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Determining the Impact of Some Wood Characteristics on the Performance of a Mobile Chipper

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A study was conducted to determine the effect of some wood characteristics such as species, moisture content and tree part on the performance and product quality offered by a mobile industrial chipper, of the type commonly used for roadside chipping. Two main species, two tree parts and two moisture content levels were combined in a factorial design yielding 8 treatments, each replicated 5 or 6 times. A flow meter was installed on the chipper engine, and all chips produced were weighed and sampled for moisture content and particle size distribution. The results indicated that some wood characteristics such as species and moisture content have a secondary effect on chipper productivity and fuel consumption, which are primarily controlled by piece size. In particular, fuel consumption per unit dry mass seem to be rather constant and in the range of 3.2 l per oven dry ton. Moisture content and tree part may have a significant effect on the particle size distribution of chips. Of course, these results were only verified for the species used in the test and for industrial chippers, and may change if substantially different species or machines are used.

Keywords chipping, productivity, biomass, fuel consumption
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1 Introduction

Comminution is an essential element of all modern energy wood chains, because automated boilers only accept homogeneous fuel particles within specified size limits. Furthermore, comminution may offer additional benefits in terms of increased load density and improved handling quality (Pottie and Guimier 1985). Bulky raw materials should be comminuted as early as possible, in order to accrue such important benefits all along the supply chain (Björheden 2008). That explains the widespread popularity of mobile chippers, which allow size reduction directly in the forest or at the roadside landing, before transportation (Asikainen and Pulkkinen 1998). In fact, the place of chipping along the supply chain is one of the main characteristics defining different work systems (Stampfer and Kanzian 2006). Within this context, chipping is often described as a main source for the cost and the emissions incurred by wood energy supply systems, and all attempts at modelling them must include some estimate of chipper productivity, cost and fuel consumption (Mälkki and Virtanen 2003). Chipping is a relatively simple process, and incurs costs that are less variable than those of the other components of the energy wood supply chain (Bjørnstad 2005). As a consequence, most current comparisons of wood energy supply chains account for chipper productivity and fuel consumption with generic models (Forsberg 2000, Wihersaari 2005) or fixed assumptions (Gustavsson et al. 2011, Eriksson 2008). However, the conditions of chipping change with the specific work system considered, and one may suspect that chipper performance will vary depending on wood species, size and moisture content. While specific models for chipper productivity are already available to the international scientific community (Spinelli and Hartsough 2001), much less information exists on chipper fuel consumption. Dedicated peer-review studies are missing and most data are currently derived from local studies, published in the national languages and less accessible to the international scholar (Andersson and Nordén 2000, Liss 2003). Some of these studies show a strong relationship between fuel consumption and wood characteristics, which would contradict the use of standardized average figures (Liss 1987). Furthermore, wood characteristics may have a significant effect on particle size distribution, which is crucial to fuel handling efficiency (Jensen et al. 2004), to its drying and reaction rate (Lu et al. 2010), to the energy required for conversion into ethanol (Hosseini and Shah 2009), and to the yield of bio-oil obtained from pyrolysis (Shen et al. 2009).

Therefore, the goal of this study was to determine the effect of wood characteristics on the performance and product quality offered by a mobile industrial chipper, of the type commonly used for roadside chipping. In particular, the study aimed at defining if tree portion (stem or branches), tree species (softwood or hardwood) and wood moisture content (fresh or dry) could be associated with statistical significance to any eventual differences in machine productivity, fuel consumption and particle size distribution.

Such information is crucial to obtaining accurate estimates of chipper fuel consumption and GHG emissions, and will therefore allow for a more realistic comparison between energy wood supply chain options.

2 Materials and Methods

The mobile industrial chipper used for the experiment was a trailer-mounted Pezzolato PTH 900/660M. This machine featured a massive steel drum, with a diameter of 660 mm and a width of 950 mm. The drum carried two large blades, as on most Italian and Nordic-made drum chippers. The drum, the hydraulic infeed system, and the evacuation augers and propeller were all powered by a 260 kW FIAT-IVECO C87 ENT diesel engine. This was a state-of-the-art common-rail Tier III industrial engine, with an 8.7 l displacement. Before starting the experiment, the manufacturer installed a new set of blades and a 50 mm vertical bar screen (Fig. 1), which was the standard screen for producing industrial fuel chips. Tighter screens could be installed when producing fine chips for small-scale users. The machine was equipped with an integral knuckle-boom loader, used for bringing the wood to the hydraulic infeed system.

