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Modifying the settings of CTL timber harvesting machines to reduce fuel consumption and CO_2 emissions

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ABSTRACT

The objectives of this study were to examine the possibility of reducing the fuel consumption and CO_2 emissions of harvesters during cut-to-length operations by applying various technical settings to the machine through the machine's own software package. The adjustment of machine settings had an effect on the fuel consumption per unit product (l m^{-3}) and can reduce the fuel consumption and CO_2 emissions in cut-to-length harvesting operations. The main factor significantly affecting both fuel consumption and productivity was stem size. The study involved three cut-to-length machines operating in thinning with comparable stand environment and silvicultural prescriptions.

The novelty of this work is in exploring the fuel saving potential of simple adjustments of machine settings in cut-to-length harvesting machines. Such adjustments have an impact on fuel efficiency and may reduce fuel consumption and CO_2 emissions in cut-to-length harvesting operations. This work may result in a reduction of energy consumption and environmental pollution, thereby contributing to cleaner production. This study bridges the gaps between research, development and implementation: it offers practical solutions that may affect manufacturers as well as practitioners and entrepreneurs in the field. The outcome of this study may result in innovative technology development with less impact on the environment.

1. Introduction

The global production of roundwood amounts to approximately 3.7 billion m^3 per year (FAO, 2016), of which over 1 billion originates from industrialized regions such as Europe, North America and Russia (Eurostat, 2016). In these countries, an increasing proportion of all harvesting work is mechanized, with shares that reach almost 100% in Atlantic, Baltic and Nordic Europe (Asikainen et al., 2009). Mechanized forestry equipment reaches high productivity but incurs high fuel consumption as well. Felling and processing alone require over 1.1 l diesel per m^3 of roundwood (Athanassiadis, 2000), and when this amount is multiplied for the volume harvested in industrialized countries, consumption soars to over 1 billion litres of diesel per year. That emphasizes the interest in increasing the efficiency of wood harvesting equipment and the reduction of pollutants emitted by diesel engines which affect human health and the environment (Petranović et al., 2015). Much work is being devoted to introducing new high-efficiency hybrid power solutions such as a hybrid-electric harvester (Johnsen, 2017) and/or to favour a switch towards biofuel blends (Mwangi et al., 2015) or mixing suitable additives to diesel (Fattah et al., 2014). These are likely to be the mainstream solutions of the near future, as older machines are being replaced with new and more modern ones. In the immediate future, however, large-scale changes can only occur through the adaptation of the existing fleet through retrofitting or suitable adjustments, as has been done in other fields, i.e. the achievement of reduced energy consumption in retrofitting of buildings (Zhou et al., 2016). Machine setting adjustment is probably the easiest solution: most tree harvesting machines can run in several modes, including a fuel saving mode like any other piece of equipment, i.e. engine operation modes in hybrid electric vehicles to reduce fuel consumption (Solouk et al., 2018). Also, mechanized harvesting machines collect a vast

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amount of data during their operation. Big data can be utilized for improvements through data mining and development of methods and models similar to those developed to solve regional energy efficiency problems (Liu et al., 2018) or using in machining optimisation within the manufacturing sector, where a 40% energy saving and 30% productivity improvement can be achieved (Liang et al., 2018).

The demand for forestry equipment, including both purpose-built machines and converted machinery, is increasing on a global scale – the demand for forestry equipment in the world was forecast to grow annually by 4.5 per cent and reach 9.3 billion US dollars in 2019 (Freedonia, 2015). The demand for machines is highest on the North-American market with an estimated need of 14 000 to 35 000 harvesting machine chains (Asikainen et al., 2009). In 2014, the US and Canadian markets accounted for a third of global product demand, followed by Western Europe as the second largest market with a share of 22% of the total equipment sales (Freedonia, 2015). Asikainen et al. (2011) estimated the need for machines in the EU in 2010–2030 for the supply of biomass potential at 18 600 harvesters and 21 600 forwarders. Consequently, if successful, modifying and adjusting work settings to reduce fuel consumption and CO_2 emissions in CTL timber harvesting could affect a large number of machines.

As a matter of fact, energy saving, reduction of greenhouse gas (GHG) emissions and machine efficiency are some of the most important key performance indicators of forest harvesting operations, regardless of the final product: timber or fuelwood. Several recent studies have analysed the efficiency of harvesting operations, their carbon footprint and the fuel consumption and emissions of all machines deployed for the task (Erber and Kühmaier, 2017; Obi and Visser, 2017; Cosola et al., 2016; Spinelli et al., 2018). While efficiency has increased through mechanization (Berg and Karjalainen, 2003), forest operations still account for the majority of emissions along the wood value chain: in that regard, harvesting is the most critical phase, due to its large consumption of fossil fuel (Dias and Arroja, 2012; Morales et al., 2015).

Within mechanized wood harvesting systems, fuel consumption is the main energy input and may account for 82% of the total (Klvac et al., 2003). For harvesting operations, productivity, fuel use and fuel type have a strong effect on energy consumption and GHG emissions, as shown by Zhang et al. (2016) in their study about the environmental impact of harvesting. Fuel consumption during harvesting operation plays an important role in the overall timber extraction process: Lijewski et al. (2017) report that the fuel consumption of CTL harvesters represents 38% of the total fuel used along the technological cycle, which is higher than that consumed during forwarding (35%) and transportation (27%).

