, assumed cost parameters and input values, which in turn may lead to differences when compared to, for instance, a specific machine cost calculation for a single machine or entrepreneur. For instance, the cubic meter-based operating costs, which were outcomes from our calculations with predefined values (see Appendix D), were slightly lower than the values presented by Strandström (2025) who reported cubic meter-based operating costs of logging operations of €13.59 m^{-3}. Moreover, it is a challenge to estimate the exact proportion of the actual productive working time increment due to reduced idling. In Scenarios 4 and 5, however, we assumed that all the reduced idling was transferred into productive working hours (cf. Table 2).

4.2. Uncertainty and limitations of national extrapolation

The national-level estimates used in CO_2 emission and cost calculations included some uncertainties related to both the assumed machine population in Finland and the representativeness of the dataset of this study. For instance, the latest reported statistics regarding the number of forest machines only extended to year 2024 (Natural Resources Institute Finland, 2026). Therefore, the extrapolation factor of 1900 for both machinery types were calculated from the average number of forest machines operating in Finland in 2020–2024 and then rounded to the nearest hundred. However, the limitations emerged from including machines from only one forest machine manufacturer and ten voluntary enterprises may have influenced the national-level estimations before the extrapolation. However, the manufacturer involved in this study was one of the largest global CTL forest machine manufacturers. Nevertheless, the extrapolation factor as well as the estimates on national-level CO_2 emissions and costs caused by idling should be regarded as illustrative values rather than definitive values.

4.3. Interpretation of the main results

In this study, the idle times of harvesters and forwarders averaged 14.0% and 11.1%, respectively, which were slightly lower than the 14.7% proportion measured for two harvesters operating in Poland (Polowy and Molińska-Glura, 2023). However, logging entrepreneurs tend to underestimate the idle times of their fleet. For instance, Pesonen et al. (2025b) reported that 75% of logging entrepreneurs estimated the idle times of their fleet to be less than 10% of the total operating time. In our study, idle times of less than 10% were observed less frequently: average idle times of harvesters and forwarders were less than 10% in only three of the ten enterprises (Fig. 2).

With regard to the impact of seasonal variation, the idle times in this study were on average 2% higher during wintertime than summertime (Fig. 3). The reason for the greater proportion of idling during wintertime may be the need to heat the cabin of the machine, as well as to keep the oil flowing through the engine while the machine is stationary. In contrast, idling during summertime may occur due to cooling activities (Rahman et al., 2013). However, we discovered that season had only a minor influence on the hourly fuel consumption during idling: during wintertime, the hourly fuel consumption when idling was approximately 3–7% units higher than in summertime (Fig. 4). Furthermore, the results indicated that fuel consumption of harvesters during idling was approximately 21% greater during the year than that of forwarders, which corresponds to Kärhä et al. (2023), who reported that hourly fuel consumption of harvesters was approximately 28% greater than that of forwarders.

The illustrative estimations presented in this study showed that reducing idling by 25–50% could result in major emissions savings. As scenarios 4 and 5 of this study indicated, converting idling time into productive working time could increase CO_2 emissions, since fuel consumption during productive working time is approximately quadruple compared to idling fuel consumption. However, while the amount of wood harvested would also increase, CO_2 emissions per cubic meter could remain at the same level, which are reportedly around 2.0–3.5 kg CO_2 m^{-3} over bark (Kärhä et al., 2023; Kaulen et al., 2024).

In addition to CO_2 emissions, idling has a major impact on operating costs. As depicted above, depreciation and repair/maintenance costs were determined as two of the factors most relevant to the operating costs of the machines (cf. Fig. 5). These are strongly associated with operating hours; as unnecessary engine running time is decreased, the need for maintenance occurs less frequently, and thus extends the life cycle of the machine. Our scenario analysis also illustrated that a decrease in idling time could increase the number of productive working hours, which could raise revenue and profitability of the operation. For instance, our estimations emphasized that when idling was reduced by 25% and the idling hours were converted into productive hours, the annual revenue was estimated at approximately €30 million for cutting and forest haulage in Finland (cf. Fig. 5). For each of the around 1900 actively operating forest machines in Finland (Koneyrittäjät, 2025), this could mean a revenue of approximately €15,000 annually.

