A Versatile Terrain and Roadside Chipper for Energy Wood Production in Plantation Forestry

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Abstract

A new industrial chipper was designed for use in short-rotation forestry plantations, which requires high productivity and all-round mobility. The new machine was tested at seven different sites, representative of the main work environments negotiated by modern agroforestry contractors. The tests produced 114 chip containers, or 929 tonnes of fresh chips (ca. 3,500 m^3 of loose chips). Productivity varied between 28 and 55 tonnes of fresh chips (or 105 and 194 m^3 of loose chips) per productive work hour, excluding delays. Pure chipping productivity (calculated on chipping time only) was higher and peaked at 70 tonnes of fresh chips or 242 m^3 of loose chips per hour. Fuel consumption ranged from 1.38 to 2.15 litres of diesel per tonne of green chips, or from 0.39 to 0.59 litres of diesel per m^3 of loose chips. Machine utilization rate varied between 69 and 83 %. Highest efficiency was reached at plant yards, due to optimum pile layout, wide space availability and easy chip discharge. Due to its remarkable off-road mobility, the new machine can restore efficiency to terrain chipping, provided that the terrain is flat and solid, the piles are duly arranged and a large enough support fleet is available for moving the chips to their destination.

Keywords: biomass; energy; poductivity; fuel consumption; quality

Introduction

Managed natural forests are an important source of wood biomass, but remote location, difficult terrain and stringent environmental constraints make forest harvesting especially difficult, which may result in expensive and irregular supplies (Spinelli and Magagnotti 2014). For this reason, an increasing proportion of the global wood biomass supply is being sourced from dedicated plantations established on farm land (Ragauskas et al. 2006). Plantation forestry is widely acknowledged as a sustainable source of wood biomass, and offers a viable alternative to the overexploitation of the remaining natural forests, where these are threatened by industrial development or demographic pressure (Berndes et al. 2003). Planted forests are generally established with fast-growing species, such as *Pinus*, *Eucalyptus* and *Populus* (FAO 2009). *Eucalyptus* and *Populus* are probably the best performers, with yields in the range from 20 to 40 m^3 per hectare and year (Siry et al. 2005). *Eucalyptus* plantations cover 18 million hectares, and are especially popular in the Southern Hemisphere. Planted poplar is mainly used in the Northern Hemisphere, and covers almost 9 million hectares worldwide (FAO 2012).

The increasingly important role of plantation forestry is also visible in Europe. On one hand, Europe still has a large forest base but struggles to exploit it and leaves it largely underutilized (Ericsson and Nilsson 2006). On the other hand, agroforestry is supported by the European Union with attractive grant schemes, in an attempt to increase wood biomass availability and to promote rural development (Stupak et al. 2007). In fact, recent projections estimate the wood biomass potential of European agriculture to be three times as large as that of European forests (EEA 2006), which partly reflects the rapid expansion of agroforestry in recent years (De Wit and Faaij 2010).

Agroforestry plantations offer a very different work environment compared with natural forests, and minimum-cost supply may be achieved with different techniques (Spinelli and Magagnotti 2011). In particular, agroforestry work may revive interest in terrain chipping, which has lost much of its appeal in natural forests (Kärhä 2011). With terrain chipping, the wood is reached by the chipper directly in the field, and is extracted to the field edge after comminution (Talbot and Suadicani 2005). This technique maximizes the benefits of size reduction by placing it at the very beginning of the supply chain (Björheden 2008). At the same time, it allows fastest drying in the open field (Civitarese et al. 2015) and minimum contamination during handling (Greene et al. 2014). However, even when it is solid and even, forest terrain hinders the access of chipping machinery and limits their size and productivity, making roadside chipping a more efficient alternative (Marchi et al. 2011). For this reason, forest biomass is generally chipped at roadside, all over Europe (Díaz-Yáñez et al. 2013). On the other hand, agroforestry plantations are much easier to access than the most accessible natural forests, and that offers a new opportunity to terrain chipping (Spinelli et al. 2014a).

