Article

Assessment of Energy, Dynamic and Economic Balance of Chipping Operation in Poplar Medium Rotation Coppice (MRC) Plantations

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Abstract: Exploiting renewable energy sources is one of the main strategies defined by the EU to overcome dependence on foreign markets for energy supply. Wood fuel sourced from the agroforestry sector can contribute significantly to achieving the goal, though its economic and environmental sustainability is intimately dependent on proper harvesting and chipping operations. In the present article, both economic and environmental aspects of Medium Rotation Coppice (MRC) were investigated regarding chipping. A small-scale chipper and tractor were equipped with real-time sensors to monitor time, t (s); fuel consumption, F (cm³); PTO torque, M (daNm); PTO speed, s (min⁻¹); and stem diameter, D (mm) during the comminution of 61 poplar plants (gathered in 5 classes according to trunk diameter) grown in MRC system. More than 29,000 records were taken and analyzed. Predictive models for working time, working productivity, CO₂ emission, energy consumption, fuel consumption and costs were also produced. Higher diametric classes exhibited lower fuel consumption, less CO₂ emission and less energy demand during chipping. Time and operating costs were statistically different among classes, with minimum values of 0.22 (SD ± 0.02) h·Mg⁻¹ and 12.07 (SD ± 0.93) €·Mg⁻¹ in class 5 and maximum values of 0.64 (SD ± 0.09) h·Mg⁻¹ and 35.34 (SD ± 4.88) €·Mg⁻¹ in class 1, respectively. Fuel consumption ranges from 3.04 (SD ± 0.88) L·Mg⁻¹ in class 5 to 7.32 (SD ± 1.46) L·Mg⁻¹ in class 1. The lowest CO₂ emission of 8.03 (SD ± 2.32) kg·Mg⁻¹ was found class 5. However, the total cost of coppice production did not exceed large-scale MRC production due to the lower purchase price of the machinery involved. Eventually, predictive models showed high reliability as estimating tools for important variables, such as working time, working productivity, CO₂ emissions, energy consumption, fuel consumption and costs.

Keywords: comminution; work productivity; sustainable forest operations; bioenergy; wood chips

1. Introduction

Global warming and energy independence are the main challenges that the EU will face in the next few years, and the exploitation of renewable energy sources can help member states to face both challenges [1,2]. The contribution of renewable energy production is expected to reach 32% of total domestic energy production by 2030, and the agroforestry sector can play a fundamental role in providing renewable fuels [3–5].
shift from fossil fuel to renewable energy will also help to reduce gas emissions, global warming effects and air pollution worldwide [6], although some authors highlighted that the emission of NOx can be even higher in case of fertilization of energy crops [7]. Nevertheless, renewable resources are not as limited as fossil fuels, which also make some countries dependent on foreign markets for their energy supply [8–13].

Solid biofuel can be obtained from either natural forests or dedicated energy crops [12,14–16]. Fast growing species, like poplar (Populus spp.), are usually employed to guarantee constant wood supply to the market and constant revenue [17]. In fact, the use of fast-growing species would enhance the supply chain by meeting the growing demand for wood fuel worldwide and keeping its price stable [18]. This condition is crucial for successfully shifting from fossil fuel to renewable energy [19,20].

In short rotation coppice (SRC) systems, wood is harvested every 2–3 years when the average diameter reaches 5–8 cm [21], while in medium rotation coppice (MRC), plants are harvested every 5–7 years and their mean diameter is 15–20 cm [20,22,23]. MRCs yield higher quantity biomass and better quality biofuel due to the reduction in the bark/fiber ratio [22,23], although harvesting operations cannot be accomplished in single-passage due to the wider stem diameter [24]. The surface of MRC plantations has increased in the last few years, mostly in Central and Eastern Europe, where artificial plantations are widely used for the combined production of fibre wood and fuel wood [25]. Wooden material from MRC plants is generally collected through common forestry machineries, such as for-warders, harvesters and feller-bunchers [26,27]. Nevertheless, in Mediterranean forests, logging is accomplished by medium and small enterprises that rely on lower performing machinery characterized by lower purchasing costs [28]. In either case, the literature includes plenty of studies that deal with energy and costs related to felling and extraction operations in both SRF and MRF [20,21,29], though it lacks studies dealing with small-scale comminution, that is, a high-energy-demanding operation that requires energy ranging from 10 to 150 kWh·Mg⁻¹ [30]. Moreover, the majority of the current literature only focuses on industrial chippers [31–33].

