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Evaluation of Wood Chipping Efficiency through Long-Term Monitoring †

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Abstract: A high volume of wood forest biomass is be available at the roadside when whole three (WT) harvesting systems are applied. Besides, salvage logging operations are favourable conditions to accumulate a large amount of low-quality biomass due to the recovery of damaged trees. In mountain regions, such as the Alps, the forest's accessibility can be a significant constraint for the eco-efficiency of chipping operations. The present study aims at evaluating the efficiency of wood-chipping operations in mountain areas based on long-term monitoring. One chipper-truck was monitored over 1200 working hours using telemetry. Different efficiency parameters were collected: machine position, collected using Global Navigation Satellite System (GNSS) receiver, and engine parameters, collected using the CAN Bus system based on J 1939. Efficiency parameters were used to compare different in-wood or landing configurations. The results show the influence of the different location of the chipping sites according to the road network. Chipping operations in space-constrained sites cause an increase in delay time and CO_2 emissions.

Keywords: telemetry; efficiency; biomass; residues; emissions

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1. Introduction

Due to climate change, the production of energy from renewable sources has increased in recent years [1]. Because of the climate neutrality 2050 EU goal [2], the European Commission is planning to reduce EU greenhouse gas (GHG) emission by at least 55% by 2030. In these situations, the energy used for producing energy from renewable sources needs to be optimised. Products made by biomass are typically considered low impact in terms of GHG emission compared to the equivalent product made from non-renewable sources [3].

The primary products from forestry and logging are industrial roundwood and fuelwood. In Italy, about four-fifths of the roundwood production was provided as fuelwood [4]. Typically, after timber harvesting, a large quantity of low-quality biomass (LQB) such as non-commercial timber and logging residues are left on site. In recent years, the demand for LQB as feedstock for energy production has increased. Therefore, resource efficiency and GHG emissions from the forestry sector can be optimised by encouraging cascading biomass use [5]. In fact, after the merchantable timber harvester, LQB can be collected and chipped at roadside landings or terminals [6]. However, in order to increase the efficiency in the recovery of LQB, all the processes involved in the biomass supply chain need to be considered [7].

Typically, whole-tree (WT) harvesting systems provide a higher volume of logging residues compared to cut-to-length (CTL) harvesting systems, where branches and unmerchantable top sections of trees are left in the cutting area [8]. Furthermore, harvesting treatment affects the quantity of wood chips yielded: clear cuts in low-quality stands can generate a large quantity of biomass as well as salvage logging operations [9]. Contrarily,, whole tree chipping in early thinning operations generate a lower quantity of fuelwood [10]. Consequently, accumulated fuelwood can be chipped at the roadside landing or transported to terminals [11]. Chipping at the roadside is less cost-effective than chipping at the terminals [12]; besides, in mountain regions, such as the Alps, forest accessibility can be a significant constraint for the eco-efficiency of chipping operations. When trucks and trailers or semitrailers are unable to reach working sites, chips can be shuttled outside forests with a truck or tractor with trailer units [13]. Furthermore, when the yarding contractor does not coincide with the chipping contractor, some problems may arise [13]. Good cooperation between yarding contractors and chipping contractors, in order to identify in advance the location to pile logging residues, can improve the efficiency of chipping (e.g., no stones or metal in the pile) and reduce the frequency of relocation (e.g., the number and size of logging residues piles)[14]. Using modern technology, it is possible to improve the economic, environmental and social sustainability of forest operations [15].

Modern devices based on data transmission via GPRS-UMTS-HSDPA connections can be used to easily monitor and collect data of the entire wood chip production [16], as it was also proposed by Holzleitner et al. [17] using a fleet management system (FMS) to monitor chipping and transport activities.

This study, based on a semi-automated method, aims to evaluate the efficiency of wood chipping through long term monitoring based on FMS. More specific goals were to evaluate the efficiency and CO_2 equivalent emissions of wood chipping activities in mountain areas and to evaluate the effect of the accessibility of the work site on efficiency and CO_2 emissions.