Recent studies have shown that under the conditions of European plantation forestry, terrain chipping is more efficient and less expensive than roadside chipping (Spinelli et al. 2012). However, these very same studies expressed concerns about the mobility of adapted farming and forestry equipment, both considered sub-optimal for terrain chipping. Apparently, there is a need for dedicated agroforestry machinery, capable of making the best of the opportunities offered by these new emerging crops. Specific machines have already been developed, such as a few large-size industrial chipper models, obtained from the combination of a forestry chipper and a large farmland carrier, typically a forager (Manzone and Spinelli 2013) or a sugar beet harvester (Mihelic et al. 2015). However, the flexible use of these machines is hindered by a base carrier that was not developed for agroforestry use. Foragers typically mount small wheels on the rear axle, which detracts from their off-road mobility and makes terrain access difficult when the soil is rough or wet. Sugar beet harvesters are not designed for carrying a heavy chipper, and once the chipper is installed on such a carrier, total axle weight exceeds the road legal limit, which requires sub-optimum solutions for allowing road access. However, in 2015 a completely new agroforestry chipper appeared on the market, which did not result from the adaptation of a farmland carrier, but had been designed from scratch so as to integrate all the requirements of agroforestry operations.

The goals of this study were 1) to determine the performance of the new agroforestry chipper, in terms of productivity, fuel consumption and chip quality and 2) to gauge how much chipper performance is affected by different work environments, in order to probe machine versatility. Although specifically designed for matching the peculiar requirements of agroforestry operations, an efficient chipper must offer a good performance also when deployed under different work environments, because industrial contractors generally manage a diversified wood basket.

Materials

The new chipper analysed in this study was the Pezzolato PTH 1400/820 Allroad (Figure 1). The machine was designed and built from scratch, in order to provide the best possible match to the needs of agroforestry contractors. It was powered by a 405 kW Scania engine, meeting Euro 6 compliance requirements (European Union 2007) through the exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) technologies. That removed the need for a conventional diesel particulate filter, which generally represents a severe fire hazard for machines working in dusty environments. The chipper was completely redesigned and featured a new 3.5 t drum, with a width of 1400 mm and a diameter of 820 mm. The drum was of the closed type (Spinelli et al. 2014b), but used 5 staggered small knives instead of the classic two full-length knives.

Chip evacuation was obtained through a new hydraulic blower with adjustable speed, for meeting variable ejection distance needs and minimizing fuel consumption. The no-stress feeding function could also be adjusted on-the-fly to match different feedstock types. The operator cab could be lifted and turned towards the infeed opening, to guarantee optimum worksite visibility through its wide polycarbonate windows.

The carrier was designed and built by Pezzolato, and featured four large diameter wheels (1,500 mm), equipped with versatile (on-off road) tractor tyres. Transmission and steering were fully hydrostatic, and three different steering modes were provided. The complete machine was 2.5 m wide and weighed 25,900 kg, equally distributed between the two axles. The vehicle was road legal and could travel on public roads up to a maximum speed of 40 km h^{-1}. This was an all-round industrial chipper that could travel across the plantations, as well as relocate rapidly and independently between worksites.

The study consisted of field trials conducted at seven different sites (Table 1). These seven test sites included a full range of work conditions encountered by agroforestry contractors. Feedstock type, operation setup and logistics varied between sites, which impacted the results of individual trials.

The seven test sites reflected a full range of working environments, from the typical agroforestry (poplar) plantations of the region, to industrial wood yards, classic mountain landings and platforms for the accumulation of park maintenance residues at the urban interface. All the poplar plantation sites (1, 2 and 3) represented terrain chipping operations on flat terrain, after the stand had been clearcut, the timber had been removed and all the residues bunched in piles containing approximately 2-3 fresh tonnes each. The two plant yards (sites 4 and 5) consisted of a large paved yard with wood neatly piled in 4-m tall stacks. Finally, the two landings (sites 6 and 7) were unpaved enlargements of an unpaved road, where wood was piled in one continuous pile about 4-m tall.