Comminution can be accomplished with either chippers or grinders that differ based on their working principle and tool type (i.e., knives and hammers) [34–36]. While grinders are mainly used to process woods contaminated with nails, stones or similar hard contaminants [37], chippers are preferred in cases of uncontaminated wood to offer more consistent products and higher quality chips [38]. Moreover, chippers result in less energy and fuel demand per unit of biomass processed [39]. However, fuel consumption and energy demand during the chipping operation is sensitive to the size of biomass processed—for example, chipping branches requires about 30 L h⁻¹ of fuel, while stem woods need 42 L h⁻¹; these results correspond to 2.6 and 3.8 L odt⁻¹ of specific fuel consumption, respectively [40]. In fact, according to Spinelli et al. (2011), the work productivity rates of the machines are less sensitive to species and moisture content than piece size [40]. Hence, the goal of this article was to provide a comprehensive analysis of chipping operations carried out using a small-scale forestry chipper powered by an agricultural tractor. We wanted to investigate the effects of tree dimension on working performance, comminution costs and CO₂ emissions in detail. Thus, we aimed to define the influence of operating parameters on the working performance of a small-scale chipper in order to gain a deeper insight into this fundamental operation’s relevance to fuel wood production in the framework of a small-scale forestry business.

2. Materials and Methods

2.1. Experimental Data, Machineries and Data Logger

The 0.42-hectare experimental field was located in a flat area of Monterotondo (Italy (46°06'06.29" N; 12°37'46.26" E). Poplar AF8 clones were grown for 7 years without artificial irrigation and fertilization. Plant spacing was 2 m × 3 m (almost 1700 plants ha⁻¹). Plants measured 13 cm in diameter (diameter at breast height—DBH) and 13.2 m in height,
on average, corresponding to a volume of 0.08 m³ (according to the national allometric equations developed for poplar) and providing an estimated yield of 43.178 Mg DM ha⁻¹. Average wood moisture at harvesting was 54.05%.

Felling was performed using a Stihl 201TX chainsaw. Afterwards, a crawler tractor equipped with a front lifter was used to carry the fallen plants outside of the field. Here, 6 piles of 10 randomly chosen plants were created to produce repetitions. Each plant was measured in length, diameter and weight. Wood moisture was calculated via the gravimetric method. Briefly, a sample of approximately 100 g of wood was taken from the middle of 10 randomly chosen trunks. Wood samples were weighted and dried over a ventilated oven set at 105 °C until achieving constant weight. Moisture content was calculated via Equation (1):

\[
\text{Wood } UR\% = \frac{\text{Fresh weight} - \text{dry weight}}{\text{Fresh weight}} \times 100
\]  

(1)

Chipping was performed using a Farmi forest chipper CH260 powered by a Landini Legend 145-S farm tractor, with a nominal power of 105 kW and a total mass of 6400 kg. The power take-off (PTO) was set at 1000 min⁻¹, corresponding to an engine speed of 1974 min⁻¹. Machines were driven by the same operator to avoid biased data.

The tractor-chipper machine system was equipped with an instrumental chain to monitor some key parameters of chipping. PTO rotational speed (min⁻¹) and torque (kNm) were measured via a digital transducer and a torquemeter (HBM, mod. T30FN, full scale: torque 2 kNm; speed 3000 min⁻¹) installed onto the tractor (Figure 1). The PTO speed and torque were used to calculate the power (kW) required by the operation [41].

![Figure 1. A torquemeter fitted with a digital encoder was installed between the PTO and the drive shaft to measure the torque and the rotational speed used to calculate the power required by the chipping process.](image)

The tractor was also equipped with a volumetric fuel consumption meter (Figure 2). The fuel consumption (dm³) resulted from the difference between the measured volumes of total fuel delivery and recovery. The hourly fuel consumption (dm³ h⁻¹) was calculated by dividing the fuel volume by the time interval (acquisition lasting). Multiplying this figure by the specific gravity of diesel fuel (0.840 kg dm⁻³) provided the fuel consumption per hour (kg h⁻¹).
Eventually, a string encoder (Celesco mod. VT 201-0025) was installed onto the chipper infeed (Figure 3) to continuously measure the upper feed roller’s vertical displacement, which corresponded to the diameter of the stem being processed as it entered the machinery.

Figure 2. Volumetric fuel consumption meter installed onto the tractor.

