

PRODUCTIVITY AND FUEL CONSUMPTION ANALYSIS OF PONSSE FORWARDERS BASED ON DATA ACCUMULATED UNDER PRODUCTION CONDITIONS

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Abstract. The availability of machine-generated data from forest operations provides opportunities for detailed analysis of work processes and evaluation of their efficiency under production conditions. This study analysed automatically recorded system data from two Ponsse forwarders, collected under operational conditions and retrieved from the Ponsse Manager platform, in order to assess fuel consumption and identify the factors influencing it. Linear regression models were applied, incorporating forest type, operator, harvesting season, average load volume, and extraction distance as explanatory variables. The results indicate that the developed models explain a substantial proportion of the variation in fuel consumption ($R^2 = 0.561-0.588$; $p < 0.001$). Extraction distance was identified as the most influential factor (η^2 up to 0.37), significantly increasing fuel consumption both per hour and per cubic metre. The analysis showed that the BUFFALO forwarder consumed $2.31 \text{ L}\cdot\text{h}^{-1}$ less fuel per hour than the WISENT ($p = 0.005$); however, no statistically significant differences were found between the two machines in terms of fuel consumption per unit of production. Significant effects of operator, harvesting season, and forest type on fuel consumption were also identified, highlighting the importance of environmental conditions, work organisation, and human factors. The results demonstrate that systematic analysis of large-scale operational data provides valuable insights for optimising forwarding operations, reducing fuel consumption, and improving cost efficiency. The study emphasises the potential of data-driven approaches to support operator training, operational planning, and decision-making in sustainable forest management.

Keywords: forwarder productivity, fuel consumption, forest type.

Introduction

Forwarder fuel consumption has most commonly been analysed in the scientific literature in relation to productivity, extraction distance, load volume, stand conditions, and operator influence. One of the earliest and most widely cited studies is that of Nordfjell, Athanassiadis, and Talbot [1], who analysed 27 forwarders under different working conditions and found that fuel consumption varies significantly depending on the work element, harvesting type, and extraction distance. The authors emphasised that a substantial proportion of fuel is consumed during loaded travel and loading, highlighting the importance of the work cycle structure in explaining fuel use [2]. Subsequent studies have expanded upon these findings. Eriksson and Lindroos [3], using large datasets from cut-to-length (CTL) systems in Sweden, demonstrated that forwarder performance – and indirectly fuel consumption – is strongly influenced by the extraction distance, load size, assortment composition, and stand characteristics. Similarly, Pandur et al. [4], in a comparative study of two forwarders operating in lowland oak stands, found that fuel consumption varies not only between machines but also with the extraction distance, harvesting method, and measurement technique. More recent studies increasingly utilise automatically collected machine data, enabling more accurate modelling of fuel consumption. Prinz et al. [5] showed that, on peat soils, forwarder fuel consumption is significantly affected by soil bearing capacity, driving speed, traffic intensity, and the type of running gear equipment used. Băcescu et al. [6] concluded that the most important factors influencing forwarder fuel efficiency are the extraction distance, load volume, number of assortments, and terrain conditions. Furthermore, Kärhä et al. [7] emphasised that in CTL systems, operational factors – rather than machine type alone – are the primary determinants of fuel consumption and emissions. Overall, the literature consistently indicates that forwarder fuel consumption is most strongly influenced by the extraction distance, load volume, and work organisation, while operator performance and working conditions can introduce substantial additional variability. This implies that the assessment of fuel consumption should consider not only the machine technical characteristics but also the specific operational context and working conditions.

Materials and methods

Data for the study were collected under production conditions following clear-cut harvesting operations in the Central Daugava region (Latvia), during the period from April 2024 to March 2026. Data acquisition was carried out using the Ponsse Manager platform, from which stored system data

were retrieved on the operation of two forwarders across 505 harvesting sites. The small-class forwarder Ponsse Wisent operated in 243 sites, with five operators, transporting 5,416 loads with a total volume of 34,269 m³. The mean forwarding distance was 519 ± 303 m, with an average load volume of 6.32 ± 1.75 m³ and a mean productivity of 6.77 ± 3.14 m³·h⁻¹. In contrast, the medium-class forwarder Ponsse Buffalo operated in 262 sites, with six operators, transporting 7,855 loads with a total volume of 95,447 m³. The mean forwarding distance was 651 ± 346 m, with an average load volume of 12.15 ± 1.62 m³ and a mean productivity of 13.9 ± 5.28 m³·h⁻¹. The operators of both forwarders had at least five years of professional experience. The Ponsse Wisent forwarder analysed in this study has an engine power of 140 kW and a payload capacity of 12,000 kg, whereas the Ponsse Buffalo has an engine power of 210 kW and a payload capacity of 14,000 kg.