The technical efficiency of the harvesting operation is influenced by factors such as the size of operation, forest terrain, number of log assortments and piece size (Obi and Visser, 2017), whereas the fuel consumption of timber harvesting machines depends largely on work type, the mechanical condition of the equipment and the driving style adopted by the operator (Ackerman et al., 2014). Fuel consumption varies also between harvesting systems (Spinelli et al., 2014) and depends on the harvesting machinery used. In that regard, Magagnotti et al. (2017) reported a 2.4 times greater fuel consumption per unit product for excavator-based units compared to purpose-built machines. These same findings have been confirmed by previous studies relating fuel consumption and emissions to machine characteristics, operator, machine operating time, work productivity and stand management options (Athanassiadis et al., 1999; Berg and Karjalainen, 2003; Cosola et al., 2016).

In general, cutting performance is affected by a complex combination of different factors (Nurminen et al., 2006). For CO_2 emissions, the most important factors are: species distribution, forest management method, terrain conditions, machine choice and operator competence (Cosola et al., 2016).

Of course, a key parameter is the productivity of machines: if productivity increases more than fuel consumption, then emission per product unit is likely to decrease. Hiesl and Benjamin (2013) mentioned in their literature review that machine productivity is most affected by stand and site conditions, equipment configurations, management objectives, and operator experience. Earlier on, Lageson (1997) mentioned that thinning intensity has a strong effect on machine productivity deployed in tending operations. Like for any other work process, the productivity of mechanized harvesting (i.e. felling, delimbing and bucking) is significantly affected by the volume of the work object – in this case the harvested tree – according to a relatively complex function (Visser and Spinelli, 2012).

Increasing resource efficiency is a key element of cleaner production and one measure is to reduce fuel input when producing the same product output (Spinelli et al., 2018). Thus, the question arose if a reduction of diesel fuel consumption in harvesting operation through the modification of work settings of CTL harvesters can be achieved. The aim of this study was to investigate the possibility to reduce the fuel consumption and CO_2 emissions of timber harvesters during CTL operation under real working conditions by modifying the technical settings of the machine through the machine's own software package. The study focussed on the determination of the effects of selected setting treatments in single-grip harvesters on the diesel fuel consumption and CO_2 emissions per unit product, as well as on relative productivity.

2. Materials and methods

The study was carried out in Central Finland north of Jyväskylä, at three sites near Konttimäki (62° 36′ N 25° 7′ E), Kyyjärvi (63° 0′ N 24° 51′ E) and Saarijärvi (62° 38′ N 25° 32′ E) from 21st to 25th August 2017.

Three Ponsse single-grip harvesters were studied under real working conditions during cut-to-length operation (Table 1). The machines were prepared with pre-selected settings defined individually for each machine (see appendices A to C); the settings compared were defined as follows:

- BAU (business as usual): the setting which the contractor and/or operator would normally use; it is adjusted carefully by the operators for the given machine and conditions and typically optimized for operator skills and preferences to obtain highest productivity
- ECO (economy mode): setting aiming at the lowest fuel consumption in litres per harvested cubic metre; implementation of various fuel saving features
- POWER (production mode): setting aiming at the highest productivity; implementation of various features to increase productivity

2.1. Experimental design

Each of the three machines was operated under each of the three settings (BAU, ECO and POWER) for 5 work bouts, each lasting approximately one hour and representing a repetition. Therefore, the experimental design included 45 repetitions (3 machines × 3 settings × 5 replications). The setting sequence for each machine was randomized, in order to dampen background noise.

Table 1
General characteristics of the harvesters (see Fig. 1).

Harvester	Beaver	Scorpion	Ergo
Make and model	Ponsse Beaver	Ponsse ScorpionKing	Ponsse Ergo
Wheels	6	8	6
Power [kW]	150	210	210
Engine model	Mercedes-Benz/MTU OM 934 LA EU Stage IV	Mercedes-Benz OM936 EU Stage IV	Mercedes-Benz OM936LA EU Stage IV
Harvester head model	H5	H6	H7
Crane type	C44+	C50	C5
Typical weight [kg]	17 500	22 500	20 000
Engine's maximum torque [Nm]	800	1150	1150
Tractive force [kN]	130	180	160
Fuel tank volume [l]	300	320	380

Fig. 1. The machines studied in the experiment, upper-left the Ponsse Beaver, upper-right the Ponsse ScorpionKing, below the Ponsse Ergo.

2.2. Study methodology

The study was conducted by collecting field data under real working conditions. Data was collected using the machine's on-board recording of the main work parameters; an additional software package was installed on the machines which recorded pre-defined machine parameters on separate files for each scenario run. The main data analysed within this study included fuel consumption, stem number, harvest volume in solid cubic metres and engine load factor.

2.3. Characteristics of the studied harvesters

The studied harvesters were three single-grip harvester models from the manufacturer Ponsse, which were prepared with pre-selected settings defined individually for each machine.

Each harvester was operated by one operator, who was among the drivers normally assigned to that machine by the company owners. During the study, operators were not switched between machines. For that reason, different operators were sitting in different machines, but all the operators were experienced professionals with working experience on their harvesting machines of 0.5–2.5 years, and as drivers of similar models of 15–30 years.

2.4. Test sites

The test sites were pine-dominated young stands, with varying shares of spruce and birch. All stands were tagged for thinning, with a planned intensity of around 50% in volume. Inventory field measurements were taken from each harvesting site before and after the operation, in order to characterize the stands and the silvicultural treatments. At each site, a minimum of 10 sample plots were measured, each represented by a circular area with a radius of 9.78 m (plot area 300 m^2). At each plot, breast height diameters at 1.3 m above the ground (DBH) of all stems above 10 cm were measured, and the species recorded. The plots were established systematically on parallel transects that covered the whole test site, and were spaced at a distance of approximately 30 m. This distance was taken between the centre points – not the edges –of measurement plots. Height measurements were done on each site with a minimum of 20 heights for each of the main species. Each height measurement was associated with the respective DBH measurement, in order to develop a local DBH to height curve. This same measurement procedure was repeated after harvesting, at approximately the same measurement plot locations.