Figure 3. (a) String encoder measuring the vertical displacements of the upper drum of the feeder, which corresponded to the diameter of the stem entering the machinery. (b) Close-up of the connection.
A PCI card connected to an on-board notebook collected data from all sensors synchronized according to the timer. The acquisition software was set up for real-time data processing at 10 Hz [42]. The parameters directly measured were as follows: time, \( t \) (s), fuel consumption, \( F \) (cm\(^3\)); PTO torque, \( M \) (daNm); PTO speed, \( s \) (min\(^{-1}\)); and stem diameter, \( D \) (mm).

2.2. Working Time, Productivity, Energy Consumption, Emissions and Cost Analysis

The data processing started based on the analysis of the diagrams reporting the curves of the instant values of stem diameters and power demands related to the chipping of each tree sampled from the 61 poplar plants. The diagrams were used to identify the most significant phases of the operation and accurately select and extract the corresponding blocks of data from the entire dataset. The analysis of each data block provided detailed information on the trend of basic parameters and permitted the calculation of derived dynamic and energetic parameters. Thus, for each tree, we obtained the following data:

- Chipping time, \( t \) (s): for each tree, this time was the difference between the last- and first-time values of the relating data block.
- Trunk volume, \( V \) (m\(^3\)): This measure was calculated by multiplying the section of the trunk by its length. The section was determined on the basis of the average trunk diameter, i.e., the length. It was the sum of all instantaneous volume values collected for each tree. The calculation of the instantaneous volume relied on the relative instant PTO speed changes, which were referred to as the mean speed of 997 min\(^{-1}\), which corresponded to the trunk forward speed of 0.217 m s\(^{-1}\) observed while chipping a series of trunks of known length. Multiplying the instant forward speed by instant diameter and acquisition time provided the trunk instant volume.
- Working productivity, \( WP \) (in Mg h\(^{-1}\)): this measure was determined on the basis of the processing times, according to the formula proposed in [43].
- Hourly fuel consumption, \( F_h \) (kg h\(^{-1}\)): this measure was calculated by \( F \) assuming a diesel density of 0.840 kg L\(^{-1}\).
- Hourly energy, \( C_h \) (MJ h\(^{-1}\)).
- Power delivered at PTO, \( W \) (kW).
- Mechanic energy, \( C_m \) (kWh).
- Specific mechanical energy, \( C_{mech} \) (kWh m\(^{-3}\)): this measure was the mechanical energy referred to the volume of chipped trunks;
- fuel specific consumption, \( F_{sp} \) (g kWh\(^{-1}\));
- \( CO_2 \) emissions, \( EM \) (kg).

The hourly energy \( Ch \) was calculated using the Formula (2) [43,44]:

\[
C_h = F_h \times LHV
\]  

(2)

where \( F_h \) is the hourly fuel consumption (kg h\(^{-1}\)) and \( LHV \) is the diesel low-heating value assumed as 42.68 MJ kg\(^{-1}\), [45].

The \( CO_2 \) emissions \( EM \) were calculated based on fuel consumption, assuming complete oxidation of all fuel carbon content to \( CO_2 \). The calculation was performed by following the COPERT method of the European Environment Agency [46] and applying Formula (3):

\[
EM = 44.11 \frac{FC}{12.01 + 1.01 r}
\]  

(3)

where \( EM \) is the calculated value of \( CO_2 \) emissions expressed in kg, \( FC \) is the fuel consumption in kg and \( r \) is the ratio of the number of hydrogens to carbon atoms in fuel (about 2.0 for diesel).

By applying Formula (3), we determined that about 3.14 kg of \( CO_2 \) were emitted into the atmosphere per kg of fuel consumed. Since, in this specific case, a diesel density of 0.840 kg L\(^{-1}\) was considered, the quantity of \( CO_2 \) emitted per liter of fuel was
approximately 2.64 kg CO₂ L⁻¹ [44]. The calculation of hourly emissions was, therefore, carried out by multiplying the hourly fuel consumption (L h⁻¹) by the aforementioned coefficient.

Furthermore, the evaluation of the operating cost of the chipping operation was carried out via an analytical method, which evaluated the fixed and variable costs related to the tractor and chipper used [47], considering operating cost to be a single operator.

2.3. Statistical Analysis and Predictive Models

The statistical analysis was performed using the database consisting of 61 observations (each plant was considered an observation) that were successively clustered into 5 groups according to trunk diameter (expressed in mm): (1) D < 60; (2) 60 ≤ D < 70; (3) 70 ≤ D < 80; (4) 80 ≤ D < 90; and (5) D > 90. Each observation included the following variables: average and maximum power delivered during operation, chipping rate, speed of feed rollers, diameter, length (excluding treetops with diameter < 30 mm), trunk volume and tree weight. These variables were used to calculate both fuel and energy consumption, as well as to build predictive models through the univariate multiple regression method.