The following variables were used in the analysis:

- dependent variables: fuel consumption per hour (L·h⁻¹), fuel consumption per unit of production (L·m⁻³);
- independent variables: machine type, soil type (mineral soils; wet mineral soils; peat soils; drained organic soils; bog soils), operator, harvesting season (spring, summer, autumn, winter), average load volume (m³), extraction distance (m).

Categorical independent variables (machine type, soil type, operator effect, season) were converted into factors, while continuous variables (load volume, distance, fuel consumption) were treated as numerical variables. Records with missing values in the analysed variables were excluded from the dataset. As the objective of the study was to evaluate the combined effects of influencing factors on fuel consumption, the operator effect was not analysed separately.

Data analysis was conducted in the R statistical environment (R Core Team) using linear regression models. Two types of models were developed:

- combined models, including data from both machines, to assess the significance of machine effects;
- separate models for each machine (Wisent and Buffalo), to identify differences in factor effects.

In the models, the dependent variable was either fuel consumption per hour or fuel consumption per cubic metre. The explanatory variables included machine (only in the combined model), forest type, operator, harvesting season, average load volume, and extraction distance. The models were fitted using the ordinary least squares (OLS) method. The significance of factor effects was evaluated using Type III analysis of variance (Type III ANOVA), which allows correct interpretation of factor effects in models with multiple categorical variables. Partial eta squared (partial η^2) values were calculated to assess the relative importance of the factors.

Data visualisation

The following figures were produced to support result interpretation:

- boxplots to compare fuel consumption between machines, forest types, and seasons, separated by machine without accounting for other factors;
- scatter plots with regression curves to evaluate the relationship between fuel consumption and extraction distance.

Results and discussion

Descriptive statistics by soil type showed that the mean forwarding distance was 589 ± 341 m in dry mineral soils, 541 ± 307 m in wet mineral soils, 614 ± 340 m in drained peat and transitional soils, and 677 ± 317 m in peat soils. The average load volume and productivity of forwarders also varied across soil types. In dry mineral soils, the Ponsse Wisent achieved an average load volume of 6.17 ± 1.77 m³ and a productivity of 6.7 ± 3.2 m³·h⁻¹, while the Ponsse Buffalo reached 11.83 ± 1.95 m³ and 13.69 ± 5.65 m³·h⁻¹, respectively. In wet mineral soils, the Ponsse Wisent achieved 6.35 ± 1.56 m³ and 6.94 ± 2.85 m³·h⁻¹, whereas the Ponsse Buffalo reached 12.43 ± 1.06 m³ and 14.19 ± 5.05 m³·h⁻¹. In drained peat and transitional soils, the Ponsse Wisent achieved 6.65 ± 1.86 m³ and 6.98 ± 3.55 m³·h⁻¹, while the Ponsse Buffalo reached 12.46 ± 1.22 m³ and 14.09 ± 4.67 m³·h⁻¹. In peat soils, the Ponsse

Wisent achieved $6.88 \pm 1.46 \text{ m}^3$ and $6.53 \pm 1.46 \text{ m}^3 \cdot \text{h}^{-1}$, whereas the Ponsse Buffalo reached $12.56 \pm 0.96 \text{ m}^3$ and $12.91 \pm 5.77 \text{ m}^3 \cdot \text{h}^{-1}$.

Effect of extraction distance on forwarder fuel consumption

The results of the combined regression model showed that fuel consumption per hour was significantly affected by the machine type, work type, operator, season, average load volume, and extraction distance, whereas the additional covariate – fuel consumption per m^3 – was not statistically significant ($p = 0.544$). The developed model explained 56% of the variation in hourly fuel consumption ($R^2 = 0.56$), indicating a good model fit. After controlling for the effects of other variables, it was found that the Buffalo forwarder had a statistically significantly lower hourly fuel consumption than the Wisent ($p = 0.005$). However, in the model of fuel consumption per m^3 ($R^2 = 0.588$; $p < 0.001$), the effect of the machine type was not statistically significant ($p = 0.747$), suggesting that differences between the machines are primarily explained by operational conditions rather than technical characteristics. The differences in fuel consumption between the two machines are presented in Figure 1. It should be noted that boxplots represent raw observations without controlling for other variables; therefore, visual differences may not fully correspond to the results obtained from regression analysis.