The tree basal area (cross-sectional area at DBH over bark) was calculated for each tree in the plot, with the sum representing the basal area of that plot. Tree volumes were roughly estimated using a cone volume formula based on the average height and tree basal area (Eq. (1)):

$$tree\ \ volume = \frac{TBA \times H}{3} \quad (1)$$

where

TBA = tree basal area, in m^2
H = average height for each species, in m

On a plot level, the sum of each tree volume was calculated. All plot figures were then converted into hectare figures. The characteristics of harvesting sites before and after harvesting are reported in Table 2 as average figures for each of the three stands.

2.5. Data analysis

Data from the harvesting machines was saved in separate files using the SignalLogger software then converted into EXCEL files for cleaning and analysis. Calculations were performed in EXCEL statistical analyses in SPSS 25 and Statview 5.01.

The number of processed stems and the volume for each tree species and replication were extracted from the machine's own records acquired through software PONSSE Opti4G, for all machines.

Fuel consumption was determined to an accuracy of 0.05 l per hour using the machine's own data collection system, which recorded instant fuel consumption at 20 ms intervals. Instant fuel consumption represents the current fuel consumption in litres per hour at the respective time interval. Thus, in order to determine the total fuel consumption for the whole repetition, the instant fuel consumption was integrated over its duration, which was defined as the time interval between the first and the last instant fuel consumption readings. In addition, the engine load factor was recorded using the same device.

The average roundwood volume – including logs as well as pulpwood – was calculated using the sum of the total processed volumes (all species) in the test hour and the number of round- and pulpwood logs. Fuel consumption was presented as litres per solid cubic metre.

In order to relate the machine's recording of fuel consumption to actual fuel consumption, measurements of diesel fuel consumption when re-fuelling the machines were performed using a Badger LM OG HF (3/4") fuel meter with an accuracy of 0.01 l. Tanks were filled up to a maximum level at the roadside before starting the trial and after completing the trial, at the same exact location and position, at the roadside. That allowed estimating a correction factor that was applied to the records from each testing period (repetition).

GHG emission calculations were limited to CO_2 emissions as they are the main contributor to the global warming potential (González-García et al., 2009). CO_2 emissions were estimated based on the diesel fuel consumption using the following equation (EPA, 2016):

$$E_{CO_2} = FC \times CC \ \times 44/12 \quad (2)$$

where

E_{CO2} = CO_2 emissions, in kg m^{-3} solid volume of wood
FC = diesel fuel consumption, in l m^{-3} solid volume of wood
CC = carbon content of diesel fuel = 0.732 kg l^{-1}
44/12 = ratio of molecular weights of CO_2 and carbon

The scope of CO_2 emission calculations was on the direct emissions of diesel consumption. Indirect emissions were not considered in this study.

The dataset was statistically analysed in order to check the significance of differences between settings and machines. Normality of data was analysed using the Shapiro-Wilk test with SPSS 25. Homoscedasticity was tested using the Levene's test and Bartlett's test. The total number of stems and volume in the testing period, productivity per hour, fuel consumption per hour and per testing period and the corrected fuel consumption per testing period were normally distributed and homoscedastic. The fuel consumption per unit product, CO_2 emissions and the average round wood volume were non-normally distributed and were normalized through LOG transformation. Regression, transformation, ANOVA and non-parametric Mann-Whitney testing

Table 2
Characteristics of harvesting sites before the harvesting operation and post harvesting indicating the thinning intensity.

Site	Konttimäki (Beaver)	Kyyjärvi (Scorpion)	Saarijärvi (Ergo)
Type	Thinning	thinning	thinning
Main species	Scots pine (*Pinus sylvestris*)	Scots pine (*Pinus sylvestris*)	Scots pine (*Pinus sylvestris*)
Other species	Norway spruce (*Picea abies*) Silver birch (*Betula pendula*) other broadleaves (alder, aspen)	Norway spruce (*Picea abies*) Silver birch (*Betula pendula*) other broadleaves (aspen)	Silver birch (*Betula pendula*)
Before harvesting			
Average diameter [cm]	18.9 ± 1.7	19.8 ± 1.9	17.6 ± 1.6
Average height [m]	17.6 ± 1.4	17.7 ± 2.0	18.9 ± 2.2
Basal area [m^2]	23.9 ± 5.7	23.4 ± 4.3	25.0 ± 5.4
Number of stems per hectare	796 ± 167	732 ± 203	968 ± 175
Volume per hectare [m^3]	144.1 ± 35.0	140.7 ± 26.4	144.7 ± 31.5
Post harvesting			
Average diameter [cm]	20.3 ± 2.1	21.7 ± 2.1	19.3 ± 1.6
Average height [m]	17.6 ± 1.4	17.7 ± 2.0	18.9 ± 2.2
Basal area [m^2]	16.0 ± 4.4	14.0 ± 3.0	15.7 ± 2.0
Number of stems per hectare	469 ± 92	373 ± 78	526 ± 75
Volume per hectare [m^3]	97.2 ± 26.9	84.8 ± 18.3	91.5 ± 12.1
Estimated thinning intensity			
Number of removed stems per hectare	326	359	443
Volume removal per hectare [m^3]	46.8	55.9	53.2

were performed using the Statview 5.01 statistical software. Significance level of $\alpha < 0.05$ was applied in all analyses.