All variables were tested for the normality and homogeneity of the variance through Shapiro–Wilk and Levene tests, respectively. ANOVA and Tukey’s Post Hoc test were performed to highlight the significant differences between the means of the groups, and their classification into homogeneous groups was performed at a level of significance of the p-value < 0.05.

Multiple Linear Regression (MLR) predictive models were developed for the estimation of the following dependent variables: (1) Wc—working productivity (Mg h⁻¹); (2) Wt—working time (h·Mg⁻¹); (3) FC—fuel consumption (L·Mg⁻¹); (4) EM—CO₂ emissions (kg·Mg⁻¹); (5) EC—energy consumption (MJ·Mg⁻¹); and (6) CO—cost (€·Mg⁻¹). MLR is a linear approach used to model the relationship between a quantitative dependent variable and a set of independent explanatory variables that can be easily quantified by the users who apply the models. The predictive model for each of these variables was built as starting from five initial predictors, such as maximum power output, average tree diameter, maximum tree diameter, length of the trunk and weight. The MLR predictive models were determined by applying the backward stepwise method with a progressive elimination of the variables deemed less significant for the model’s goodness, selecting, among the proposed models, the model with the highest corrected R² value and the lowest estimation error. The analysis was conducted via SPSS version 18 statistical software.

3. Results and Discussions

3.1. Experimental Data

Data acquisition for time, stem diameter, fuel consumption, PTO torque and PTO speed produced as many as 29,045 records, which required a post-processing step to sync variables and permit the elaboration.

In fact, a preliminary data analysis highlighted a delay of about 3 s between the peaks of the trunks’ diameters and the peak of the PTO torque. This delay was probably due to the time needed by trunks to slide from feed rollers (where the diameter is measured) to chipping organs (where torque and rotation speed is recorded via the torque transducer). Based on this assumption, data were synchronized to align diameter, PTO torque and fuel consumption. Thus, Figure 4 shows the strict connection between the curve of the power (calculated based on PTO torque and speed) and those of the trunks’ diameters [34]. Base power was constantly experienced and ranged between 10.5 and 9.1 kW from the beginning to the end of the experiment. Moreover, the slight decrease in base power absorption was due to the increased temperature of transmission oil in both tractors and woodchippers during the experiment. Since this measure represented the power needed by woodchippers to sustain approximately 1000 rpm and it did not contribute to the mere
chipping operation, a mean value of 10 kW was assumed and subtracted from global power to calculate net power (Figure 4, lower diagram). Base power contributed to 10 kg·h⁻¹ of fuel consumption.

![Figure 4](image-url)

**Figure 4.** Variations in the trunk diameters and associated power requirements during the chipping of 61 poplar trees. Upper diagram (a): trunk diameter (red) and global power required (blue). Lower diagram (b): net power required by the chipping process.

Figure 5 shows the characteristics of the distributions through the representation of box plots, with the relative statistically significant differences (*p*-value < 0.05) expressed using different letters. In Figure 5, the distributions related to the maximum values observed for the power delivered during the chipping operation, the length of the trunk and the relative weight are reported. For the maximum power absorbed at the power take-off, the average values measured vary from a minimum of 38.85 (SD ± 7.58) kW for class 1 to a maximum of 58.86 (SD ± 12.95) kW for class 5. Regarding trunk length, the difference is only notable between class 1 (9.28 m ± 2.49 m) and class 5 (12.09 m ± 2.82 m). Greater differentiation is found in the average weights of the tree, with more significant differences noted between the class 1 and the class 5, starting from a minimum of 19.20 (SD ± 6.52) kg to a maximum of 72.63 (SD ± 20.21) kg, thus confirming the findings of the previous literature regarding the strong effect of piece size on chipping power requirements [40,48].
Figure 5. Box plot of the characteristics of the distributions related to the maximum power output, length and weight of the trunk grouped based on the diameter class of the trees subjected to chipping. Different letters indicate a statistically significant difference (p-value<0.05) of the dependent variable with respect to the different diameter classes.

