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Industrial harvesting of olive tree pruning residue for energy biomass

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ABSTRACT

In Mediterranean countries, olive tree pruning residue represents an abundant source of energy biomass, still largely unexploited for lack of cost-effective harvesting technology. The authors tested two industrial pruning harvesters, capable of overcoming the limits of lighter units appeared in the past years. One of the machines was designed for application to a powerful farm tractor, whereas the other was a self-propelled dedicated harvester. Data were collected from 10 operations, covering a total of 69 hectares and producing over 190 tonnes of wood fuel. Recorded productivity varied between 3 and 9 tonnes per scheduled machine hour (SMH), or 2–7 oven dry tonnes (odt) SMH^{-1}. Harvesting cost varied from 17 to 52 € t^{-1}, with an average value of 28 € t^{-1}: these values correspond, respectively to 22, 70 and 40 € odt^{-1}. This compares very favourably with the average 1–1.5 ton SMH^{-1} offered by lighter commercial units. Productivity was related to residue density, row length and forwarding distance. Mechanical availability was high and over 90%, for both machines. The authors also developed a simple deterministic model capable of predicting harvesting productivity and cost, as a function of significant site and economic conditions. The model can also be used to determine the break-even utilization level, below which the operational flexibility of a tractor-mounted operation becomes preferable to the higher productivity of a specialised unit.

1. Introduction

Olive tree groves are a typical feature of the Mediterranean landscape, and in Europe they represent the ancestral crops of countries such as Italy and Spain, where olive oil production has represented an export-oriented industrial activity since at least two millennia (Talbert, 1985). The worldwide surface grown with olive trees amounts to almost 8.6 million hectares (FAOSTAT, 2009), basically grown in the Mediterranean Sea basin. Such crops require frequent pruning, which generates the equivalent of at least 1 oven dry ton (odt) of residue biomass per hectare (Laraia et al., 2001). In Italy alone, the annual amount of residue derived from the pruning of olive groves, vineyards and other orchards has been estimated to 2.85 million tonnes, net of the amounts already recovered for traditional utilization (Di Blasi et al., 1997). That explains why pruning residue generally plays an important role in any analysis of biomass availability conducted in these regions (Bernetti et al., 2004).

Until present, however, the management of pruning residue has generally represented a disposal problem, rather than an opportunity for additional revenue. Pruning residue is either mulched or piled and burned, at a cost estimated, respectively to about 100 and 200 € ha^{-1} (ARSIA, 2009). The rapid development of bioenergy has generated a growing demand for energy biomass (Masera et al., 2006), thus providing a potential outlet for pruning residue. However, such opportunity can be seized only if the biomass is delivered to the end user within set price limits. Hence, the interest in developing cost-effective technologies for the collection, processing and delivery of pruning residue.

Since a few years, a number of machine manufacturers have been offering dedicated implements for collecting pruning residue. These machines generally derive from conventional mulchers, equipped with a storage bin or with a blower, the latter designed to direct the flow of comminuted residue to an accompanying trailer. Such implements are relatively cheap, and are designed for being towed or carried by farm tractors in the 50–70 kW class. For this very reason they cannot achieve industrial performance, and their productivity is commonly in the range of 1 green tonnes per hour (Recchia et al., 2009). Such a low productivity level may compromise the economic sustainability of the operation, unless the work is conducted with surplus resources obtained at marginal cost. Besides, the rear-mounted design of these units implies that the tractor must straddle the windrowed residue, which is particularly difficult when the pruning has been concentrated in tall windrows, as a consequence of heavy pruning.

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Fig. 1. Tractor-mounted machine while harvesting olive pruning residues. The high-tipping bin is not installed here and biomass is blown onto a towed trailer.

Fig. 2. Self-propelled machine complete of 22 m^3 bin trailer.