3. Results

The dataset showed remarkable differences between machines and settings (Table 3). In particular, stem size varied between 0.14 and 0.23 m^3, and was significantly larger for the Ergo harvester (Kruskal-Wallis test: $p = 0.047$), as could be expected for the largest machine in the group. On the other hand, there was no significant difference in the mean tree size between the setting treatments (Kruskal-Wallis test: $p = 0.835$), which confirmed that the comparisons were conducted under equal conditions.

Fuel consumption per unit product ranged between 1.02 and 1.48 $l\,m^{-3}$, but treatment differences were blurred by the different behaviour of different machines ($p = 0.129$). The same accounted for CO_2 emissions that were calculated on the basis of fuel consumption, and varied between 2.8 and 4.0 $kg\,m^{-3}$. The effect of machine setting on productivity was different for different machines: switching from BAU to ECO determined a productivity loss for Beaver and Ergo, but not for Scorpion King. Productivity losses also occurred when switching from BAU to POWER, for Beaver and Scorpion King. In contrast, the switch to POWER increases the productivity of Ergo. The different reaction of different machines explained why it was difficult to get a statistically significant result when pooling all machines together.

That is best demonstrated by the box plot graphs at Figs. 2 and 3. The graph in Fig. 2 shows the effect of setting treatments on the fuel consumption per unit product, with the lowest fuel consumption of 1.16 $l\,m^{-3}$ for the ECO setting, 1% below the BAU setting, whereas the POWER setting was 17% above the BAU setting; an outlier was not excluded from the dataset as no experimental error was identified. This graph does not highlight any large and significant

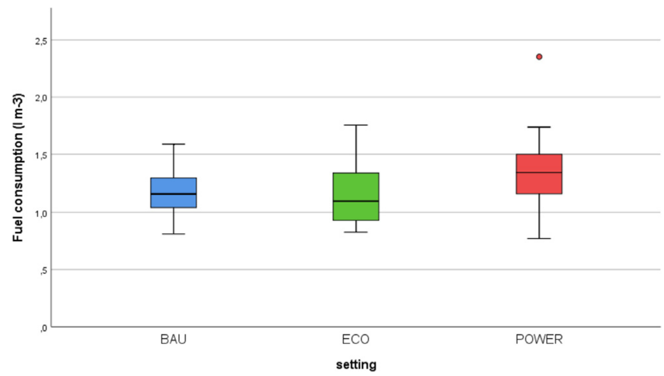

Fig. 2. Box plot graph of fuel consumption per unit product (l m^{-3}) for the three studied machine setting treatments.

Table 3
Tree size, fuel consumption, CO_2 emission and relative hourly productivity levels by machine and setting treatment.

		machine	setting	N	Mean	SE	SD	Min	max
tree size	(m^{-3})	Beaver	BAU	5	0.177	0.029	0.065	0.110	0.284
		Beaver	ECO	5	0.167	0.021	0.048	0.116	0.219
		Beaver	POWER	5	0.150	0.022	0.048	0.075	0.200
		Scorpion	BAU	5	0.158	0.012	0.026	0.130	0.201
		Scorpion	ECO	5	0.154	0.024	0.054	0.089	0.217
		Scorpion	POWER	5	0.140	0.016	0.035	0.097	0.182
		Ergo	BAU	5	0.206	0.028	0.062	0.140	0.298
		Ergo	ECO	5	0.200	0.035	0.078	0.114	0.321
		Ergo	POWER	5	0.229	0.058	0.130	0.143	0.458
		total		45	0.176	0.010	0.067	0.075	0.458
Fuel consumption	(l m^{-3})	Beaver	BAU	5	1.024	0.106	0.237	0.812	1.401
		Beaver	ECO	5	1.045	0.080	0.180	0.862	1.318
		Beaver	POWER	5	1.395	0.252	0.562	1.003	2.352
		Scorpion	BAU	5	1.233	0.060	0.134	1.045	1.383
		Scorpion	ECO	5	1.192	0.139	0.311	0.886	1.691
		Scorpion	POWER	5	1.482	0.101	0.226	1.210	1.738
		Ergo	BAU	5	1.255	0.093	0.207	1.040	1.589
		Ergo	ECO	5	1.254	0.167	0.373	0.827	1.755
		Ergo	POWER	5	1.244	0.132	0.295	0.771	1.525
		total		45	1.236	0.046	0.309	0.771	2.352
CO_2 emissions	(kg m^{-3})	Beaver	BAU	5	2.751	0.284	0.636	2.181	3.764
		Beaver	ECO	5	2.806	0.216	0.483	2.314	3.541
		Beaver	POWER	5	3.747	0.676	1.511	2.695	6.319
		Scorpion	BAU	5	3.313	0.161	0.361	2.807	3.717
		Scorpion	ECO	5	3.203	0.373	0.835	2.381	4.543
		Scorpion	POWER	5	3.980	0.271	0.607	3.252	4.668
		Ergo	BAU	5	3.373	0.249	0.556	2.793	4.269
		Ergo	ECO	5	3.370	0.448	1.001	2.222	4.716
		Ergo	POWER	5	3.341	0.354	0.792	2.070	4.097
		total		45	3.320	0.124	0.830	2.070	6.319
Relative productivity	(BAU set as 1.0)	Beaver	BAU	5	1.000	1.000	1.000	1.000	1.000
		Beaver	ECO	5	0.876	0.572	0.572	1.001	0.863
		Beaver	POWER	5	0.831	1.223	1.223	0.602	0.868
		Scorpion	BAU	5	1.000	1.000	1.000	1.000	1.000
		Scorpion	ECO	5	1.015	1.940	1.940	0.714	1.087
		Scorpion	POWER	5	0.958	1.344	1.344	0.876	1.009
		Ergo	BAU	5	1.000	1.000	1.000	1.000	1.000
		Ergo	ECO	5	0.962	2.430	2.430	0.725	1.232
		Ergo	POWER	5	1.127	2.266	2.266	1.109	1.471
		total		45					

Notes: m^3 = cubic metres solid volume; SE = Standard error; SD = Standard deviation; min = minimum value; max = maximum value.