According to Kärhä et al. (2024), the global amount of annually harvested industrial roundwood is approximately 875 million m^3. Hence, reducing idling times globally would generate major cost and emissions savings, as well as productivity increments. However, it is extremely difficult to remove all idling phases from forest operations, as operating conditions, such as air temperature or size of the harvesting site, vary between countries, and thus affect the potential to reduce idling in different parts of the world. Furthermore, the total absence of idling could even be detrimental to operations, as some idling is needed to ensure the performance of the machines and the comfort of the driver (Rahman et al., 2013; Pesonen et al., 2025b). Forest machine manufacturers may also recommend running the machine at idle for some time after operations to allow the engine to cool down sufficiently. Nevertheless, this study illustrated that even a small reduction in idling phases can be profitable if transferred into productive working hours.

4.4. Increasing the focus on idling

Since the machine operator has a significant effect on efficient operations (Rutty et al., 2013; Haavikko et al., 2022; Kärhä et al., 2024), we recommend that future operator training is expanded to also cover the effects of idling. This may be beneficial even though the skills acquired by simulator training most likely differ from the actual working environment (Burk et al., 2024). Nevertheless, the attitudes, motivation, and working methods are largely based on education and knowledge (Haavikko et al., 2019). Therefore, training should be from the entrepreneurs' point of view and applied to each operator (Kavanagh and Ashkanasy, 2006).

In addition to operator training, comprehensive planning of forest operations is crucial (Haavikko et al., 2022). Within the wood harvesting chain, delays occur and miscellaneous working times are an inherent feature (Nurminen et al., 2006; Kärhä et al., 2018a; Hildt et al., 2020). Unproductive working hours may occur due to challenging operating conditions or in harvesting sites with abundant undergrowth. Since high-quality forest management is one of the key factors that drive efficient operations (Kärhä et al., 2023), thorough planning can save time and reduce idling. Indeed, logging entrepreneurs consider that the time used for planning during the operation should be minimized to maximize efficiency (Pesonen et al., 2025b).

Although several studies have highlighted ways to improve the efficiency of logging operations (e.g., Prinz et al., 2018; Haavikko et al., 2022; Kärhä et al., 2023), there are still research gaps and a need for research information. One possible step to reduce the impact of idling periods may be stop-and-go systems, which already exist in timber trucks (Volvo Trucks, 2017), and could be a possible innovation in the future with forest machines. However, especially in Nordic countries, their application in forest machines is currently limited by, among other things, frequent cold starts caused by harsh operating conditions, and safety issues due to automatic shutdowns. These challenges could be mitigated through, for instance, electrifying auxiliary systems, more robust batteries and starter systems, as well as with hybrid powertrains, which would improve reliability and safety of the operations. While Pesonen et al. (2025b) highlighted several operational phases where idling could be reduced during logging operations, this study has shown that the effects of lower idle times are noticeable. Therefore, we recommend further investigation of the potential to reduce idling in other NRMM, as well as in road transport fleets in the future.

5. Conclusions

In this study, the idle times of harvesters and forwarders were examined based on machine big data. The results showed that the proportion of idle time of harvesters was approximately 3% greater than that of forwarders. It was also observed that the individual operators within different enterprises had a greater impact on the proportion of idle time than seasonal variation; the largest difference in the average proportion of idle time of harvesters and forwarders across enterprises was approximately 9%, whereas idle times were found to be approximately 2% higher during wintertime than during summertime. Therefore, the interest in reducing idling should be increased within forest enterprises to accelerate environmentally friendly and efficient harvesting operations.

This study also estimated the impact of idling on CO_2 emissions and operating costs with different scenarios, although the scenario analysis included some statistical uncertainties in the national extrapolation. Nevertheless, it was depicted that the total annual CO_2 emissions caused by idling exceeded 10,000 t CO_2 in Finland, whereas the total costs caused by idling were over €50 million. Based on the scenario analysis, it was found that reducing idling could result in major emission savings, also enabling possibilities for additional annual revenues. However, to gain benefits from lower idle times, the ability of the operators to incorporate more efficient working methods must be improved through operator training. A comprehensive understanding of the impacts of idling and ways to control these impacts, combined with appropriate working techniques and attitudes, would result in efficiency improvements and cost savings, while also bringing forest machines one step closer to environmentally friendly harvesting operations. If the actions towards lower idle times were extended to the entire NRMM fleet globally, the results would be even more promising. Nevertheless, while this is still a work in progress, this study strengthened the foundation for low-emissions and efficient NRMM operations in the future.