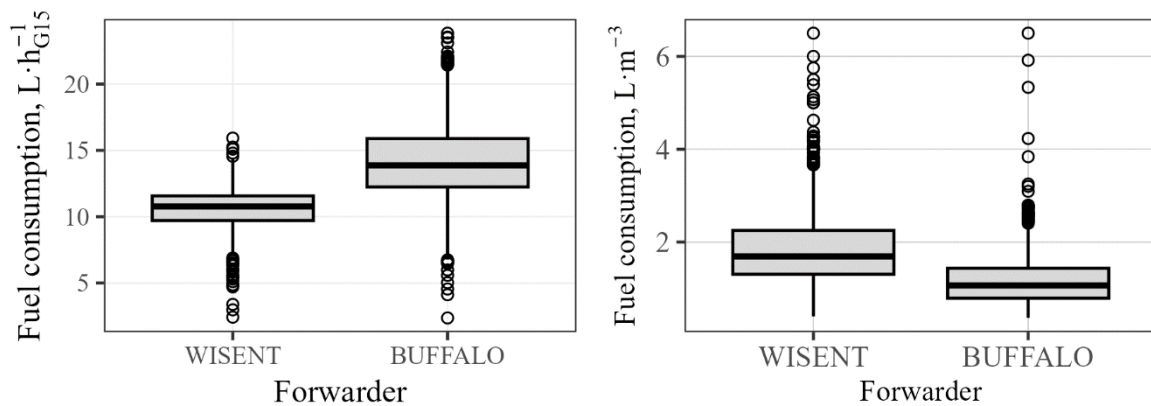


Fig. 1. Fuel consumption per hour and per unit of volume for both forwarders

In contrast, the combined model for fuel consumption per m^3 ($R^2 = 0.588$; $p < 0.001$) showed that, after controlling for other factors, the effect of the machine type was not statistically significant ($p = 0.747$). Therefore, the observed differences in hourly fuel consumption between the machines are largely explained by differences in operating conditions and other influencing factors, rather than by the machines themselves. Extraction distance was one of the most influential factors in both models ($p < 0.001$). As the distance increased, fuel consumption increased both per hour and per cubic metre. This relationship is also evident in the scatter plots (Fig. 2); however, it should be noted that these figures do not account for the influence of other variables.

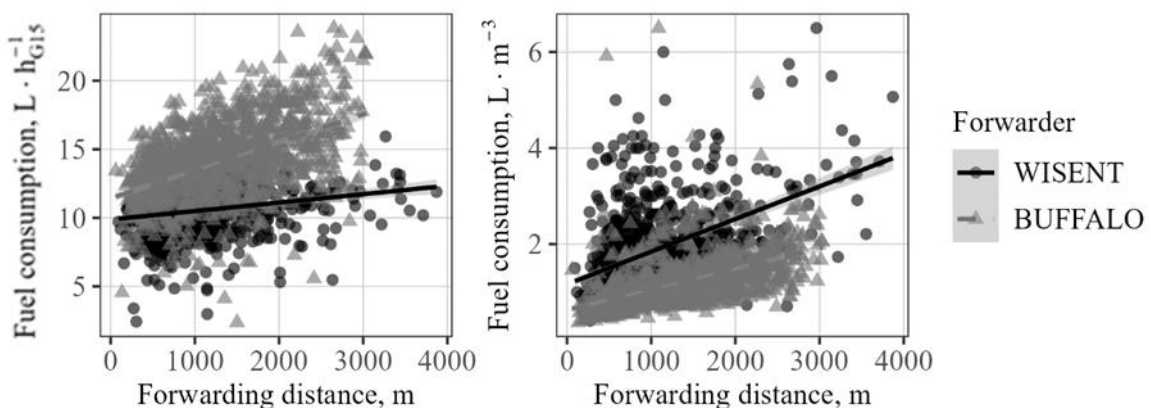


Fig. 2. Fuel consumption ($\text{L} \cdot \text{h}_{\text{G15}}^{-1}$ and $\text{L} \cdot \text{m}^{-3}$) in relation to extraction distance

Table 1 summarises the model results, indicating that extraction distance is the dominant factor, followed by load volume and operator effect. Machine type has a significant effect on fuel consumption per hour, but not per cubic metre.

Table 1

Effect of explanatory variables on fuel consumption

Factor	Fuel consumption, L·h _{G15} ⁻¹	p-value	η ²	Fuel consumption, L·m ⁻³	p-value	η ²	Interpretation
Forwarder (Buffalo)	-2.31	0.005**	0.44	-0.068	0.747	0.31	Buffalo consumes less
Soil type	-	0.007**	0.02	-	0.310	~0.00	Minor effect
Operator	+6.29	<0.001**	0.11	±0.82	<0.001**	0.11	Significant human factor effect
Season	±0.50	<0.001**	0.05	±0.10	<0.001**	0.02	Seasonal effect
Load volume, m ²	+0.255	<0.001**	0.09	-0.204	<0.001**	0.18	Larger load – more efficient
Extraction distance	+0.00139	0.544	-0.00	+0.00062	<0.001	0.37	Strongest factor

Both models were statistically significant ($p < 0.001$) and demonstrated good explanatory power ($R^2 = 0.561$ and $R^2 = 0.588$), indicating that the selected factors adequately describe the variation in fuel consumption.