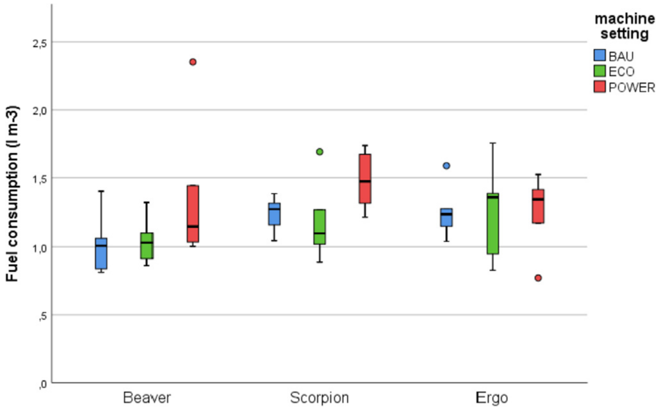

Fig. 3. Box plot graph of fuel consumption per unit product (l m^{-3}) for the three studied machines under the three machine setting treatments.

differences between the three treatments, when all machines are taken together and included in the analysis as a random factor.

In contrast, the box plot in Fig. 3 shows clear differences for the POWER setting with Beaver and ScorpionKing, and a relative indifference to settings for Ergo.

Therefore, machine type was included as a factor in ANOVA (Table 4). The analysis showed that the stem size has the strongest and most significant effect on fuel consumption per unit product (transformed figure), but machine setting also has a significant effect. The statistical significance of the interaction factor *machine * settings* demonstrates what was observed just above, i.e. the different reaction of the different test machines to setting adjustments. In particular, Ergo goes the opposite direction than the others, and for that reason the same analyses were repeated after removing Ergo observations from the data pool.

The new analysis also focused on the two extreme settings – ECO and POWER – in order to highlight possible differences between two radically different approaches. Descriptive statistics indicated that differences between BAU and ECO were small. Finally, restricting the analysis to a pair of alternatives solved the issue of pinpointing differences, even when no reliable post-hoc tests can be conducted, as in the case of non-parametric analysis. The new analysis shows the strong significance of the setting treatment ($p = 0.0026$), even though stem size remains dominant. This time, neither machine type nor any of the interactions effect proved significant: after removing Ergo samples from the data pool, all effects went in the same direction, without any contrasting responses (Table 5).

Reducing the degrees of freedom of both the setting and machine treatments facilitated the use of non-parametric statistics, and allowed running the analysis on the non-transformed fuel consumption data. This was performed with the Mann-Whitney test and showed that fuel consumption differences between the ECO and POWER treatments were statistically significant ($p = 0.04$) for the Beaver and Scorpion data.

Regression analysis was conducted on the same data (i.e. no machine Ergo, no setting BAU) for both fuel consumption and productivity. The effect of machine settings was introduced to the analysis by generating a dummy variable for the ECO setting, based on the clear stratification shown in the scatter plot (Fig. 4). Interestingly enough, no such stratification was observed in the productivity graphs, confirming that the neither setting had any effect on product output rate.

The regression equation obtained from the study is significant and explains over three quarters of the total variability in the data pool (Table 6). Once again, the analysis confirms the strong effect of stem size, while indicating that machine setting also has a significant effect. The latter is fixed and does not change with stem size, which was confirmed by the lower significance of the stem size * treatment interaction variable.

Results of the CO_2 emission calculations follow the same trends as the fuel consumption results, since CO_2 emissions estimates were based on diesel fuel consumption. CO_2 emissions per unit product were below 4 kg m^{-3} for all studied machines. The overall average for the ECO setting was 3.13 kg m^{-3}, which was 1% lower with the BAU setting and 18% below the POWER setting.

Table 4
Results of the ANOVA analysis for the LOG transformed fuel consumption per unit product (l m^{-3}).

Effect	DF	SS	η^2	F-Value	P-Value
Setting	2	0.014	0.04	3.560	0.0424
Machine	2	0.001	0.00	0.193	0.8255
Stem size	1	0.185	0.56	91.765	<0.0001
Setting * Machine	4	0.030	0.09	3.738	0.0152
Setting * Stem size	2	0.008	0.02	2.040	0.1495
Machine * Stem size	2	0.014	0.04	3.465	0.0458
Machine * Setting * Stem size	4	0.027	0.08	3.295	0.0253
Residual	27	0.054	0.16		

Where: DF = Degrees of freedom; SS = Sum of squares; η^2 = Effect size, expressed as the ratio between the SS for the specific effect and the total SS.

Table 5
Results of the ANOVA analysis for the LOG transformed fuel consumption per unit product (l m^{-3}) without the Ergo machine and BAU setting input data.

Effect	DF	SS	η^2	F-Value	P-Value
Setting	1	0.026	0.13	12.709	0.0026
Machine	1	0.003	0.01	1.565	0.2289
Stem size	1	0.146	0.71	72.886	<0.0001
Residual	16	0.032	0.15		

Where: DF = Degrees of freedom; SS = Sum of squares; η^2 = Effect size, expressed as the ratio between the SS for the specific effect and the total SS.