2. Materials and Methods

2.1. Wood Chipper Details

The chipper-truck was based on the chipper unit, a Mus-Max Wood Terminator 10 XL, mounted on a three-axles truck, a MAN TGS-28.540. The 397 kW truck's engine powered the chipper unit. Chipping operations were carried out by the operators seated in the external cabin (Figure 1). Net productivity declared by the manufacturer of the chipper unit is 180 m^3/h. Details of the machine are reported in Table 1.

Figure 1. Mus-Max Wood Terminator 10 XL chipper-truck.

Table 1. Detail of Mus-Max 10 Wood Terminator XL chipper-truck.

Truck		
Manufacturer	-	MAN
Model	-	Man TGS 28.540
Engine type	-	Man 6 cylinders
Engine power	kW	397
Chipper unit		
Manufacturer	-	Mus-Max
Model	-	Wood-Terminator 10 XL
Feed opening	(w × h) mm	980 × 750
Tree diameter max	mm	750
Drum diameter	mm	900
Chopping knives	n°	12
Crane		
Model		Penz 14 L
Gross lifting torque	kNm	136
Maximum boom reach	m	10.1
Chipper-truck		
Weight	kg	27,000
Length	m	9
Width	m	2.5

2.2. Data Collection and Analysis

The chipper-truck was equipped with GSM/GNSS Teltonika FM3612 receiver in order to collect Can-BUS and machine position data. Data were recorded from January 2019 to May 2020 with an acquisition rate set at 1 Hz, as proposed by a similar study [17]. The web-server application for the acquisition of the data remotely was specifically developed for the study by Transpobank s.r.l. The data, downloaded from the server, include the following information: date-time stamp, position, altitude (m), travelling speed (km/h), engine temperature (°C), engine hours, engine speed (rpm), total fuel used (l) and odometer (m).

In order to detect working site and information related to the road characteristics, the position of the machine was linked with the regional and provincial road database of Lombardia, Veneto and Trentino-Alto Adige The accessibility of chipping sites was derived with respect to the public road and forest road classification: primary state and regional public roads (Easy condition), secondary public roads and main truck forest roads (Moderate condition) and secondary truck forest roads with few sites where the trucks can turn (Difficult condition).

A dedicated R code was developed for time and motion study analysis based on cycle level [18] considering chipper position, chipper speed, engine speed and their combinations to detect the following work elements:

- Chipping (C): when travelling speed is under 1 km/h and engine speed is above 1500 rpm;
- Travelling (T): when travelling speed exceeds 1 km/h and engine speed is above 0 rpm;
- Operational delay (OD): when travelling speed is below 1 km/h and engine speed is below 1500 rpm;
- Non-operational delay and other delays (NOD): when engine (rpm) and travelling speed (km/h) are equal to 0.

The observation units were the working sites and the observations started with the first chipping element and finished with the end of the last one. The operator was instructed to record the chipping volume produced for in all the working sites separately.

2.3. Efficiency Calculation and Statistical Analysis

In order to evaluate the efficiency of the wood chipping operation, the following equation was used:

$$Efficiency(\%) = \left(\frac{\mathrm{C}}{\mathrm{C + T + OD + NOD}}\right) * 100 \quad (1)$$

The environmental impact of wood chipping was evaluated in terms of total CO_2 equivalent emission (kg CO_2 eq) in the different working sites taking in consideration the emission derived from all the work elements per working sites (T, C and OD). As proposed by De la Fuente et al. [12], fuel consumption (l) was converted into CO_2 eq using emission factors per litre of diesel fuel of 2.61 kg CO_2 eq.

Afterwards, all the data were analysed considering the working site as observational unit and classified per type of accessibility as defined before. The coefficient of determination (R^2) was used to evaluate the goodness of fit of the linear model. The significance level of the statistical analysis was set to 0.05. In case of non-normal distribution of the residual, square root and logarithmic transformations were tested on both dependent variables and independent variables.

3. Results

The total working days were 168, and the chipping activities were divided into 288 different working sites. Working activities in the different working sites covered over 1200 h, 127 working sites (399 h) of these were registered as easy conditions, while 126 working sites (494 h) and 35 working sites (307 h) were recorded as moderate and difficult conditions, respectively.