All tests were conducted in June 2015 in the Piemonte region, northwestern Italy. Each field trial lasted long enough to produce a minimum of 8 loads. Total study time

Figure 1. The Pezzolato Allroad at work

Table 1. Characteristics of the test sites

Site type	Feedstock		mc %		Piece mass Kg		Output		
	Material type	species	Mean	SD	Mean	SD	Loads	t	m^3
1. Poplar clearcut	Tops	Poplar	48.2[a]	2.7	70.0[a]	5.8	9	80.9	276
2. Poplar hill	Tops	Poplar	45.5[a]	3.6	52.9[a]	6.7	10	89.5	342
3. Poplar salvage	Tops	Poplar	39.2[c]	2.8	50.5[a]	20.2	15	108.8	479
4. Poplar yard	Slabs, offcuts	Poplar	41.8[c]	4.1	6.4[b]	1.3	20	106.6	500
5. Chestnut yard	2m logs	Chestnut	47.3[a]	2.8	72.0[a]	12.3	40	284.5	1000
6. Mountain operation	Tops	Chestnut, pine	31.6[b]	2.4	49.6[a]	23.5	8	100.4	374
7. Pruning residues	Slash	Garden trees/shrubs	39.4[c]	5.5	21.2[a]	5.0	12	158.7	522
Total							114	929.4	3493
Average			43.2	5.8	42.9	25.4			

Notes: mc = moisture content (or water mass fraction); SD = Standard deviation; m^3 = bulk volume of loose chips; Chestnut = *Castanea sativa* L.; Pinus = *Pinus strobus* L.; Poplar = *Populus ×Euroamericana*; Garden trees/shrubs = *Cupressus* sp., *Pinus* sp., *Laurus nobilis* L., *Magnolia grandiflora* L. etc. Different superscript letters along the same column indicate statistically significant differences between treatments (sites) for $\alpha = 0.05$, according to Scheffe's post-hoc test.

amounted to 35.4 hours, including mechanical, personnel and operational delays but excluding local transfers and study delays. During the study, the chipper produced 114 containers, amounting to 3,493 m^3 loose chips or 929 tonnes of fresh chips (mean moisture content = 42.6%). The mean bulk density of the fresh chips was 266 kg m^{-3}. The machine was operated by the same driver, a well-trained, experienced and efficient professional, who was very proficient with his job and equipment. He had about 5 years of experience with the industrial chippers built by the same manufacturer. The same 35 mm cut length adjustment and 100 × 100 mm square-mesh screen were used for all trials.

Methods

The authors carried out a typical time-and-motion study, designed to evaluate machine productivity and to identify those variables that are most likely to affect it (Magagnotti et al. 2013). Each work cycle was timed individually, using hand-held field computers, running dedicated time study software. Productive time was separated from delay time, but excessive further detail was avoided in order to contain error and guarantee repeatability of the experiment (Spinelli et al. 2013). Productive time was divided between chipping work proper and other work (e.g.

moving the chipper along the piles, parking the container by the chipper and loader work other than chipper feeding). The filling of a chip container was considered as one cycle. All delays were included in the study, and not just the delays below a set duration threshold, because such practice may misrepresent the incidence of downtime (Spinelli and Visser 2008). However, delays caused by the study itself were removed from the data set.

Total volume output was estimated by measuring the internal volume of all containers and visually assessing the volume of any mounds or voids on the container top. Total mass output was determined by taking all loads to a certified weighbridge at the load reception site, a local wood-fired power station. Piece size (i.e the size of the individual wood element - log, top or branch - inserted into the chipper) was determined by dividing the mass of each load by the count of wood elements inserted into the chipper when producing that load. Two 500 g samples were collected from each container load in order to determine moisture mass fraction and particle size distribution. Each 500 g sample was obtained after reduction of a larger sample assembled by mixing subsamples collected at different points from the container top. Moisture mass fraction was determined with the gravimetric method, according to European standards (CEN 2009). Fresh weight was determined on-site with a portable scale, immediately after sample collection. Particle size distribution was determined with the oscillating screen method using four sieves to separate the sample into five chip length classes: > 63 mm (oversize particles), 63-46 mm (large-size chips), 45-17 mm (medium-size chips), 16-3 mm (small-size chips), < 3 mm (fines). Each fraction was then weighed with a precision scale (0.1 g). For the purpose of the analysis, particle size data was consolidated into three functional classes: oversized (> 63 mm), accepts (63-3 mm) and fines (< 3 mm).