CRediT authorship contribution statement

Jarkko Pesonen: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Topi Rantala:** Formal analysis, Data curation, Conceptualization. **Robert Prinz:** Writing – review & editing, Supervision. **Heikki Ovaskainen:** Writing – review & editing, Supervision. **Asko Poikela:** Writing – review & editing. **Pertti Kauranen:** Writing – review & editing. **Kalle Kärhä:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Funding

This study was funded by ACE EU Life project (grant number 101104613 for LIFE-IPC-FI-ACE LIFE).

Declaration of competing interest

The authors declare that they have no known financial interests or personal relationships that could have influenced the work reported in this study.

Appendix A

Characteristics of the machines involved in this study and their engine running hours, fuel consumption, and harvesting volume during the data collection period.

Machine ID	Year of manufacture	Engine power (kW)	Data collection period (months)	Engine running hours (h)	Fuel consumption (L)	Harvesting volume (m^3)
Harvesters						
1	2014	170	30	4630	69,699	39,005
2	2015	145	12	1464	22,309	16,675
3	2016	145	30	5178	74,958	58,177
4	2018	155	30	6706	98,924	79,856
5	2018	200	29	6291	102,696	115,564
6	2019	155	31	8969	142,992	86,750
7	2019	200	36	9701	175,200	126,504
8	2019	200	36	6291	96,895	122,291
9	2019	200	36	10,007	158,202	115,815
10	2020	155	30	8949	139,798	77,292
11	2020	200	30	3687	75,870	83,412
12	2020	200	30	7341	132,430	232,101
13	2021	155	29	6738	109,962	107,393
14	2021	155	28	6376	119,469	100,854
15	2021	155	30	6162	87,957	84,765
16	2021	155	30	7528	129,691	82,903
17	2021	200	36	9116	161,686	237,784
18	2022	155	18	4977	79,088	55,547

(*continued on next page*)

(*continued*)

Machine ID	Year of manufacture	Engine power (kW)	Data collection period (months)	Engine running hours (h)	Fuel consumption (L)	Harvesting volume (m^3)
19	2022	155	21	4840	76,723	73,980
20	2022	200	20	3909	60,048	73,592
21	2022	200	23	5967	99,735	141,583
22	2022	200	25	7010	126,134	111,227
23	2023	155	12	2464	37,142	32,621
24	2023	155	7	1632	26,945	27,812
25	2023	200	12	2125	37,844	69,891
26	2023	200	12	3706	66,564	46,912
27	2024	155	1	320	6301	7827
28	2024	200	4	983	16,094	12,679
Forwarders						
29	2012	136	30	7483	89,789	.
30	2014	136	30	7748	106,175	.
31	2016	156	36	5234	59,223	.
32	2017	156	36	6701	104,610	.
33	2019	145	33	5686	74,351	.
34	2019	164	25	5390	75,031	.
35	2019	164	36	10,323	124,806	.
36	2019	200	29	6380	94,610	.
37	2020	145	36	4360	63,282	.
38	2020	156	32	8270	106,404	.
39	2020	156	36	9485	129,037	.
40	2020	164	36	5038	78,725	.
41	2021	131	36	7896	85,530	.
42	2021	131	36	9503	95,865	.
43	2021	156	36	9401	118,322	.
44	2021	156	25	6245	77,955	.
45	2021	164	30	5904	77,884	.
46	2022	164	18	2804	36,973	.
47	2022	164	21	5533	69,879	.
48	2023	156	12	1570	19,873	.
49	2023	164	14	2978	35,430	.
50	2023	164	7	1658	24,983	.
51	2024	164	2	129	1796	.

.Unable to determine.

Appendix B

Total number of forest machines and annual harvesting volume of the enterprises involved in the study. The number of machines includes sub-contractors. Table 1 presents the enterprise-specific number of forest machines from the data-providing machine manufacturer.

Enterprise code	Total number of machines	Annual volume (m^3)
A	21	> 300,000
B	2	< 100,000
C	9	200,000–299,999
D	48	> 300,000
E	12	200,000–299,999
F	2	< 100,000
G	30	> 300,000
H	13	200,000–299,999
I	4	< 100,000
J	2	< 100,000

Appendix C

Operating hour cost calculations for forest machinery in Scenario 1 (BAU). Costs are presented excluding VAT (VAT 0%).