Effect of soil type on forwarder fuel consumption

The effect of the soil type on fuel consumption differed between machines and between the analysed indicators (Fig. 3). In the combined model, soil type had a statistically significant effect on fuel consumption per hour ($p = 0.0068$), whereas its effect on fuel consumption per m³ was not significant ($p = 0.310$).

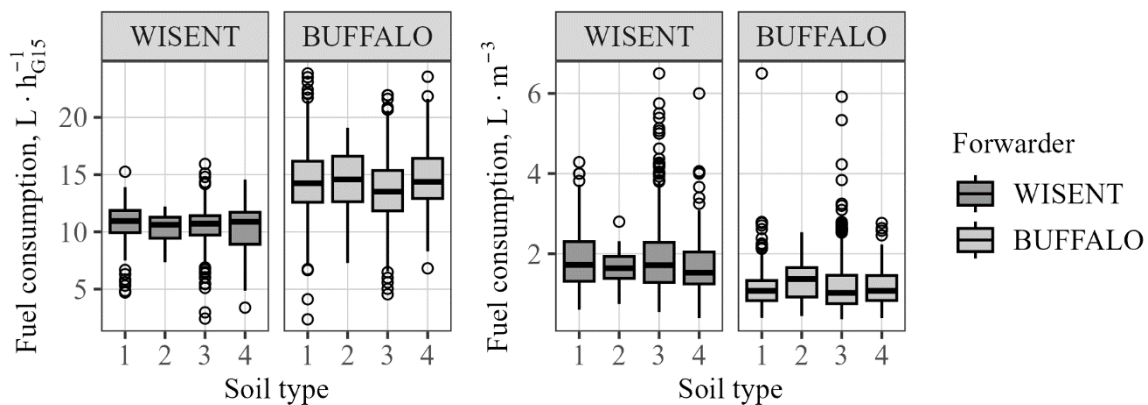


Fig. 3. Effect of soil type on fuel consumption: 1 – drained mineral soils; 2 – peat soils; 2 – bog soils; 3 – dry mineral soils; 4 – wet mineral soils

Compared to the reference category, fuel consumption per hour decreased in bog soils and dry mineral soils, while no significant differences were observed in wet mineral soils. This indicates that the soil type influences the work intensity but does not necessarily affect the efficiency per unit of production. In the Wisent model, the soil type had no statistically significant effect on either fuel consumption per hour or per m³. This suggests that the performance of this machine is relatively stable across different soil types, and that other factors – such as the extraction distance, load volume, and operator – play a more dominant role. In contrast, in the Buffalo model, the soil type had a statistically significant effect on fuel consumption per hour ($p = 0.0215$), although its effect on fuel consumption per m³ was not significant. This indicates that Buffalo performance is more sensitive to working conditions, while efficiency per cubic metre remains relatively consistent. Overall, it can be concluded

that soil type affects fuel consumption per hour, but not fuel consumption per m^3 , suggesting that operational factors are more important than site classification in explaining fuel efficiency.

Effect of harvesting season on forwarder fuel consumption

Harvesting season had a significant effect on fuel consumption in both models (Fig. 4). In the combined model, the fuel consumption per hour was found to be higher in summer and lower in the autumn and winter ($p < 0.001$).