4. Discussion

The study confirms that machine work settings have an effect on the fuel consumption of harvesters during cut-to-length operations. In particular, the POWER setting is designed for maximum performance, but achieves its goal at the cost of increased fuel consumption and should be switched on only when full power is actually needed. This normally occurs when a machine is engaged with trees at the upper limit of its capacity, in which case task completion is the primary goal and fuel saving becomes secondary. Results obtained for the Ergo machine – the largest in the test range – show that productivity gains can be achieved by switching the power mode with trees that are still in the ideal size range. However, the increase in productivity is matched by a proportional increase in fuel consumption, and no fuel savings are accrued. Under these conditions, switching to the POWER mode can be a sensible strategy because it allows cutting on non-fuel cost (depreciation, labour etc.) and may achieve a reduction of total harvesting cost. However, longer-term studies should ascertain if the additional stress imposed by the more aggressive work mode on the machine and the operator may lead to higher maintenance cost and early fatigue onset for the driver. On the other hand, working under the ECO mode generally leads to reduced fuel consumption and emissions, and is likely easier on both the machine and the driver.

Of course, stem size remains the main factor affecting machine productivity and fuel consumption per unit product, as

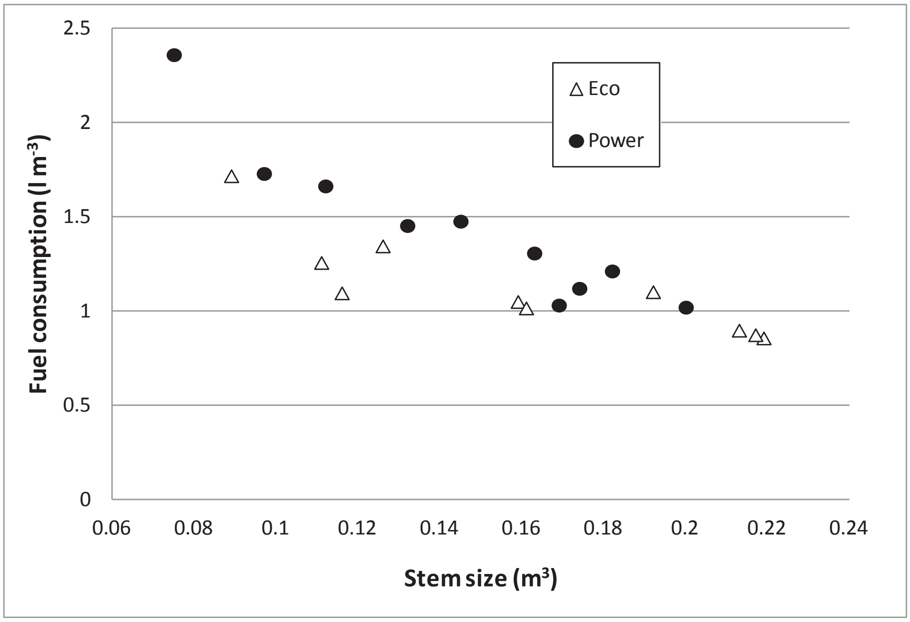

Fig. 4. Scattergram of the fuel consumption (l m^{-3}) data as a function of stem size, for the two setting treatment. The analysis excludes the Ergo machine and BAU setting input data.

Table 6
Results of the regression analysis for the fuel consumption per unit product (l m^{-3}). The Analysis excludes the Ergo machine and BAU setting input data.

Fuel consumption = a + b S + c ECO				
R^2 adj = 0.765; n = 20; F = 31.994; p < 0.0001				
	Coeff	SE	T	P
a	3.384	0.148	16.127	<0.0001
b	−6.523	0.943	−6.918	<0.0001
c	−0.220	0.081	−2.711	0.015

Where: Fuel consumption = l m^{-3}; S = stem size in m^3; n = number of valid observations; SE = Standard error; ECO = indicator variable for the ECO setting: if ECO = 1, if POWER = 0.

demonstrated in countless studies (e.g. Eriksson and Lindroos, 2014; Visser and Spinelli, 2012; Purfürst and Erler, 2011; Nakagawa et al., 2007; Nurminen et al., 2006; Sirén and Aaltio, 2003; Kuitto et al., 1994).

By conducting trials on similar and comparable field conditions, the effect of working environment was minimized, although small residual effects cannot be excluded. The effect of the operator on the fuel consumption was not studied, but the operator was kept constant across all settings which allowed for a reliable comparison. On the other hand, one cannot exclude that differences between machines might partly be associated with potentially different operator skills, competence or motivation (Purfürst and Erler, 2011). After the experiment, operators gave their own subjective feedback on the differences between settings, and all agreed that under the conditions of the study the ECO setting enabled them to proceed without any major changes of their operating technique and behaviour. On contrary, one operator stated that the POWER setting was very aggressive and may have an effect on the ergonomics and productivity in the long run.

Each setting was based on a mix of specific parameter changes and therefore it is not possible to establish an exact correlation between the adjustment of a specific parameter and a visible effect on fuel consumption under the current experiment design; the effect on fuel consumption between settings are rather the effect of a combination of all performed technical setting changes combined. However, the fixed effect of the ECO setting shown in the regression analysis may suggest that fuel savings were obtained by cutting consumption for fixed work elements and was not dependent on stem size. That may hint at the reduction of "parasitic" power drains for set repetitive functions.