Cost factor	Harvester	Forwarder
Operating hours (G_{15}-h a^{-1})	2352 [a]	2368 [a]
Idling times (h a^{-1})	329 [b]	265 [b]
Degree of machine utilization (%)	82	85
Productivity (m^3 G_{15}-h^{-1})		
Final felling	22.9 [b]	19.3 [c]
Thinning	11.2 [b]	12.8 [c]

(*continued on next page*)

(*continued*)

Cost factor	Harvester	Forwarder
Harvesting volume (m^3 a^{-1})	37,986	37,986
Investment cost (incl. equipment) (€)	550,000	420,000
Interest rate (%)	3.9	3.9
Life span (years)	5.0 [a]	5.5
Annual depreciation (%)	15.0 [a]	15.0 [a]
Labor costs		
Wage cost of the operator (€ h^{-1})	18.0 [d]	16.8 [d]
Indirect wage cost (%)	60 [d]	60 [d]
Kilometer allowance for operators (€ km^{-1})	0.59 [e]	0.59 [e]
Operational costs		
Fuel consumption (L G_{15}-h^{-1}) and price [€ L^{-1}]	16.5 [b] [1.02 [f]]	12.9 [b] [1.02 [f]]
Fuel consumption during idling time (L h^{-1}) and price [€ L^{-1}]	4.28 [b] [1.02 [f]]	3.38 [b] [1.02 [f]]
AdBlue consumption (L G_{15}-h^{-1}) and price [€ L^{-1}]	0.91 [g] [0.66]	0.71 [g] [0.66]
Chainsaw oil consumption (L G_{15}-h^{-1}) and price [€ L^{-1}]	0.57 [a] [2.40]	–
Chainsaw consumption (pc. G_{15}-h^{-1}) and price [€ $pc.^{-1}$]	0.06 [h] [19.0]	–
Chainsaw blade consumption (pc. G_{15}-h^{-1}) and price [€ $pc.^{-1}$]	0.02 [h] [60.0]	–
Stump treatment (€ G_{15}-h^{-1})	1.50 [i]	–
Repair and maintenance (incl. lubricant and hydraulic oils) (€ G_{15}-h^{-1})	14.0	10.0
Average harvesting removal (m^3 $site^{-1}$)	492 [j]	492 [j]
Machine relocation (€ km^{-1})	2.40	2.40
Insurance (€ a^{-1})	3600	2400
Administration, management, real estate, and IT costs (€ a^{-1})	18,000	12,000
Total operating costs (€ G_{15}-h^{-1}) [€ m^{-3}]	**131.3 [8.13]**	**96.2 [6.00]**

[a] Statistics Finland (2023).
[b] This study.
[c] Kärhä et al. (2023).
[d] Industrial Union (2024).
[e] Tax Administration (2025).
[f] Statistics Finland (2025b).
[g] Yara (2025).
[h] Ahtikoski et al. (2024).
[i] Kärhä et al. (2018b).
[j] Haavikko et al. (2022).

Appendix D

Scenarios (1–5) used in the study. Machine cost calculations were based on gross-effective operating hours (G_{15}) (i.e., effective time including delays of less than 15 min).

Scenario Machinery type	Operating hours (G_{15}-h a^{-1})	Idling times (h a^{-1})	Harvesting volume (m^3 a^{-1})	Depreciation (€ G_{15}-h^{-1})	Total operating costs (€ G_{15}-h^{-1}) [€ m^{-3}]
Scenario 1: BAU					
Harvester	2352	329	37,986	32.94	131.3 [8.13]
Forwarder	2368	265	37,986	19.06	96.2 [6.00]
Scenario 2: −25					
Harvester	2352	247	37,986	32.94	131.1 [8.12]
Forwarder	2368	199	37,986	19.06	96.1 [5.99]
Scenario 3. −50					
Harvester	2352	165	37,986	32.94	131.0 [8.11]
Forwarder	2368	133	37,986	19.06	96.0 [5.99]
Scenario 4: −25_PH					
Harvester	2434	247	39,316	31.83	129.8 [8.04]
Forwarder	2434	199	39,045	18.54	95.7 [5.97]
Scenario 5: −50_PH					
Harvester	2517	165	40,649	30.78	128.1 [7.93]
Forwarder	2501	133	40,117	18.04	95.1 [5.93]

Data availability

The authors do not have permission to share data.