Fuel consumption was measured by parking the chipper on the same level spot and filling the diesel tank with a fuel pump accurate to 0.1 dm^3, before starting and after completing each test. The fuel tank, pump and meter were loaded on a pick-up truck that followed the chipper to the work site. Fuel consumption was the gross fuel consumption for the chipper and the loader, since both were powered by the same engine.

The dataset was analyzed with the Minitab 16 and Statview advanced statistics softwares, in order to check the statistical significance of eventual trends. Before analysis, the data was tested for normality using Ryan-Noyer's test. Non-normal distributions were normalized using transformations. In particular, the arcsine transformation was used for the percent efficiency data, and the logit transformation for the percent particle size data; the latter already used in the same application by Eliasson et al. (2015). The dataset was then checked for homoscedasticity using Bartlett's test. Normal, homoscedastic data were tested using the Tukey-Kramer test, which is especially suited to handle unbalanced datasets and is relatively powerful. In contrast, heteroscedastic data were handled with non-parametric and post-hoc tests, robust to violations of statistical assumptions, although less powerful than the Tukey-Karmer's test. In particular, the Kruskal-Wallis test was used for checking the presence of statistically significant differences between groups, and the Scheffe's post-hoc test for pinning such differences onto specific groups. Both such tests are suitable for data sets flawed by unequal numbers of observations, non-normal distribution of data and heteroscedasticity (SAS 1999). The significance of any relationships between productivity and piece size was tested with regression analysis. In that case, compliance with the statistical assumptions was checked through the analysis of the residuals.

Results

The feedstock stored at the different worksites differed for type, size and moisture content (Table 1). Tops were chipped at all agroforestry plantations sites and at the forest landing, whereas sawmill residues (slabs and offcuts) and logs were chipped at the two industrial yards. However, the sawmill residues handled at the poplar yard were significantly smaller (ca. 6 kg apiece) than the logs at the chestnut yard, and than any other feedstock types used for the trials, except for the pruning residues that consisted of branches. With a water mass fraction of 31 %, tops stacked at the mountain landing were significantly drier than any other feedstock used for the trials, as the result of their longer storage time. Freshly cut poplar and chestnut were significantly wetter than the rest (45 to 48 % moisture content), except for the diseased poplars coming from the salvage operations, where a high proportion of standing deadwood contributed to decrease mean moisture content. The moisture content of freshly-cut salvaged poplar (39 %) did not differ significantly from that of sawmill and pruning residues (42 % and 39 %, respectively).

Mechanical availability was 94 %, as could be expected for a new machine. A large proportion of mechanical delays consisted of knife replacement. Mean machine utilization rate was 77 % and ranged from 69 to 83 %, due to the effect of all delays combined (Figure 2). Utilization was the lowest in the mountain operation, as the result of landing space constraints and irregular chip truck flow - both related to the typical accessibility constraints of mountain landings (Spinelli et al. 2014c). The proportion of accessory work to net work time was significantly lower at both the chestnut and the poplar yards than at the other sites, as a result of an easier working environment in terms of larger and more orderly stacks, and wider space for manoeuvring. Actual chipping time represented between 55 and 80 % of total worksite time, with the highest figures being recorded again at the plant yards.