As shown in Figure 2a, net productivity, evaluated in terms of total volume (cubic meters of loose chips produced) during chipping activity, was higher in easy and moderate accessibility, on average 85.71 m^3/h and 81.10 m^3/h, respectively, and lower in difficult conditions, on average 38.35 m^3/h. Efficiency in difficult conditions (Figure 2b) was 10% lower than moderate condition and 7% lower than easy conditions. On average, efficiency was 67.91%, 70.91% and 60.97%, respectively in easy, moderate and difficult condition of accessibility. Higher efficiency, close to 100%, was recorded in both easy and moderate conditions.

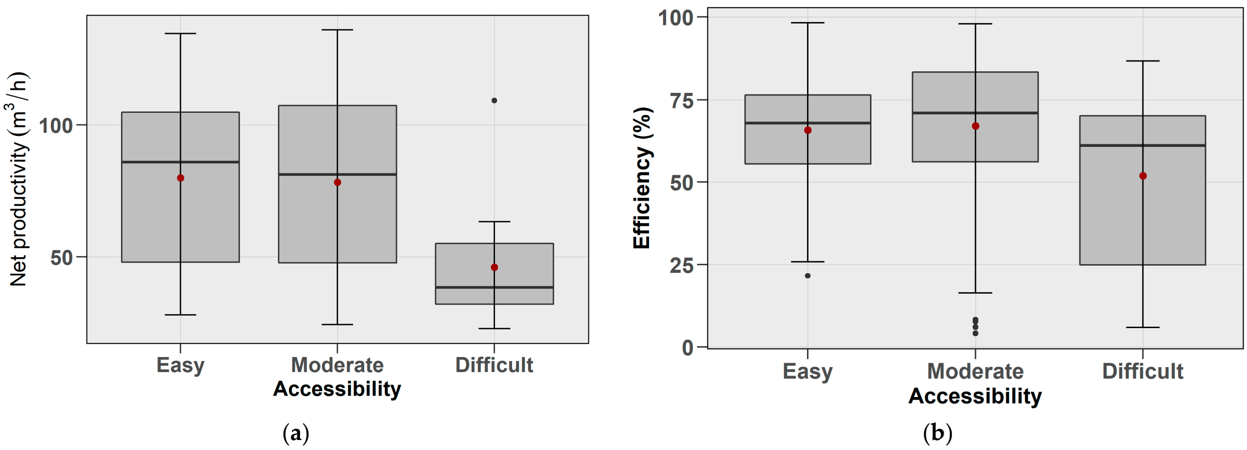

Figure 2. Variability of net productivity in cubic meters of loose chips produced per hour (**a**) and chipping efficiency considering all the operational and non-operational activity (**b**) classified by accessibility of the working site. The boxes include the variability of the data between the 25th and the 75th percentiles. The horizontal black line represents the median while the circle in dark red represent the mean.

The highest efficiency is related to the working sites where NOD and travelling elements were not recorded probably due to working sites located at the terminal. As reported in Table 2, OD and NOD increase when the difficulty in the accessibility increases. Besides, time travelling inside working sites increases from easy to difficult accessibility. The frequent relocation could explain the higher value of time travelling and travel distance in difficult conditions of accessibility. As expected, travelling fuel consumption was higher in difficult working sites than in easy and moderate ones. This confirms, with the hight time travelling in difficult condition, the challenging task to chip in mountain areas.

Chipped volume and different accessibility to working sites significantly affect the total emission produced (R^2 = 0.43, $p < 0.001$). In particular, as reported in Figure 3, the predicted total emission (kg CO_2 eq) was higher in difficult conditions (1.25*volume chipped) than in easy (0.61*volume chipped) or moderate conditions (0.72*volume chipped).

Table 2. Descriptive statistics for time and fuel consumption based on Can-BUS system. OD: operational delay; NOD: non-operational delay.