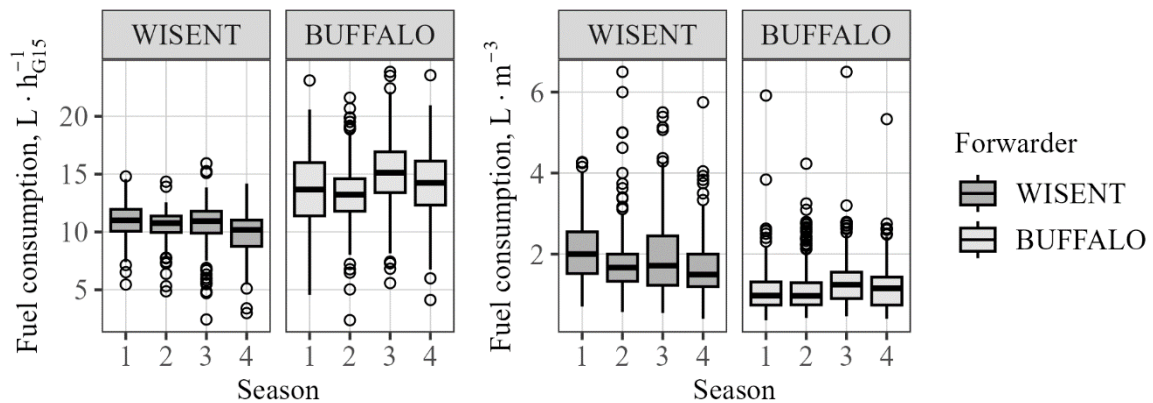


Fig. 4. Effect of harvesting season on fuel consumption:
1 – spring; 2 – autumn; 3 – summer; 4 – winter

The effect of the harvesting season on fuel consumption per m^3 was also statistically significant ($p < 0.001$), although it was not equally pronounced across all seasons. This indicates that seasonal effects depend on specific working conditions and machine performance characteristics. For the Wisent forwarder, lower fuel consumption was observed both per hour and per m^3 during winter, indicating higher efficiency under these conditions. In contrast, for the Buffalo forwarder, significantly higher fuel consumption was observed in summer, both per hour and per cubic metre. These results suggest that the machines respond differently to seasonal conditions: Wisent performance is more stable, whereas Buffalo is more sensitive to summer conditions.

The obtained results confirm that the extraction distance and load volume are the most influential factors affecting fuel consumption. Similar conclusions have been reported in previous studies, which emphasise the dominant role of distance in determining fuel consumption and operational costs [8-10]. Furthermore, studies have demonstrated that digital data from forest machinery enable more precise analysis of these relationships and highlight the importance of both distance and work organisation [10]. It has also been shown that larger load volumes reduce fuel consumption per cubic metre, thereby improving operational efficiency [4; 10; 11]. The lower explanatory power of the Wisent model ($R^2 = 0.138$) may indicate the influence of additional factors, such as terrain conditions [12] or operator working style. The importance of the operator as a key variable has also been widely emphasised in the literature [13]. In contrast, the Buffalo model demonstrates higher explanatory power ($R^2 = 0.446$), which may be related to the use of more advanced technological systems and more stable operating conditions. Overall, fuel consumption per cubic metre for both machines is better explained by operational factors than by the machine type itself, which is consistent with findings reported by other authors.

Conclusions

1. The combined regression models demonstrated good explanatory power: the model explained 56.1% of the variation in hourly fuel consumption ($R^2 = 0.561$; $p < 0.001$) and 58.8% of the variation in fuel consumption per m^3 ($R^2 = 0.588$; $p < 0.001$), confirming that the selected factors adequately describe changes in fuel consumption.
2. Extraction distance was the most influential factor in both models ($\eta^2 = 0.16$ for fuel consumption per hour and $\eta^2 = 0.37$ for fuel consumption per m^3 ; $p < 0.001$). As the distance increased, both hourly fuel consumption and fuel consumption per cubic metre increased significantly.

3. A significant difference in hourly fuel consumption was observed between the machines: the Buffalo consumed $2.31 \text{ L} \cdot \text{h}_{\text{G15}}^{-1}$ less than the Wisent ($\beta = -2.310$; $p = 0.005$). However, this difference was not statistically significant for fuel consumption per m^3 ($p = 0.747$), indicating the dominant influence of operational conditions.
4. Average load volume and operator had a significant effect on fuel consumption ($p < 0.001$). Larger load volumes reduced fuel consumption per m^3 ($\eta^2 = 0.18$), while the operator influence reached up to $\pm 6.29 \text{ L} \cdot \text{h}_{\text{G15}}^{-1}$ confirming the substantial importance of the human factor.
5. Harvesting season significantly affected fuel consumption for both forwarders, although the nature of the effect differed between the machines. In the combined model, hourly fuel consumption was higher in summer (+0.505) and lower in the autumn (-0.500) and winter (-0.410) ($p < 0.001$). For the Wisent, the lowest consumption was observed in winter (-1.079; $p < 0.001$), whereas the Buffalo showed a pronounced increase in summer (+1.222; $p < 0.001$), indicating different sensitivities of the machines to seasonal working conditions.

Author contributions

Conceptualization, A.S. and A.Z.; methodology, A.S. and A.Z.; software, N.J.; formal analysis, A.S. and A.Z.; data extraction and grouping, N.J.; writing – original draft preparation, A.S.; writing – review and editing, A.S. and A.Z.; visualization, A.S. and A.Z. All authors have read and agreed to the published version of the manuscript.

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