Chain model and sharpness of chains for cross cutting might influence the cutting time and energy consumption (Jönsson et al., 2016); this possible source of bias was offset by the random sequence in the application of setting treatments for all machines, while the change and check of cross-cutting chains followed standard operating procedure and routines.

At the end of the experiment, conventional fuel measurements were performed with the refill method in order to achieve close-to-real fuel consumption figures. Due to practical reasons when working under real conditions, conventional fuel measurements were not made for each individual testing period and setting. Since the fuel measurements recorded by the on-board recording unit of the machine do not take all machine movements into account, the values were corrected based on the fuel measurements. Fuel use for moving the machine, for instance within the stand and from the roadside to the beginning of the cutting operation, might be quite substantial depending on the distance; in this case the applied correction factors varied between 16.3% and 23.1%.

The difference in fuel consumption per unit product is apparent between the setting treatment POWER and the other settings whereas the differences between BAU and ECO are less obvious. This may indicate that the currently used BAU setting already integrates aspects of the ECO setting regarding fuel economy concerns within the regular entrepreneurial harvesting operations. In that regard, it is worth mentioning the potential effect of operator adaptation, which is especially influential with thinning operations (Kärhä et al., 2003). Obviously, operators were most adapted to the BAU setting, and it is likely that if they had used the other two settings for a few weeks before the study, their performance under those two settings may have increased – at least marginally. That provides additional justification for the second part of the analysis, where the comparison was limited to the ECO and POWER settings, which were those that may not have gained any advantage from adaptation and could be compared under the same exact footing.

Previous studies have analysed the fuel consumption of forest machines and provide functions to estimate the fuel consumption of harvesters (Ackerman et al., 2014). When the function provided by Ackerman et al. (2014) was applied to the collected data, the results indicate higher hourly fuel consumption compared to the presented results in this study, which represent between 67% and 69% (SD 5% or 4%, respectively) of the theoretical calculated value. The load factor, the percentage of load in current rpm as one input parameter, is higher in the data gained within this study compared to the figure used by Holzleitner et al. (2011). Ackerman et al. (2014) rated the presented figures roughly as values above average hard work; this is in line with earlier findings that harvesters operate with heavy loads for over two-thirds of the productive cycle (Spinelli et al., 2010). The load factor varied little between the settings within this study – load factors for ECO compared to BAU were reduced by 1%, whereas the difference between ECO and Power was 4%. A reason for the higher load factor might be the recording of cutting operation after removing a large proportion of machine movement in the forest stand.

The fuel consumption per unit product presented in this study is in line with some previous findings (Klvac and Skoupy, 2009; Athanassiadis et al., 1999), but tends to be above the figures reported by other studies (Lijewski et al., 2017; Knechtle, 1997; Berg and Karjalainen, 2003) or calculations (Schwaiger and Zimmer, 2001). One may expect a higher fuel consumption per unit product in thinning operations compared with clear felling operations; this is confirmed by Ackerman et al. (2017) who reported a mean diesel fuel consumption of 0.64 $l\,m^{-3}$ for CTL operation in pine clear-felling in South Africa. Brunberg (2013) reported an average fuel consumption of 1.86 $l\,m^{-3}$ for harvesting and forwarding in Sweden in 2012. Ackerman et al. (2017) state that machine characteristics seem to be particularly important, which is in line with the findings of this study. Dependent on the engine power, Holzleitner et al. (2011) have found a diesel consumption of 0.095 ± 0.012 L per kW and productive machine hours (PMh15) with a load factor of 31% for harvesters.

Findings on the calculated CO_2 emissions based on the fuel consumption are generally in line with previous studies (Dias et al., 2007). Our figures range from values that are slightly lower than in earlier studies (Lijewski et al., 2017; Dias et al., 2007) to results which are higher (Cosola et al., 2016; Klvac and Skoupy, 2009; Athanassiadis, 2000).

In general, the described influence of stem size on the productivity of harvesters is in line with the findings of previous studies (Eriksson and Lindroos, 2014; Purfürst and Erler, 2011; Nakagawa et al., 2007; Sirén and Aaltio, 2003; Nurminen et al., 2006; Kuitto et al., 1994). Hourly productivity was calculated in order to investigate the effect of setting changes to the hourly productivity rates. Consequently, productivity figures were presented as relative productivity values compared to the BAU setting, which was set to 100%. Absolute hourly productivity figures were outside the scope of this study and would be considered proprietary by the contractors, therefore further comparisons with literature data were not made.

Further studies will need to investigate the effect of particular technical setting changes on fuel economy and emissions. Also, the origin of fuel consumption savings during operation could be investigated by looking at the detailed processing of single stems. Thus, further research would be needed in order to identify hot spots of fuel use during CTL operation, thus increasing the potential for improved fuel efficiency through machine setting modification.

The possible use of various pre-defined settings could provide new opportunities for operators and entrepreneurs when adjusting machine performance for instance to stand characteristics or operational targets. The option for operators to change between different setting alternatives might be a new opportunity to be introduced to the harvesting practice in the future.

Taking the growing demand of forestry equipment and numbers of harvesting machinery into account, improved fuel efficiency through machine setting modification generally implemented in CTL harvesting machines could generate large energy savings on a global scale and may result in a reduction of environmental pollution and a more efficient use of energy sources.

A quick estimate of the wood harvested mechanically in the Nordic and Baltic countries indicates a total of about 160 million m^3 per year (Eurostat, 2016), and multiplying that amount by an average saving of 0.3 $l\,m^{-3}$ will return a total of 47 million litres of diesel, which represents a substantial saving at the regional level. Obviously, this is a general estimate based on the gross average saving, and it does not take into account the distribution of Nordic and Baltic machines between different type and size classes. Actual fuel saving will vary with machine type, engine size and work conditions, but such detail is not available at the moment and the gross average values presented above still offer a good appreciation of saving potential, although the details may vary. Furthermore, these figures do not account for the large quantity of wood that is harvested with the same technology in Central Europe, and especially in France and Germany that account for additional 100 million m^3 per year, harvested with machines for a large proportion.