For the purpose of the experiment, the machine was fed with 8 different raw material types, deriving from the combination of tree portion (stem or

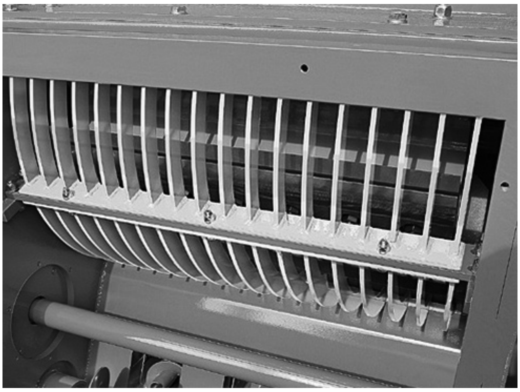

Fig. 1. Chipper blade and bar screen.

branches), tree species (softwood or hardwood) and wood moisture content (fresh or dry). European larch *(Larix decidua* Mill.) and common beech (*Fagus sylvatica* L.) were used to represent softwood and hardwood species, respectively (Table 1). In fact, larch is a very peculiar softwood species, which sheds its needles in winter and has a rather strong wood. However, no significant amounts of spruce or pine were available in the area, and the larch was harvested during the growing season, so that both fresh and dry branch material retained most of the needles. The experiment included 5 replications per treatment, each replication consisting of just one grapple load. Two treatments were actually replicated 6 times in order to use up all the test wood (Table 2). The amount of material used for each replication was kept intentionally small, in order to avoid the effect of blade wear. This has a significant impact on chipper productivity and fuel consumption, which increase rapidly with the amount of wood processed by the same set of blades and can be predicted with specific equations (Nati et al. 2010). These equations were used to estimate the productivity drop and the fuel consumption increase occurred between the beginning and the end of the study, as a consequence of blade wear. The total amount of wood processed for the study was 8.17 fresh tonnes, and the resulting figures

Table 1. Wood characteristics of the species used for the test.

		Beech (*Fagus sylvatica* L.)	Larch (*Larix decidua* Mill.)
Wood density at 15% m.c.	kg m^{-3}	650	550
Compression strength	N mm^{-2}	62	50
Traction strenght	N mm^{-2}	110	107
Shear strength	N mm^{-2}	8	9
Ultimate bending strength	N mm^{-2}	115	94
Modulus of elasticity	N mm^{-2}	14500	14000

Source: Giordano (1986).

Table 2. Test description: experimental design.

Treatment code	Tree species	Tree part	Moisture content	Number of replications	Piece size kg (fresh)	Batch size kg (fresh)	m.c. %
SSF	Softwood	Stem	Fresh	5	34.8 b	326.6 a	38.8 bc
SBF	Softwood	Branches	Fresh	5	3.8 a	141.0 b	41.7 c
SSS	Softwood	Stem	Stored	6	24.2 b	174.3 b	41.4 c
SBD	Softwood	Branches	Dry	5	2.7 a	125.6 b	21.5 a
HSF	Hardwood	Stem	Fresh	5	23.5 b	243.6 a	37.4 bc
HBF	Hardwood	Branches	Fresh	5	3.6 a	119.0 b	34.9 b
HSD	Hardwood	Stem	Dry	5	40.5 c	271.4 a	20.8 a
HBD	Hardwood	Branches	Dry	6	2.4 a	126.3 b	19.5 a

Note: different letters on the average values in the same column indicate statistical significance at the 5% level; m.c. = moisture content as % of total weight