References

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

Amishev, D., 2010. A review of fuel consumption in New Zealand harvesting operations. Harvest. Tech. Note 3, 1–5.

Antila, M., Galimova, T., Breyer, C., Norouzi, S., Repo, S., Pihlatie, M., Pettinen, R., Shah, S., 2025. Future energy technology for nonroad Mobile machines. Adv. Energy Sustain. Res. 6, 2400257. https://doi.org/10.1002/aesr.202400257.

Auvinen, K., Kaminen, K., Karhinen, S., Rekola, A., Pelkonen, J., Child, M., Kärhä, K., Rantsi, J., Ihonen, J., Suomalainen, E., Hyrynen, J., Pesonen, J., Rasi, S., 2025. Politiikkatoimet liikkuvien työkoneiden puhtaan siirtymän edistämiseksi [Suggestions for a policy-mix to promote the clean technology transition and the growth of low-emission and zero-emission mobile machines in Finland]. Syke-hankkeiden julkaisuja. Ilmastoratkaisujen vauhdittaja (ACE) -hankkeen raportti. http://urn.fi/URN:ISBN:978-952-11-5745-5. (Accessed 1 April 2025).

Burk, E., Han, H.-S., Smidt, M., Fox, B., 2024. Incorporating simulators into a training curriculum for forestry equipment operators: a literature review. Croat. J. For. Eng. 45, 199–215. https://doi.org/10.5552/crojfe.2024.2142.

Chermack, T., Crawford, M., Haigh, N., Phadnis, S., Ramírez, R., Schoemaker, P., 2026. Scenario planning for strategic decision-making, learning, and managing uncertainty. Calif. Manag. Rev. 68, 5–19. https://doi.org/10.1177/00081256261432933.

de Ruijter, P., 2014. Scenario Based Strategy: Navigate the Future, first ed. Routledge. https://doi.org/10.4324/9781315607689.

Eriksson, M., Lindroos, O., 2014. Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. Int. J. For. Eng. 25, 179–200. https://doi.org/10.1080/14942119.2014.974309.

European Commission, 2023. Climate action. 2050 long-term strategy. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en. (Accessed 14 November 2024).

Ghaffariyan, M.R., Apolit, R., Kuehmaier, M., 2018. A short review of fuel consumption rates of whole tree and cut-to-length timber harvesting methods. Curr. Inv. Agr. Curr. Res. 5, 603–606. https://doi.org/10.32474/CIACR.2018.05.000209.

Giechaskiel, B., Clairotte, M., Valverde-Morales, V., Bonnel, P., Kregar, Z., Franco, V., Dilara, P., 2018. Framework for the assessment of PEMS (Portable Emissions Measurement Systems) uncertainty. Environ. Res. 166, 251–260. https://doi.org/10.1016/j.envres.2018.06.012.

Grigorev, I., Kunickaya, O., Prosuzhih, A., Kruchinin, I., Shakirzyanov, D., Shvetsova, V., Markov, O., Egipko, S., 2020. Efficiency improvement of forest machinery exploitation. Diagnostyka 21, 95–109. https://doi.org/10.29354/diag/122797.

Haavikko, H., Kärhä, K., Hourula, M., Palander, T., 2019. Attitudes of small and medium-sized enterprises towards energy efficiency in wood procurement: a case study of stora enso in Finland. Croat. J. For. Eng. 40, 107–123.

Haavikko, H., Kärhä, K., Poikela, A., Korvenranta, M., Palander, T., 2022. Fuel consumption, greenhouse gas emissions, and energy efficiency of wood-harvesting operations: a case study of stora enso in Finland. Croat. J. For. Eng. 43, 79–97. https://doi.org/10.5552/crojfe.2022.1101.

Hildt, E., Leszczuk, A., Mac Donagh, P., Schlicter, T., 2020. Time consumption analysis of forwarder activities in thinning. Croat. J. For. Eng. 41, 13–24. https://doi.org/10.5552/crojfe.2020.615.

Industrial Union, 2024. Metsäkonealan työehtosopimus 2024–2026 [Forestry machinery industry collective agreement 2024–2026]. https://www.teollisuusliitto.fi/tyoelama/tyoehtosopimukset/puutuotesektori/metsakoneala/. (Accessed 29 August 2025).