Figure 6 shows the distributions of the working time and fuel consumption for chipping operations, as well as the relative CO2 emission, energy consumption, and chipping cost per tree. It is evident that as diameter increases, working time, fuel consumption, emissions and costs proportionally increase [34]. A statistically significant difference between classes 1 and 5 for all variables was found, while values in the intermediate classes were similar. The working time records range from a lower mean time of 42.62 (SD ± 11.37) s·tree−1 (class 1) to a higher mean time of 55.99 (SD ± 13.37) s·tree−1 (class 5). Instead, the average fuel consumption per tree of wood chips varied from a minimum value of 133.53 (SD ± 28.30) mL to a maximum value of 220.69 mL (SD ± 86.89). Class 4 was not statistically different from classes 5, 3 and 2.

CO2 emission and energy consumption exhibited the same statistical distribution because they both depend directly on fuel consumption. Values ranged from a minimum of 0.35 (SD ± 0.07) kg·CO2·tree−1 and 4.23 (SD ± 0.90) MJ·tree−1 to a maximum of 0.58 (SD ± 0.23) kg·CO2·tree−1 and 7.00 (SD ± 2.76) MJ·tree−1, respectively. As for the chipping cost per tree, it ranged from a minimum value of 0.66 (SD ± 0.18) €·tree−1 for class 1 to a maximum value of 0.87 (SD ± 0.21) €·tree−1 for class 5.

Figure 6. Box plot of the characteristics of the distributions related to the working time, fuel consumption, CO2 emissions, energy consumption and cost per tree, which are grouped based on the diameter class of the trees subjected to chipping. Different letters indicate a statistically significant difference (p-value<0.05) of the dependent variable with respect to the different diameter classes.

Figure 7, on the other hand, shows the distributions of the same variables but refers to the unit of weight used. The box plots show marked statistical differences between the diameter classes, with higher values for class 1 and lower values for class 5. Time and operating costs are statistically different between classes, with minimum values of 0.22 (SD ± 0.02) h·Mg−1 and 12.07 (SD ± 0.93) €·Mg−1 in class 5 and 0.64 (SD ± 0.09) h·Mg−1 and 35.34 (SD ± 4.88) €·Mg−1 in class 1, respectively. Fuel consumption ranges from 3.04 (SD ± 0.88) L·Mg−1 in class 5 to 7.32 (SD ± 1.46) L·Mg−1 in class 1, highlighting that the higher working productivity obtained when chipping larger trees also leads to a reduction in fuel consumption per unit of weight chipped. Emission and energy consumption also show similar trends. The lowest CO2 emission of 8.03 (SD ± 2.32) kg·Mg−1 was found in class 5, while the highest value of 19.32 (SD ± 3.87) kg·Mg−1 was found in class 1. This finding
corresponds to energy consumptions of 96.41 (SD ± 27.84) MJ·Mg⁻¹ and 232.12 (SD ± 46.44) MJ·Mg⁻¹, respectively.

The recorded values of working performance are greater than those reported in the literature. Nevertheless, this outcome was expected after comparing the working performance of small-scale chippers to industrial chippers, which showed working productivity ranging between 21 Mg h⁻¹ and 58 Mg h⁻¹, corresponding to 0.047 and 0.017 h Mg⁻¹, respectively [31–33], as well as specific fuel consumption lower than 2 L·Mg⁻¹ [32]. On the other hand, the chipping costs per unit of biomass found in the present study were only similar to those of industrial chippers in relation to the larger diameter classes, which was a consequence of the low working productivity for smaller trees when using small-scale machinery [32,33].

![Graphs showing various energy-related metrics](image)

**Figure 7.** Box plot of the characteristics of the distributions related to the working time, fuel consumption, CO₂ emissions, energy consumption and cost per Mg, with variables grouped based on the diameter class of the trees subjected to chipping. Different letters indicate a statistically significant difference (p-value<0.05) of the dependent variable with respect to the different diameter classes.

### 3.2. Predictive Models

The proposed MLR model formulas, predictors and statistical analysis ratios are shown in Table 1.

**Table 1.** Predictive models to estimate working time, working productivity, fuel consumption, CO₂ emissions, Energy consumption and cost per Mg of biomass chipped (*).