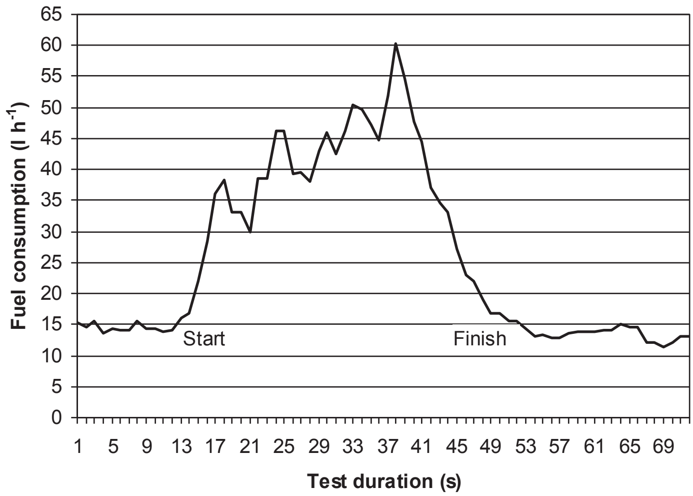

Fig. 2. Fuel consumption graph obtained from Test no. 7 (example). Note: the test concerned fresh hardwood branches.

were –0.6% and 1.9%, respectively for productivity and fuel consumption. These hypothetical variations were randomly spread across treatments using a randomised study design.

Fuel consumption was determined by installing a mechanical-electromagnetic flow meter on the injection pump lines. The flow meter was checked and calibrated before starting the test. Instantaneous fuel consumption readings were recorded at one second intervals. Before starting the test, the engine was run for about 30 minutes in order to reach a stable temperature. Each measurement lasted between 17 and 90 seconds, with an average of 40 seconds.

Output was determined by weighing the chips produced within each replication with a portable scale. To this end, the chips were blown onto a tarpaulin, which was then folded, tied and lifted with a separate hydraulic loader. The portable scale was placed between the loader hook and the tarpaulin, whose weight was recorded separately and subtracted from the individual readings. The scale had a rated accuracy of 200 g.

Two one-kg samples were collected from each replication for determining moisture content and particle size distribution. The former was obtained with the gravimetric method, according to European standard CEN/TS 14774-2; the latter with the oscillating screen method, according to European Standard CEN/TS 15149-1. Four sieves were used to separate the five following chip length classes: >63 mm (oversize particles), 63–45 mm (large-size chips), 45–16 mm (medium-size chips), 16–3 mm (small-size chips), <3 mm (fines). Each fraction was then weighed with a precision scale.

Effective time consumption was determined on the fuel consumption graphs, rather then by a stopwatch during actual work. When the chipper is processing such small batches, it is very difficult for an external observer to determine with absolute accuracy when the machine is actually working and when it is running idle. In fact, the machine evacuation system will keep spitting small amounts of chips for many seconds after the drum has finished its job. During this time the engine regime is dropping again. Under real work conditions, a new load would be engaging the drum at this stage, and the engine regime would not be decreasing so sharply and for so long. To determine the beginning and the end of process time, all graphs were analyzed in order to estimate a basal fuel consumption figure, taken as a reference for the running machine before its drum actually engages the wood. This figure was found at the 15 l h^{-1} level, which was then adopted as the threshold for defining actual chipping time. All test time when fuel consumption was above this level was counted as chipping time and used for calculating net chipping productivity, whereas all the other test time was excluded from calculations (Fig. 2). Average fuel consumption when chipping was calculated on the records above the 15 $l\ h^{-1}$ threshold.

Data were analyzed with the Statview advanced statistics software, in order to check the statistical significance of the eventual differences between treatments. Data satisfying the normality assumption were analyzed with Scheffe's post-hoc test, which is considered most conservative and robust (SAS 1999). In the few cases were the normality assumption was not verified, the Kruskal-Wallis non-parametric test was used.

3 Results

Table 2 shows a first important distinction between tree parts, namely: the substantially different piece size. Stem treatments offered 10 times the piece size of branch treatments, which is both logical and most likely to have a considerable impact on test results. Hence, any "tree part" treatment incorporated a possibly dominant piece size component. A further consequence was that batch size (grapple load) was proportionally larger for stem material than for branch material. In any case, piece size was relatively small, since large logs were not chipped, but processed into more valuable structural assortments. As expected, fresh material was heavier than dry material. Table 2 also shows that there was no difference in the moisture content of dry softwood stems and fresh softwood stems. Although the first batch was harvested 18 months before the test, it had undergone a minimal moisture content loss, no greater than that obtained by the second batch after just one month in the open air. That effectively eliminated the "dry softwood stem" treatment from the comparison, and the treatment was renamed "stored softwood stems". However, one could expect that the resistance properties of old moist wood were different from those of both fresh and dry wood.