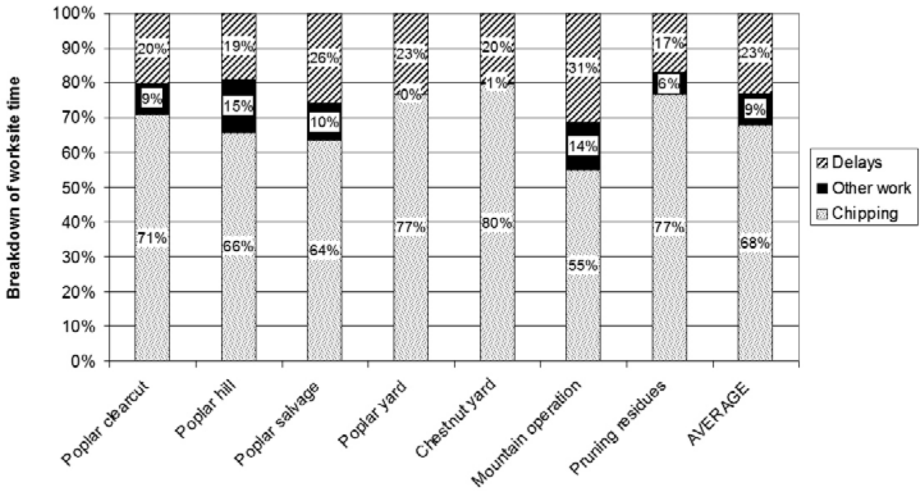

Figure 2. Breakdown of worksite time by activity

Note: Other work = moving the chipper along the piles, parking the container by the chipper and loader work other than chipper feeding

Total worksite productivity (inclusive of delays) varied between 19 and 44 fresh tonnes per scheduled hour, or between 72 and 156 m^3 loose chips per scheduled hour (Table 2). Expressed as fresh weight, gross productivity was clearly stratified: highest at the chestnut yard, lowest at the mountain landing and intermediate in between. These differences were statistically significant. When productivity was expressed as loose volume the same pattern repeated, but further divisions appeared within the intermediate stratum.

Pure chipping productivity was calculated on the basis of chipping time only, excluding other work time and delays, and ranged from 28 to 55 tonnes per hour, or from 104 and 194 m^3 loose chips per hour (Table 2). Again, the best performance was reached at the chestnut yard, where productivity reached the peak values of 70 tonnes and 242 m^3 per hour. Expressing productivity in volume rather than weight increased the resolution of the analysis, by removing the confounding effect of variable moisture content. Chipping productivity had a positive but relatively weak correlation (R^2 = 0.10) with piece size. However, when the yard data were removed from the analysis, correlation improved remarkably (R^2 = 0.33).

Specific fuel consumption varied between 1.38 and 2.15 litres of diesel per fresh tonne, or between 0.30 and 0.59 litres per m^3 of loose volume. Fuel consumption figures seemed to follow productivity trends, and were low-

Table 2. Productivity of the chipper at the seven test sites

Site		Total worksite productivity				Pure chipping productivity			
		t SMH^{-1}		m^3 SMH^{-1}		t h^{-1}		m^3 h^{-1}	
type	n	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1. Poplar clearcut	9	28.7^{c}	2.7	99.2^{bc}	13.2	35.9^{bc}	3.4	124.2^{bcd}	16.5
2. Poplar hill	10	30.7^{c}	3.5	118.5^{cd}	12.7	37.8^{bc}	4.3	146.1^{cd}	15.7
3. Poplar salvage	15	25.4^{c}	5.6	112.5^{c}	24.8	34.3^{c}	7.6	151.8^{cd}	33.5
4. Poplar yard	20	28.3^{c}	3.9	133.1^{d}	18.1	36.9^{c}	5.1	173.7^{ad}	23.6
5. Chestnut yard	40	44.3^{a}	4.9	155.7^{a}	14.8	55.1^{a}	6.1	193.6^{a}	18.4
6. Mountain operation	8	19.4^{b}	2.7	72.2^{b}	9.1	28.2^{b}	3.9	105.2^{b}	13.2
7. Pruning residues	12	26.2^{c}	3.6	86.5^{b}	13.4	31.6^{bc}	4.3	104.2^{b}	16.1
Average		32.9	9.7	125.2	32.1	41.8	11.5	159.4	39.1
Post-hoc test		Tukey-Kramer		Scheffe		Tukey-Kramer		Scheffe	

Notes: SMH = Scheduled Machine Hour, inclusive of delays; m^3 = bulk volume of loose chips; *SD* = Standard deviation; Different superscript letters along the same column indicate statistically significant differences between treatments (sites) for $\alpha = 0.05$. Tukey-Kramer's post-hoc test was used for normally-distributed homoscedastic data, whereas Scheffe's test was used for normally-distributed heteroscedastic data.

est when productivity was highest. However, differences in fuel consumption were not tested for statistical significance, because there were no replications within the treatments. The chipper tank was filled only twice per test: before the test started and right after it ended. The tank was not refilled for each container load, because the amount of diesel used for producing a single chip load was too small for obtaining accurate enough fuel use figures when the tank-refill technique was used. Therefore, any statements regarding the differences in fuel consumption between treatments cannot be taken as conclusive.