In summary, this study showed that the adjustment of machine settings had an impact on fuel efficiency and CO_2 emissions in CTL harvesting operations. Statistical analysis proved that stem size had the strongest and most significant effect on fuel consumption per unit product, but machine setting also had a significant effect. A Mann-Whitney test showed that fuel consumption differences between the ECO and POWER treatments were statistically significant for the Beaver and Scorpion machine data. A regression analysis was conducted on the same data for both fuel consumption and productivity. No stratification was observed in the productivity graphs, confirming that the neither setting had any effect on product output rate. Calculated CO_2 emissions followed the same trends, since CO_2 emissions estimates were based on diesel fuel consumption

5. Conclusions

Adjustment of machine settings can have an impact on fuel efficiency and can reduce the fuel consumption and CO_2 emissions in CTL harvesting operations. However, the highest impact on fuel consumption derived from stem size, which was the only factor affecting productivity. The study was planned carefully and involved three machines with one operation each over the experiment duration of several days. The operation took place in thinning for all machines where the stand environment was comparable and balanced for stem size.

The novelty of this work is to demonstrate the possibility of improving fuel efficiency by altering machine setting adjustments in cut-to-length harvesting machines. Adjustment of machine settings were shown to significantly impact fuel efficiency. Optimal adjustments can reduce fuel consumption and CO_2 emissions in cut-to-length harvesting operations. This work may result in a reduction of energy consumption and environmental pollution, thereby contributing to a cleaner production. This study bridges the gaps between research, development and implementation: it offers practical solutions that may affect manufacturers as well as practitioners and entrepreneurs in the field. The outcome of this study may result in innovative technology development with less impact on the environment. Having been successfully tested for CTL harvesters, similar measures could be now considered for other machine types, such as forwarders, used in timber extraction.

Taking the growing demand of forestry equipment and the numbers of harvesting machinery into account, improved fuel efficiency through machine setting modification generally implemented in CTL harvesting machines could generate large energy savings, estimated to many million litres of diesel fuel per year on a global scale. Machine setting modification may also result in a reduction of environmental pollution and a more efficient use of energy sources. In that regard, the possible use of various predefined settings could provide new opportunities for operators and entrepreneurs when adjusting machine performance to stand characteristics or operational targets. The option for operators to change between different settings might be a new opportunity to be introduced to the harvesting practice in the future, and become part of formal operator training efforts.

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Declarations of interest

None.

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Abbreviations

CTL	cut-to-length
CO_2	carbon dioxide
GHG	greenhouse gasl litre
m^3	solid cubic metre
ms	millisecond
DBH	breast height diameter
PMh	productive machine hour
kW	kilowatt

Appendix

Appendix A
Specifications for each of the three setting modes with the harvester model Beaver.

Beaver	BAU	ECO	POWER
Setting			
Engine			
Engine RPM [r min^{-1}]	1700	1550	1750
Harvesterhead pump flow			
Fast feeding [l min^{-1}]	215	220	250
Sawing [l min^{-1}]	242	210	231
Harvesterhead pump pressure			
Fast feeding [bar]	280	250	280
Slow feeding [bar]	280	250	280
Sawing [bar]	250	235	250
Base level [bar]	160	130	160
Tilt up [bar]	160	130	160
Engine control			
Increase of engine speed [r min^{-1}]	100	60	100
Increase of engine speed [ms]	500	300	500
Droop of engine speed when power limitation starts [r min^{-1}]	100	80	125
Power limitation function, decrease of pump control current [mA]	50	50	50

Appendix B
Specifications for each of the three setting modes with the harvester model Scorpion.

Scorpion	BAU	ECO	POWER
Setting			
Engine			
Engine RPM [r min^{-1}]	1600	1450	1750
Harvesterhead pump flow			
Fast feeding [l min^{-1}]	300	265	320
Sawing [l min^{-1}]	245	245	245
Harvesterhead pump pressure			
Fast feeding [bar]	280	250	280
Slow feeding [bar]	280	250	280
Sawing [bar]	250	235	250
Base level [bar]	160	130	160
Tilt up [bar]	160	130	160
Engine control			
Increase of engine speed [r min^{-1}]	125	0	100
Increase of engine speed [ms]	500	0	500
Droop of engine speed when power limitation starts [r min^{-1}]	70	not used	125
Power limitation function, decrease of pump control current [mA]	80	not used	60

Appendix C
Specifications for each of the three setting modes with the harvester model Ergo.

Ergo	BAU	ECO	POWER
Setting			
Engine			
Engine RPM [r min^{-1}]	1650	1550	1750
Harvesterhead pump flow			
Fast feeding [l min^{-1}]	366	300	387
Sawing [l min^{-1}]	225	225	225
Harvesterhead pump pressure			
Fast feeding [bar]	280	250	280
Slow feeding [bar]	280	250	280
Sawing [bar]	280	250	280
Base level [bar]	160	130	160
Tilt up [bar]	160	130	160
Engine control			
Increase of engine speed [r min^{-1}]	125	50	100
Increase of engine speed [ms]	500	280	500
Droop of engine speed when power limitation starts [r min^{-1}]	100	not used	125
Power limitation function, decrease of pump control current [mA]	80	not used	60

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