The results in Table 3 show that tree part had a dominant effect on net chipping productivity: tests conducted on stem wood returned significantly higher productivity figures than tests on branch wood. As an average, the productivity recorded when chipping stem wood was 50 to 60% higher than that obtained when chipping branch wood. That held true when productivity was expressed in fresh tons, and in oven dry tons (odt). For the same tree part, tree species and moisture content had no significant effect on net chipping productivity.

A similar grouping was obtained for hourly fuel consumption. The chipping of branch wood required about 30 $l\ h^{-1}$ and that of stem wood 42 $l\ h^{-1}$. The results for unit fuel consumption were somewhat more articulated, and data stratified in three different groups. The lowest consumption levels (in the range of 1.7 $l\ t^{-1}$) were recorded on fresh stem wood: this allowed high chipping productivity, and did not prove too hard to hack.

Table 3. Net chipping productivity and fuel consumption.

Treatment code	Tree species	Tree part	Moisture content	Productivity		Consumption		
				$t\ h^{-1}$	$odt\ h^{-1}$	$l\ h^{-1}$	$l\ t^{-1}$	$l\ odt^{-1}$
SSF	Softwood	Stem	Fresh	27.4 b	16.7 d	45.7 b	1.68 b	2.74 ab
SBF	Softwood	Branches	Fresh	12.9 a	7.5 ac	28.1 a	2.20 ab	3.79 b
SSS	Softwood	Stem	Stored	21.3 b	12.4 b	37.7 ab	1.78 b	3.04 ab
SBD	Softwood	Branches	Dry	11.2 a	8.9 ab	30.8 a	2.86 a	3.66 ab
HSF	Hardwood	Stem	Fresh	22.9 b	14.3 bd	41.4 b	1.84 b	2.94 ab
HBF	Hardwood	Branches	Fresh	14.8 a	9.6 abc	31.8 a	2.17 ab	3.32 ab
HSD	Hardwood	Stem	Dry	16.4 ab	13.0 bcd	44.0 b	2.70 a	3.42 ab
HBD	Hardwood	Branches	Dry	14.8 a	11.9 b	31.0 a	2.11 ab	2.63 a

Note: different letters on the average values in the same column indicate statistical significance at the 5% level; odt = oven-dry ton

Table 4. ANOVA table for chipping productivity and fuel consumption.

	Effect	DF	SS	MS	F-Value	P-Value	Power
t h^{-1}	Part	1	761.49	761.49	99.64	<0.0001	1.00
	Species	1	10.37	10.37	1.36	0.2521	0.19
	MC	1	131.29	131.29	17.18	0.0002	0.99
	Part * Species	1	143.71	143.71	18.80	0.0001	0.99
	Part * MC	1	80.25	80.25	10.50	0.0027	0.90
	Species * MC	1	1.23	1.23	0.16	0.6912	0.07
	Part * Species * MC	1	2.95	2.95	0.39	0.5382	0.09
	Residual	34	259.85	7.64			
odt h^{-1}	Part	1	222.46	222.46	61.34	<0.0001	1.00
	Species	1	7.02	7.02	1.93	0.1733	0.26
	MC	1	2.65	2.65	0.73	0.3988	0.13
	Part * Species	1	32.89	32.89	9.07	0.0049	0.85
	Part * MC	1	55.85	55.85	15.40	0.0004	0.98
	Species * MC	1	10.20	10.20	2.81	0.1027	0.36
	Part * Species * MC	1	2.75	2.75	0.76	0.3898	0.13
	Residual	34	123.31	3.63			
l h^{-1}	Part	1	1446.93	1446.93	100.29	<0.0001	1.00
	Species	1	23.02	23.02	1.60	0.2151	0.22
	MC	1	8.14	8.14	0.56	0.4577	0.11
	Part * Species	1	2.19	2.19	0.15	0.6987	0.07
	Part * MC	1	33.54	33.54	2.32	0.1366	0.30
	Species * MC	1	33.32	33.32	2.31	0.1378	0.30
	Part * Species * MC	1	130.25	130.25	9.03	0.0050	0.85
	Residual	34	490.54	14.43	.		
l t^{-1}	Part	1	1.19	1.19	12.76	0.0011	0.95
	Species	1	0.06	0.06	0.67	0.4169	0.12
	MC	1	1.57	1.57	16.82	0.0002	0.99
	Part * Species	1	2.26	2.26	24.15	<0.0001	1.00
	Part * MC	1	0.08	0.08	0.89	0.3498	0.15
	Species * MC	1	0.01	0.01	0.01	0.9352	0.05
	Part * Species * MC	1	1.41	1.41	15.06	0.0005	0.98
	Residual	34	3.18	0.09			
l odt^{-1}	Part	1	1.05	1.05	4.90	0.0337	0.57
	Species	1	0.54	0.54	2.53	0.1212	0.32
	MC	1	0.00	0.00	0.01	0.9192	0.05
	Part * Species	1	2.80	2.80	13.03	0.0010	0.96
	Part * MC	1	1.67	1.67	7.80	0.0085	0.78
	Species * MC	1	0.10	0.10	0.44	0.5113	0.10
	Part * Species * MC	1	0.35	0.35	1.63	0.2105	0.22
	Residual	34	7.30	0.22			