Chip quality closely related with feedstock type. The proportion of accepts ranged from 72 % to 92 % of total sample weight (Table 4). It was the highest for fresh poplar tops and the lowest for pruning residues. The reverse was true for the incidence of oversized particles, which were the highest for pruning residues and the lowest for fresh poplar tops. In general, the incidence of oversized particles was relatively high for short (sawmill residues) or branchy materials (pruning residues and tree tops). The box-plots in Figure 3 also show a neat stratification for

Table 3. Diesel fuel consumption per product unit

Site type	Fuel use l t^{-1}	Fuel use l m^{-3}
1. Poplar clearcut	1.67	0.49
2. Poplar hill	1.84	0.48
3. Poplar salvage	1.70	0.39
4. Poplar yard	1.43	0.30
5. Chestnut yard	1.38	0.39
6. Mountain operation	2.15	0.58
7. Pruning residues	1.95	0.59
Average	1.67	0.45

m^3 = bulk volume of loose chips

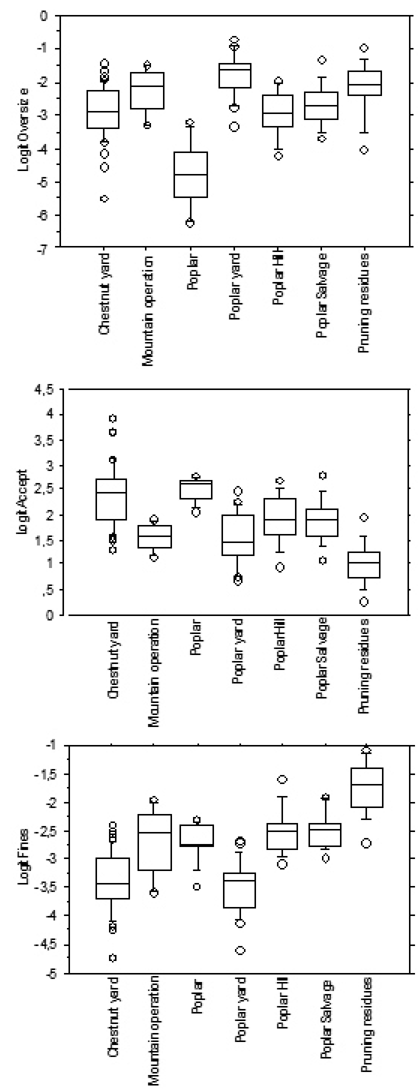

Figure 3. Box-plot of logit-transformed particle size distributions

Table 4. Particle-size distribution of wood chips

Site type	n	Oversize, % Mean	Oversize, % *SD*	Accepts, % Mean	Accepts, % *SD*	Fines, % Mean	Fines, % *SD*
1. Poplar clearcut	9	1.1^{c}	1.2	92.4^{ac}	1.8	6.5^{c}	1.8
2. Poplar hill	10	5.9^{b}	3.7	86.0^{abc}	6.1	8.1^{bc}	3.5
3. Poplar salvage	15	5.9^{a}	5.4	86.2^{ac}	5.2	7.9^{bc}	2.5
4. Poplar yard	20	15.7^{d}	8.1	81.1^{bd}	7.8	3.2^{a}	1.4
5. Chestnut yard	40	5.9^{a}	4.6	90.5^{a}	15.0	3.6^{a}	1.9
6. Mountain operation	8	10.8^{bd}	5.6	82.1^{bd}	4.0	7.1^{bc}	3.4
7. Pruning residues	12	11.9^{a}	6.7	72.4^{a}	8.2	15.7^{d}	5.9
Average		8.2	6.9	84.6	11.4	6.2	4.7
Post-hoc test		Tukey-Kramer		Scheffe		Tukey-Kramer	