International Energy Agency (IEA), 2024. CO_2 emissions in 2023. https://www.iea.org/reports/co2-emissions-in-2023. (Accessed 14 November 2024).

Jylhä, P., Jounela, P., Koistinen, M., Korpunen, H., 2019. Koneellinen hakkuu: seurantatutkimus [Mechanized cutting: follow-up study]. In: Natural Resources and Bioeconomy Studies 11/2019. Natural Resources Institute Finland. http://urn.fi/URN. (Accessed 14 November 2024). ISBN:978-952-326-717-6.

Kärhä, K., Anttonen, T., Poikela, A., Palander, T., Laurén, A., Peltola, H., Nuutinen, Y., 2018b. Evaluation of salvage logging productivity and costs in windthrown Norway spruce-dominated forests. Forests 9, 280. https://doi.org/10.3390/f9050280.

Kärhä, K., Eliasson, L., Kühmaier, M., Spinelli, R., 2024. Fuel consumption and CO_2 emissions in fully mechanized cut-to-length (CTL) harvesting operations of industrial roundwood: a review. Curr. For. Rep. 10, 255–272. https://doi.org/10.1007/s40725-024-00219-3.

Kärhä, K., Haavikko, H., Kääriäinen, H., Palander, T., Eliasson, L., Roininen, K., 2023. Fossil-fuel consumption and CO_2eq emissions of cut-to-length industrial roundwood logging operations in Finland. Eur. J. For. Res. 142, 547–563. https://doi.org/10.1007/s10342-023-01541-4.

Kärhä, K., Koivusalo, V., Palander, T., Ronkanen, R., 2018a. Treatment of *picea abies* and *Pinus sylvestris* stumps with urea and *Phlebiopsis gigantea* for control of *Heterobasidion*. Forests 9, 139. https://doi.org/10.3390/f9030139.

Kaulen, A., Engler, B., Purfürst, T., 2024. Net carbon storage of supplied timber in highly mechanized timber harvest. Silva Fenn. 58, 24011. https://doi.org/10.14214/sf.24011.

Kavanagh, M.H., Ashkanasy, N.M., 2006. The impact of leadership and change management strategy on organizational culture and individual acceptance of change during a merger. Br. J. Manag. 17, 81–103. https://doi.org/10.1111/j.1467-8551.2006.00480.x.

Koneyrittäjät, 2025. Metsäkoneala [Forestry machinery industry]. https://www.koneyrittajat.fi/pages/etusivu/koneyrittaejaet/jaesenet/metsaekoneala.php. (Accessed 29 August 2025).

Magagnotti, N., Spinelli, R., Acuna, M., Bigot, M., Guerra, S., Hartsough, B., Kanzian, C., Kärhä, K., Lindroos, O., Roux, S., Talbot, B., Tolosana, E., Zormaier, F., 2012. Good practice guidelines for biomass production studies. COST Action FP-0902, WG 2 Operat. Res. Measurement Methodol.c. ISBN 978-88-901660-4-4.

Menzies, J., 2005. Five ways to boost log truck efficiency. Can. For. Industries 2005 (March) 48, 41–42. https://www.proquest.com/docview/216248490/fulltext/5C1F3EA55A274DB7PQ/1?accountid=11739.

Mercier, G., Makkonen, I., 2004. In Forestry Operations, Fuel Economy Counts! the Forest Innovation Partnership. Canada. https://library.fpinnovations.ca/en/permalink/fpipub8077. (Accessed 14 November 2024).

Michelin, J., Figueras, B., Bouly, C., Maret, D., 2000. Optimized diesel particulate filter system for diesel exhaust aftertreatment. SAE Technic. Paper 2000-01-0475. https://doi.org/10.4271/2000-01-0475.

Ministry of the Environment, 2024. Annual Climate Report 2024, 2024. Publications of the Ministry of the Environment, p. 36. http://urn.fi/URN. (Accessed 14 November 2024). ISBN:978-952-361-171-9.

Molari, G., Mattetti, M., Lenzini, N., Fiorati, S., 2019. An updated methodology to analyse the idling of agricultural tractors. Biosyst. Eng. 187, 160–170. https://doi.org/10.1016/j.biosystemseng.2019.09.001.

Mollenhauer, K., Tschöke, H. (Eds.), 2010. Handbook of Diesel Engines, 1. Springer. https://doi.org/10.1007/978-3-540-89083-6.