Note: Part = stem or branches; Species = hardwood or softwood; MC = moisture content, i.e. fresh or dry; DF = Degrees of freedom; SS = Sum of squares; MS = Mean square

On the other hand, the highest consumption levels (in the range of 2.8 l t^{-1}) were recorded for dry hardwood stems and dry softwood branches, the former probably hardest to hack, the latter offering such a low productivity that unit consumption grew highest. Fresh softwood branches and hardwood branches were associated to intermediate unit consumption levels. However, when the effect of moisture content was removed and unit consumption was referred to dry matter output, then most differences evened out, and only two material types stuck out from an otherwise rather homogenous picture, with consumption levels in the range of 3.2 l odt^{-1}. These were dry hardwood

Table 5. Particle-size distribution of the chips produced during the experiment.

Treatment code	Tree species	Tree part	Moisture content	Oversize % weight	Large % weight	Medium % weight	Small % weight	Fines % weight	Accepts % weight
SSF	Softwood	Stem	Fresh	0.0 a	2.1 a	63.0 a	30.6 b	4.3 ab	95.7 a
SBF	Softwood	Branches	Fresh	6.4 b	17.7 b	61.1 a	11.7 a	3.1 ab	90.5 b
SSS	Softwood	Stem	Stored	0.2 a	4.8 a	56.4 a	35.9 b	2.7 a	97.1 a
SBD	Softwood	Branches	Dry	0.0 a	5.0 a	44.8 a	46.8 b	3.4 ab	96.6 a
HSF	Hardwood	Stem	Fresh	0.2 a	1.2 a	47.9 a	48.0 b	2.7 a	97.1 a
HBF	Hardwood	Branches	Fresh	1.8 a	6.6 a	60.6 a	24.1 a	6.9 b	91.3 b
HSD	Hardwood	Stem	Dry	0.0 a	1.3 a	28.2 a	68.0 c	2.5 a	97.5 a
HBD	Hardwood	Branches	Dry	1.0 a	4.3 a	50.4 a	41.0 b	3.3 ab	95.7 a

Note: different letters on the average values in the same column indicate statistical significance at the 5% level; "Accepts" represent the sum of chips in all classes (i.e. Large, Medium and Small), excluding oversize particles and fines.

branches and fresh softwood branches, respectively associated to a fuel consumption of 2.6 and 3.8 l odt^{-1}.

The ANOVA in Table 4 confirms the dominant effect of tree part (i.e. piece size) on net productivity. When productivity is expressed in dry weight, then tree species and moisture content have no effect on productivity, except when interacting with tree part. Tree part is the only factor with a significant effect on hourly fuel consumption. The situation is more complex when considering fuel consumption per unit product, because interactions also have their specific effects.