Notes: Oversize = particle length > 63 mm; Accepts = particle length 63-3 mm; Fines = particle length <3 mm; SD = Standard deviation; Different superscript letters along the same column indicate statistically significant differences between treatments (sites) for $\alpha = 0.05$. Tukey-Kramer's post-hoc test was used for normally-distributed homoscedastic data, whereas Scheffe's test was used for normally-distributed heteroscedastic data what concerns the incidence of fines, with pruning residues at the top, yard operations at the bottom and tops in between. That may indicate a relationship between the incidence of fine and the proportion of foliage in the feedstock. Yard feedstocks contained no leaves, while pruning residues included the largest proportion of foliage. Tops had a significant foliage component, but also included a much larger stem portion than pruning residues.

Discussion

The trial sites represented a wide variety of working environments and allowed testing the new machine under the conditions offered by terrain chipping, roadside chipping and yard chipping. In no case the incidence of delays exceeded 30 %, which is the benchmark reported for conventional chipping operations in Italy (Spinelli and Visser 2009). Utilization and productivity were the highest when working at a yard, regardless of feedstock type (chestnut logs or sawmill residues). Neat stack arrangement facilitated regular feeding, while quick trailer turnover allowed minimizing interaction delays. In contrast, utilization was the lowest and delays were the highest when working at a mountain landing, due to the access constraints typical for mountain sites, eventually resulting in extended manoeuvres and irregular chip van turn out. In this respect, the most noteworthy result is the high efficiency achieved in the terrain chipping operations, which demonstrates the success of the new design. The machine moved easily across the plantations, matching the performance of forwarder-mounted units while maintaining independent relocation capacity. In contrast, forwarder-mounted chippers need to be moved around on low-bed trucks, because they are too slow for independent relocation on any distances longer than few kilometres, and they are not road-legal in most European countries. Of course, the good results achieved with terrain chipping was not the exclusive merit of machine mobility and productivity, but arose from good organisation as well. A sufficient number of chip transports had been detached to support the chipper and the tops had been bunched before chipping, so that interaction delays were minimized and productivity was maximized. Even so, if the machine had struggled manoeuvring or it had bogged down, overall efficiency would have dropped significantly. That was certainly not the case. In fact, the chipper was even used to boost a slipping tractor, when its trailer was so full that it could not drive up a ramp. In turn, restoring financial viability to terrain chipping would allow solving a number of practical problems, including the need for a suitable space by the roadside for storing the biomass. Once chipped and loaded on a trailer, the product can be moved more efficiently, and it can be taken to a terminal or to the user plant, when this is located nearby. Terrain chipping does not avoid extraction and stacking, but makes them more efficient.

The new machine also fares well in terms of production potential, when compared with similar units currently available on the market (Table 5). Net chipping productivity is about 20% higher than recorded for an agroforestry chipper obtained from the conversion of a powerful forager, and used for chipping the same feedstock (Manzone and Spinelli 2013). The productivity of the new machine is on par with that recorded for the Silvator 2000, its most direct competitor in terms of size class and general design. In this respect, it is worth mentioning that the new Pezzolato chipper is almost twice as heavy as the modified forager, and about 20% lighter than the Silvator, which the manufacturer considers as a good balance between strength and agility.

As a family of machines, the new agroforestry chippers seem to have a higher productive and fuel efficiency than conventional forestry chippers despite the fact that two of the forestry chippers – the Erjo and the Jenz – were fed by a separate loader powered independently, whereas all other chippers featured integral loaders powered by the same engine as the chipper. Of course, the data in Table 5 must be interpreted with much caution, because they