Natural Resources Institute Finland, 2025. Teollisuus- ja energiapuun markkinahakkuut (1 000 m^3) omistajaryhmittäin [Commercial industrial roundwood and energy wood removals (1000 m^3) by ownership category]. https://statdb.luke.fi/PxWeb/pxweb/fi/LUKE/LUKE__met__marhak__v/0600_marhak.px/. (Accessed 20 March 2025).

Natural Resources Institute Finland, 2026. Labour force and forestry machines in harvesting of industrial roundwood by month and labour force and forestry machines. https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE__met__marhak__zz_arkisto/03_Tyovoima_ja_kalusto_kk.px/table/tableViewLayout2/. (Accessed 11 August 2026).

Nurminen, T., Korpunen, H., Uusitalo, J., 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fenn. 40, 346. https://doi.org/10.14214/sf.346.

Ovaskainen, H., Kivilinna-Korhola, T., 2016. Fleet Management -ohjelmistovertailu Ponsse, Komatsu ja John Deere [Fleet Management system comparison Ponsse, Komatsu and John Deere]. Metsätehon Tuloskalvosarja 14/2016. https://www.metsateho.fi/wp-content/uploads/Tuloskalvosarja_2016_14_Fleet_management_ohjelmistovertailu_ho.pdf. (Accessed 2 December 2024).

Pesonen, J., Jeskanen, J., Kangas, M., Prinz, R., Ovaskainen, H., Kauranen, P., Kärhä, K., 2025b. Idle times of forest machine and truck fleets in Finnish logging and timber-hauling enterprises. Eur. J. For. Res. 144, 1537–1550. https://doi.org/10.1007/s10342-025-01824-y.

Pesonen, J., Prinz, R., Ovaskainen, H., Kauranen, P., Poikela, A., Kärhä, K., 2025a. Alternative powertrains and fuels in heavy non-road mobile machinery and their future expectations – a review. Curr. For. Rep. 11, 10. https://doi.org/10.1007/s40725-024-00244-2.

Poikela, A., Strandström, M., 2023. Puun korjuun ja kuljetusten päästöjen nykytila ja vähennyskeinot – 2. päivitys: liiteraportti 1: Ainespuun korjuun ja kaukokuljetuksen suorat CO_2-päästöt ja energiankulutus 2022 [The current status of logging operations and transportation emissions and ways to reduce them – 2nd Update: Annex Report 1: Direct CO_2 emissions and energy consumption for logging and timber-hauling in 2022]. ISSN 1796-2390. https://www.metsateho.fi/puun-korjuun-ja-kuljetusten-paastojen-nykytila-ja-vahennyskeinot-2-paivitys/. (Accessed 26 November 2024).

Polowy, K., Molińska-Glura, M., 2023. Data mining in the analysis of tree harvester performance based on automatically collected data. Forests 14, 165. https://doi.org/10.3390/f14010165.

Ponsse, 2025. Ponsse Active Care. https://www.ponsse.com/fi/palvelut/huoltosopimukset#/. (Accessed 22 January 2025).

Prinz, R., Spinelli, R., Magagnotti, N., Routa, J., Asikainen, A., 2018. Modifying the settings of CTL timber harvesting machines to reduce fuel consumption and CO_2 emissions. J. Clean. Prod. 197, 208–217. https://doi.org/10.1016/j.jclepro.2018.06.210.

Rahman, S.M.A., Masjuki, H.H., Kalam, M.A., Abedin, M.J., Sanjid, A., Sajjad, H.J.E.C., 2013. Impact of idling on fuel consumption and exhaust emissions and available idle-reduction technologies for diesel vehicles – a review. Energy Convers. Manag. 74, 171–182.

Rieppo, K., Örn, J., 2003. Metsäkoneiden polttoaineen kulutuksen mittaaminen: Esitutkimus [Measuring the fuel consumption of forest machines: preliminary study]. Metsätehon raportti 148. https://metsateho.fi/wp-content/uploads/2015/02/metsatehon_raportti_148.pdf. (Accessed 13 November 2024).

Ringdahl, O., Hellström, T., Lindroos, O., 2012. Potentials of possible machine systems for directly loading logs in cut-to-length harvesting. Can. J. For. Res. 42, 970–985. https://doi.org/10.1139/X2012-036.