Table 5 shows the main results obtained for particle size distribution. Chips produced from fresh softwood branches emerged for the significantly higher proportion of oversize particles compared to the other chips. In general, fresh softwood branches showed a tendency to produce a large proportion of large particles, even within the limits of acceptable chip sizes. On the contrary, fresh hardwood branches produced a significantly larger proportion of fines, compared to all other raw material types. This was probably related to beech leaves, which turned dry and brittle within few days from cutting, but not as dry as to fall from the branch. Once into the chipper, leaves pulverized, generating a significant amount of dust material. Overall, fresh branches produced the lowest proportion of acceptable chips, in the range of 90% . They also showed a visible tendency to produce chips in the larger size classes, although this difference was not statistically significant. On the contrary, chips produced from dry branches presented about the same proportion of accept particles as chips produced from stem wood.

The Anova in Table 6 allows appreciating the complex relationships between the incidence of particle-size classes and the wood characteristics considered in this study. Tree part, species and moisture content have significant effects on particle size distribution, both singularly and in combination.

4 Discussion

When it comes to drying, storage conditions seem to have a stronger effect than storage duration: if the wood is placed in a well-ventilated location, then one summer period is enough to bring moisture content below the 40% threshold (Nurmi and Hillebrand 2007). However, storage in the forest does not guarantee the same result, especially if the wood is stored in the form of logs and the bark is intact. Despite the long storage period, softwood stems did not dry significantly, and therefore the study did not include a "dry softwood stem" treatment. This had a significant impact on the test, effectively skewing design balance and preventing any conclusive statements on the effect of this specific combination on chipper performance.

The experiment confirms previous findings about the dominant effect of piece size on pro-

Table 6. ANOVA table for particle size distribution.

	Effect	DF	SS	MS	F-Value	P-Value	Power
Oversize particles	Part	1	36.23	36.23	21.98	<0.0001	1.00
	Species	1	12.45	12.45	7.56	0.0097	0.77
	MC	1	23.44	23.44	14.23	0.0007	0.97
	Part * Species	1	12.85	12.85	7.80	0.0087	0.78
	Part * MC	1	22.90	22.90	13.90	0.0007	0.97
	Species * MC	1	22.68	22.68	13.76	0.0008	0.96
	Part * Species * MC	1	29.56	29.56	17.94	0.0002	0.99
	Residual	34	52.73	1.65			
Large chips	Part	1	390.91	390.91	25.77	<0.0001	1.00
	Species	1	133.38	133.38	8.79	0.0057	0.83
	MC	1	108.21	108.21	7.13	0.0118	0.74
	Part * Species	1	21.79	21.79	1.44	0.2395	0.20
	Part * MC	1	220.03	220.03	14.50	0.0006	0.97
	Species * MC	1	25.57	25.57	1.68	0.2035	0.23
	Part * Species * MC	1	80.31	80.31	5.29	0.0281	0.60
	Residual	34	485.49	15.17			
Medium chips	Part	1	387.36	387.36	1.92	0.1758	0.26
	Species	1	695.04	695.04	3.44	0.0729	0.42
	MC	1	1926.64	1926.64	9.53	0.0041	0.87
	Part * Species	1	1632.77	1632.77	8.08	0.0077	0.80
	Part * MC	1	11.32	11.32	0.06	0.8144	0.06
	Species * MC	1	72.80	72.80	0.36	0.5526	0.09
	Part * Species * MC	1	141.10	141.10	0.70	0.4096	0.12
	Residual	34	6466.53	202.08			
Small chips	Part	1	2355.73	2355.73	10.57	0.0027	0.90
	Species	1	1630.20	1630.20	7.31	0.0109	0.75
	MC	1	3938.55	3938.55	17.67	0.0002	0.99
	Part * Species	1	1299.29	1299.29	5.83	0.2170	0.65
	Part * MC	1	562.20	562.20	2.52	1.2210	0.32
	Species * MC	1	0.08	0.08	0.00	0.9850	0.05
	Part * Species * MC	1	505.44	505.44	2.27	0.1419	0.29
	Residual	34	7133.61	222.925			
Fines	Part	1	9.39	9.39	4.00	0.0539	0.48
	Species	1	1.14	1.14	0.48	0.4914	0.10
	MC	1	13.11	13.11	5.59	0.0243	0.63
	Part * Species	1	15.14	15.14	6.46	0.0161	0.70
	Part * MC	1	0.53	0.53	0.23	0.6378	0.07
	Species * MC	1	2.47	2.47	1.05	0.3129	0.16
	Part * Species * MC	1	14.40	14.40	6.14	0.0187	0.67
	Residual	34	75.04	2.34			