Table 5. Performance comparisons

Machine characteristics			Productivity		Fuel		Reference
Make	Model	kW	$m^3 h^{-1}$	$t h^{-1}$	$l m^{-3}$	$l t^{-1}$	Study
				Agroforestry			
Pezzolato	AllRoad	405	105-195	28-55	0.39-0.59	1.3-2.1	Current study
Albach	Silvator	450	161-180	38-56	0.43-0.68	1.0-2.3	Mihelic et al. 2015
Pezzolato	Forager	409	100-110	25-30	0.48-0.55	1.6-1.8	Manzone and Spinelli 2013
				Forestry			
Pezzolato	Chippertruck	400	69-97	22-28	0.55-0.76	1.8-2.8	Spinelli et al. 2015
Erjo	12/90	430	67-94	20-28	0.39-0.50	1.3-1.7	Marchi et al. 2011
Jenz	561 HEM	335	113-174	33-51	0.50-0.62	1.7-2.1	Spinelli et al. 2012

Notes: all studies were joined by the same principal investigators, which assured consistent methodology; the Erjo and Jenz units were fed by a separate loader, whereas the other units featured integrated loaders powered by the same engine as the chipper come from separate studies, and not from a single comparative study conducted under controlled conditions. For this reason, different work conditions and operator proficiency may account for part of the differences despite the use of similar feedstock types and experienced operators in all studies. Furthermore, all studies mentioned in Table 5 were conducted or participated by the same principal investigators, which guarantees methodological consistency and facilitates comparisons.

This study also confirms the important relationship between productivity and piece size, as well as the capacity of other factors to confound it. Piece shape, pile arrangement and chipping site do have their own additional influence, as already demonstrated by previous studies (Spinelli and Hartsough 2001, Spinelli and Magagnotti 2010, Spinelli et al. 2015). The results obtained from site 4 can be taken as an example: there, the better handling quality of regularly-shaped tightly-packed slabs and the favourable work space offered by an industrial yard explained a very high productivity, despite the extremely small piece size.

Chip quality is generally good, and shows the expected relationship with feedstock type. The highest proportion of oversized particles occurred with sawmill and pruning residues. The former offered a multitude of small, short and brittle pieces that could easily turn sideways when engaged by the chipper drum and produce long splinters; the latter contained a high proportion of thin flexible twigs that could occasionally bend rather than cut, and pass through the drum as long sticks. The same dynamics may explain the large proportion of oversized particles found in chips produced from forestry tops, which were also rich with small branches (Spinelli and Hartsough 2001).

The incidence of fines seems to be directly proportional to the amount of foliage, being the highest with pruning residues (maximum incidence of foliage) and the lowest with sawmill residues and logs (no foliage at all). This relationship has already been reported in many previous studies (Saudicani and Gamborg 1999, Nati et al. 2010, Spinelli et al. 2011, Spinelli et al. 2015).

Again, unit choice confirms its strong effect on productivity estimates (Spinelli et al. 2015). Direct measurement of chipper output is only made in fresh weight (green tonnes) or bulk volume (m^3 loose chips): dry weight and heating value are artificial figures that are extremely useful for a correct evaluation of fuel production cost, but much less valuable for estimating machine performance in a typical engineering study. A chipper does not move oven-dry tonnes or kilowatt hours: it moves an actual fresh mass and bulk volume. Which of these two ones is chosen for evaluating machine productivity, has a strong effect on the results of the evaluation itself. Fresh weight estimates may be biased by different moisture content, because drier fuels will produce artificially low production figures. In that respect, volume estimates are somewhat fairer, but they may underestimate the additional effort made with wetter and heavier feedstock, and the resulting higher fuel consumption. In general, it is advisable to use both measurements in conjunction, because use of a single reference unit may not tell the whole story.

Conclusions

The new chipper can reach a very high productivity, when deployed under the appropriate conditions. Its main advantage is that of bringing a full-scale industrial operation directly to the stump site. This operation can release its full production potential if the biomass is duly prepared, and a large enough support fleet is tasked with moving the chips to their destination. One of the most important characteristics of the new chipper is the capacity to combine the off-road mobility of a forwarder-mounted unit with the road capability of a truck-mounted machine, although its maximum speed is substantially lower than that of a truck. Fortunately, this is not a serious problem, unless relocation distances are particularly long: that is rarely the case in plantation forestry, and generally in rural areas. The combination of favourable terrain and dedicated chippers may restore profitability to terrain chipping, when deployed in plantation forests. As the surface of fast-growing plantations expands, these new chippers may become increasingly popular.

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