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Equation</th>
<th>R²</th>
<th>R² Adj.</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working time</td>
<td>WT = 1.727 − 0.018 Dm + 0.01 Pm − 0.027 Tl + 0.007 Tw</td>
<td>0.949</td>
<td>0.946</td>
<td>0.0323</td>
</tr>
<tr>
<td>Working productivity</td>
<td>WP = −1.699 + 0.062 Dm − 0.002 Pm − 0.046 Tl + 0.013 Tw</td>
<td>0.994</td>
<td>0.994</td>
<td>0.0776</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>FC = 22.409 − 0.246 Dm + 0.043 Pm − 0.545 Tl + 0.113 Tw</td>
<td>0.848</td>
<td>0.837</td>
<td>0.6794</td>
</tr>
<tr>
<td>Emissions</td>
<td>EM = 59.178 − 0.651 Dm + 0.112 Pm − 1.440 Tl + 0.298 Tw</td>
<td>0.848</td>
<td>0.837</td>
<td>17.932</td>
</tr>
<tr>
<td>Energy consumption</td>
<td>EC = 710.847 − 7.815 Dm + 1.348 Pm − 17.298 Tl + 3.580 Tw</td>
<td>0.848</td>
<td>0.837</td>
<td>215.383</td>
</tr>
<tr>
<td>Cost</td>
<td>CO = 96.070 − 1.012 Dm + 0.030 Pm − 1.489 Tl + 0.402 Tw</td>
<td>0.949</td>
<td>0.946</td>
<td>18.007</td>
</tr>
</tbody>
</table>

(*) where WT = Working Time (h·Mg⁻¹); FC = Fuel Consumption (L·Mg⁻¹); EM = CO₂ Emissions (kg·Mg⁻¹); EC = Energy Consumption (MJ·Mg⁻¹); CO = Cost (€·Mg⁻¹).

The regression models discriminated between four independent regressors using a constant for each model, as shown in Table 1. All models were high performers and showed adjusted R² values of between 0.837 and 0.994. In Figures 8–10, the model-predicted values were compared to the observed values for the variables WT and WP.
(Figure 8), EM and EC (Figure 9), and FC and CO (Figure 10), respectively. The observed R² values were the highest found for this type of study, being even higher than the predictive performance of more complex mixed-effects models [49].

![Figure 8. Predicted and observed values of working time (h·Mg⁻¹) and fuel consumption (L·Mg⁻¹) related to 61 trees.](image1)

![Figure 9. Predicted and observed values of CO₂ emissions (kg·Mg⁻¹), energy consumption (MJ·Mg⁻¹) and unit cost (£·Mg⁻¹) related to 61 trees.](image2)

![Figure 10. Predicted and observed values of fuel consumption (L·Mg⁻¹) and cost (£·Mg⁻¹) related to 61 trees.](image3)

3.3. Study Limitations

This study represents a preliminary attempt to investigate the effects of operative parameters on the performance of chipping operations in MRC plants, which was carried out within the framework of small-scale forestry. Although the working conditions in actual forestry environments may be more challenging, the main limitation is probably
related to having developed the study in a single study area, which is represented by an experimental field located within a research institute. On the other hand, this research framework also represented a strong point of the present study, as it allowed us to produce an in-depth investigation by installing complex sensors on moving machinery, which, in most cases, is not possible to carry out in forestry. Future development of the present trial should, therefore, involve repeating the study in different contexts, relying on the collaboration between research centers operating within a research consortium, which can apply more complex models, like linear mixed effects models, which are able to account for the effects of random factors.

4. Conclusions

This study aimed to provide deeper insight into poplar chipping process used at medium-rotation plantations developed on a small scale. The chipping process was analyzed by applying sensors and instruments to the machine for direct measurement of absorbed power, fuel and energy consumption and CO₂ emissions produced as a function of the size of the trees sampled.

Prediction models were also evaluated together with estimations of tractor-driven forest chippers’ performances, chipping costs and CO₂ emissions. The main findings of the present article suggest that the productivity of the chipping operations using trees from small-scale MRC poplar plantations increases in proportion to the increase in the average trunk’s diameter. Consequently, optimal economic and environmental sustainability is expected at the highest diameter class. However, the total cost of producing wood chips was not higher than for large-scale developed systems, which require more powerful and expensive machines to accomplish the same task. The predictive models based on working time per produced unit, work productivity, CO₂ emissions, energy consumption, fuel consumption and costs were very promising and returned values very close to the experimental data collected, making them suitable for similar practical applications in the future. However, further studies are also required in order to strengthen these preliminary results and apply the predictive models to other species involved in MRC plantation wood production.

**Author Contributions:** Conceptualization, all authors; methodology, W.S., G.S. and D.P.; data curation, G.S., D.P. and R.F.; writing—original draft preparation, all authors; writing—review and editing W.S., F.L. and G.S.; supervision, G.S. and D.P.; funding acquisition, G.S. All authors have read and agreed to the published version of the manuscript.

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