Note: Part = stem or branches; Species = hardwood or softwood; MC = moisture content, i.e. fresh or dry; DF = Degrees of freedom; SS = Sum of squares; MS = Mean square

ductivity (Spinelli and Magagnotti 2010), power requirement (Liss 1986) and fuel consumption (Van Belle 2006). In a previous modelling study, Spinelli and Hartsough (2001) postulated that the absence of any significant effects of tree species and wood moisture content on productivity derived from the lack of a controlled design, which made their experiment unable to detect secondary effects. However, the present study was performed under controlled conditions, and yet no evidence could be found for the effect of tree species and moisture content on machine productivity and fuel consumption. As to tree species, one may question the capacity of European larch to represent the softwood family as a whole, although it would be problematic to find any single species capable of representing such a large group. Concerning moisture content, one may notice that Liss (1987) did find a significant relationship between wood moisture content and chipper power requirements. However, he worked on a much smaller machine than that used for our experiment, and it is possible that machine sensitivity to external factors is inversely proportional to engine power. All that could be summarized in the obvious statement that the results of this study are only valid for the specific machine and tree species used to conduct it. At most, these results could be extended to other similar machines in the same size class. However, developing a more general model would require extending the study to include other machines and tree species (Van Belle 2006). What one could infer from this study, is that the net productivity and the hourly fuel consumption of medium-size industrial chippers have a very strong correlation with piece size, and a much weaker correlation – if any – with tree species and wood moisture content.

Readers must also consider that the figures in this study refer to net chipping productivity and fuel consumption, and are calculated for chipping time only, excluding all accessory work time and all delays (Björheden et al. 1995). In particular, delays can represent a significant proportion of a chipper's scheduled work time, and may occupy up to 50% of the total work site time (Spinelli and Visser 2009). In actual operations, the effect of delays will not only reduce machine productivity and decrease hourly fuel consumption, but may also blur the eventual differences related to wood characteristics. On the other hand, focusing the study on the actual chipping phase allowed minimizing operator effect, because the machine was totally independent from operator control in this phase. Operator effect is a main source of variability (Purfürst and Erler 2006), and may account for productivity differences up to 77% (Harstela 1988). In fact, it is not certain that using the same operator for different tests or in the same test will categorically exclude operator effect (Lindroos 2010). Hence, limiting the observation to a totally "robotic" phase guarantees the exclusion of operator effect, which is generally much stronger than the secondary effects one was trying to detect in this experiment, and could have confounded the results.

Fuel consumption per dry unit is rather constant, and no clear stratification is evident. The only significant difference is between fresh softwood branches and dry hardwood branches, at opposite ends of the spectrum. A possible reason for such difference, is that dry hardwood branches are brittle and compact, thus allowing rapid feeding with minimum effort; the contrary is true for fresh softwood branches, bulkier and much more resilient. For the rest, it appears that the higher productivity obtained when processing larger pieces can offset the higher fuel consumption per hour. This seems to indicate that adopting an average fuel consumption per dry mass unit is a reasonable way to account for the energy inputs and the GHG emissions associated to chipping operations, when analysing chip supply chains (Yoshioka et al. 2006).

Another separate study conducted by the same authors (Spinelli et al. 2010) did find that the percent weight of accept particles was lowest in fresh softwood branches. This was true regardless of chipper type, despite its significant effect on particle size distribution (Spinelli et al. 2005). Hence, the result obtained in the current study confirms a primary effect of wood characteristics on particle size distribution. The fact that neither study found the same effect for dry branches points at the significant benefit obtained by letting branch material dry before comminution, as already found by Suadicani and Gamborg (1999).

5 Conclusions

Wood characteristics such as species and moisture content seem to have a secondary effect on chipper productivity and fuel consumption. In fact, machine performance appears to be controlled primarily by piece size, which also mediates the effect of tree part. On the contrary, tree part and moisture content may have a strong effect on the particle size distribution of the chips. Moisture content could be managed to manipulate particle size distribution. Of course, these results were only verified for the species used in the test and are valid for industrial chippers only. Different results might be obtained if substantially different species or machines are used. Nevertheless, the indications of the study seem rather clear, and may reflect a more general trend.

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