		Easy		Moderate		Difficult	
	Unit	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Chipping	min	103.14	93.06	102.01	78.92	150.95	118.65
Travelling	min	3.02	3.42	5.99	7.91	9.21	11.18
OD	min	75.47	176.29	117.88	575.1	341.4	588.38
NOD	min	14.67	22.94	22.92	36.74	29.23	44.87
Travelling distance	km	0.55	1.09	1.17	1.95	1.29	1.9
Chipping fuel consumption	l/m³	0.41	0.25	0.46	0.27	0.59	0.34
Travelling fuel consumption	l/h	0.5	1.57	0.62	1.97	0.98	4.09
OD fuel consumption	l/h	4.76	7.02	12.99	6.52	3.11	5.26

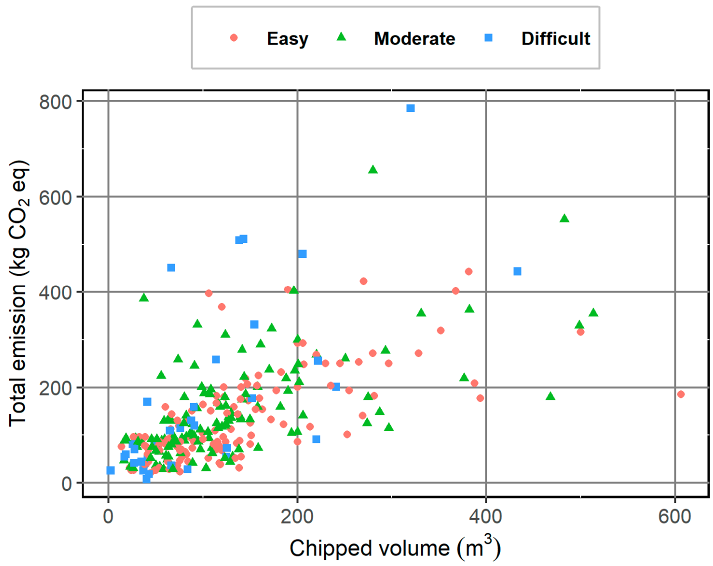

Figure 3. Total emission per working sites with the respect of chipped volume (cubic meters of loose chips produced) and accessibility.

4. Discussion

Time consumption of chipping operation and total emission in different working site classified by different conditions of accessibility was analysed. Similarly, Holzleitner et al. [17] used the FMS and semi-automated method to monitor the supply processes of forest fuels. In this study, the data were analysed with the working site as observational unit. Isolating working activity, and related activity (travelling in working site, OD and NOD), our results show the effect of the accessibility on the efficiency and emission. Chipping activities in easy conditions, along primary public road, were the most effective method in terms of net productivity and total emission produced during all the operations (chipping, travelling and idle time while the engine is running). Chipping in mountainous conditions, especially with difficult accessibility and poor quality of road infrastructures, is a hard challenge and could lead to a decrease in efficiency of about 7–10% compared to easy and moderate conditions. Besides, the CO_2 eq emissions in these conditions can increase up to double the emission in easy conditions.

Higher variability in terms of chipping efficiency was recorded in difficult conditions of accessibility. These higher values were probably related to the higher OD, NOD and lower net productivity compared to easy and moderate accessibility. Analysing different chippers, Spinelli et al. [19] estimate, on average, total delay factor of 37.3% for chipping at the landing and 32.1% for chipping operation in the forest. Our results show higher efficiency for chipping operation in moderate conditions (70.91%) and lower in easy and difficult conditions (67.91% and 60.97%).

5. Conclusions

Chipping forest residues is considered an important economic and forest tending activity; besides the recovery of LQB after natural disturbances could reduce the risk of forest fires, diseases and pests [6]. Environmental impact of recovery and chipping LQB are challenging operations especially in mountainous conditions, where the quality of road infrastructures (e.g., steep gradient and turning radius), quantity and distance between biomass piles and distance from the primary road network play an important role. Chipping in complex situations, as working sites along secondary forest road, lead to an increase in terms of CO_2 eq emission and a reduction of chipping efficiency. Time spent and travel distance are higher inside difficult working sites. Quantity and position of piles should be planned before starting the forest operations in order to favour the cooperation between the yarding contractor, chipping contractor and forest manager. Long term monitoring based on FMS has great potential and it is available for different truck-based models [17]. At present, additional information about wood quality and quantity need to be manually recorded by the operators and linked with machine activity parameters in order to better understand productivity and efficiency of chipping activity and fuelwood supply chain.

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