Rutty, M., Matthews, L., Andrey, J., Del Matto, T., 2013. Eco-driver training within the city of Calgary's municipal fleet: monitoring the impact. Transp. Res. D: Transp. Environ. 24, 44–51. https://doi.org/10.1016/j.trd.2013.05.006.

Saarijärvi, J., 2024. Koneyrittäminen Suomessa 2024 [Logging Entrepreneurship in Finland, 2024]. Presentation in the course of Forest Technology at the University of Eastern Finland, 15th April 2024.

Shancita, I., Masjuki, H.H., Kalam, M.A., Fattah, I.R., Rashed, M.M., Rashedul, H.K., 2014. A review on idling reduction strategies to improve fuel economy and reduce exhaust emissions of transport vehicles. Energy Convers. Manag. 88, 794–807. https://doi.org/10.1016/j.enconman.2014.09.036.

Söderena, P., Pihlatie, M., Nylund, N., 2024. Pathways for CO_2 regulation in NRMM. VTT Res. Rep. VTT-CR-0032-24.

Sparrevik, M., Qiu, X., Stokke, R.A., Borge, I., de Boer, L., 2023. Investigating the potential for reduced emissions from non-road mobile machinery in construction activities through disruptive innovation. Environ. Technol. Innov. 31, 103187. https://doi.org/10.1016/j.eti.2023.103187.

Statistics Finland, 2023. Metsäalan kone- ja autokustannusindeksi 2020=100: menetelmäseloste [Forestry machinery and vehicle cost index 2020=100: methodological description]. https://stat.fi/media/uploads/tup/kustannusindeksit/metsaalan_kone_ja_autokustannusindeksi_2020-100_menetelmaseloste.pdf. (Accessed 14 January 2025).

Statistics Finland, 2025a. Polttoaineluokitus [Fuel classification]. https://stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html. (Accessed 15 September 2025).

Statistics Finland, 2025b. Kuluttajahintaindeksi 2024, polttonesteiden keskihinnat [Consumer price index 2023, average prices of liquid fuels]. https://stat.fi/julkaisu/cl8cz5nd8aezw09w2i6mnk5hu. (Accessed 14 January 2025).

Strandström, M., 2025. Puunkorjuu ja kaukokuljetus vuonna 2024. Metsätehon tuloskalvosarja 9/2025 [Timber Harvesting and Long-distance Transportation of Roundwood 2024]. https://www.metsateho.fi/puunkorjuu-ja-kaukokuljetus-vuonna-2024/. (Accessed 29 August 2025).
Tax Administration, 2025. Kilometre and per Diem Allowances. https://www.vero.fi/en/individuals/deductions/kilometre-and-per-diem-allowances/. (Accessed 29 August 2025).
Viitamäki, K., Laitila, J., Malinen, J., Väätäinen, K., 2015. Metsäkoneiden vuotuiset käyttötunnit ja vaihtokonemarkkinoiden rakenne Euroopassa [Annual operating hours of forest machines and structure of the second-hand machine market in Europe]. In: Natural Resources and Bioeconomy Studies 37/2015. Natural Resources Institute Finland. http://urn.fi/URN:ISBN:978-952-326-046-7. (Accessed 26 November 2024).
Viklund, E., 2012. Jobbaiskogen.se – nytt webbstöd för bättre drivningsarbete [Jobbaiskogen.se – new web support for better driving work]. Skogsforsk, Resultat 3/2012. https://www.skogforsk.se/cd_20190114161716/contentassets/3095d92183cc4bb9964b8ce3b2fde897/resultat-3-2012.pdf. (Accessed 13 November 2024).
Volvo Trucks, 2017. Älykäs kuljetus -testiraportti [Smart transportation - test report]. https://docplayer.fi/106620632-Alykas-kuljetus-testiraportti.html. (Accessed 27 November 2024).
Wihersaari, H., 2015. Työkoneen Pakokaasupäästöjen Mittaaminen Todellisissa Käyttöolosuhteissa [Application of Portable Emission Measurement System to Non-road Mobile Machinery]. Tampere University of Technology. Master's thesis. https://urn.fi/URN:NBN:fi:tty-201511171721.
Yara, 2025. AdBlue® for non-road mobile machinery. https://www.yara.co.uk/chemical-and-environmental-solutions/adblue-for-vehicles/adblue-for-non-road-mobile-machinery/. (Accessed 25 March 2025).