Hence, there is a growing interest in developing powerful industrial units with frontal collection devices, which can overcome both the productive and the structural limits of lighter tractor-mounted machines. In recent years, two such units have appeared, both showing considerable potential. The German manufacturer Jordan has developed a collection and comminution implement for application to the three-point hitch of a powerful (>150 kW) reverse-drive tractor. The implement is based on a 30 cm capacity disc chipper, powered by the tractor PTO and equipped with a special hydraulic-drive pick-up and feeding device (Fig. 1). Chipped residue is blown into a 10 m^3 high-tipping bin, applied to the tractor nose and also serving as a counterweight. Further South, Valoriza Energia and the public Energy Agency for Andalusia, Spain, have built a self-propelled unit by applying a dedicated hydraulic pick-up and a high-speed belt-driven grinder to a dedicated prime mover. The machine is called SAT-4, and in its final version has a 200 kW engine and weighs 12.8 tonnes. Ground residue is blown into a 22 m^3 bin trailer towed by the harvesting unit (Fig. 2). Both the German and the Spanish machines have been under development for some years, and are now available in their commercial versions, a few specimen having already been sold.

The goal of this study was to determine the performance of both machines with scientific methods, so as to build a simple model for estimating harvesting productivity and cost under varying work and economic conditions. This model can assist prospective users when checking the profitability of an operation, or when assessing the competitiveness of alternative options. The model should return harvesting costs, as a function of residue density, row length, extraction distance, depreciation schedules etc. For any given set of working conditions, the model must be able to detect the break-even utilization level below which the versatility of the tractor-mounted option makes this solution preferable to the dedicated unit. In addition, the model may assist with the preparation of reliable biomass production forecasts and machine schedules.

2. Methods

The tests with the German tractor-mounted Jordan machine were conducted in 2007 at the National Research Council (CNR) experimental station in Follonica, Southern Tuscany. The machine was rented for the purpose and transported from Germany, so that these tests could only last a few days, including tune-up. Here the machine was applied to a 162 kW farm tractor and tested on three different fields for a total of about 4 ha. The Spanish SAT-4 unit was tested in 2009 during commercial activity in the area of Palenciana, Southern Spain: the tests lasted about a work week and covered 7 fields for a total of 65 ha. A description of the test fields is shown in Table 1. Slope details are neglected since it resulted to be always lower than 10%.

The study was designed to evaluate machine productivity and to identify the most significant variables affecting it. The data collection procedure consisted of a set of detailed time-motion studies conducted at the cycle level, where the harvesting of a full row was considered as a complete cycle. In general, detailed time studies are more discriminating than shift-level studies and can detect smaller differences between treatments (Olsen et al., 1998). Valid observation time amounted to 30 total work hours, covering 215 work cycles.

Cycle times for each machine were defined and split into time elements (Björheden et al., 1995) considered to be typical of the functional process analyzed: this was done with the intent of isolating those parts of a routine that are dependent on one or more external factors in order to enhance the accuracy of the productivity models (Bergstrand, 1991). In particular, five main elements were identified and separated, namely: collecting-comminuting, turning, forwarding the load, unloading, delays. All time elements and the related time-motion data were recorded with Husky Hunter® hand-held field computers running Siwork3 time-study software (Kofman, 1995).

Output was determined by measuring the volume of all chip containers produced during each test, and by taking sample containers to a certified weighbridge. Moisture content determination was conducted on three samples per container: these were collected randomly, put in sealed bags and then weighed fresh and after drying for 48 h at a temperature of 103° C in a ventilated oven, according to the European standard CEN/TS 14774-2.

Tree spacing was measured with a tape, whereas field boundaries, field surface area, the length of row harvested for each run and the distance covered while moving the loads to the collection point were measured with a hand-held GPS device.

Data were statistically analyzed with regression techniques to calculate any significant relationships between collecting-chipping time and windrow density (SAS, 1999). These equations were used to assemble a simple deterministic model, capable of returning residue collection costs as a function of user-entered independent variables. Such model does not require complicated programming and can be effectively assembled with a standard workbook package. Its simplicity is justified by the comparatively simple process to be modelled, which involves single units, so that machine interaction in the system is virtually absent. Although more realistic, discrete-event simulation models do not seem to offer dramatic

Table 1
Field description.

Machine	#	Self-propelled, Spain							Tractor-mounted, Italy		
Field		1	2	3	4	5	6	7	8	9	10
Spacing	m	9 × 7	14 × 14	14 × 14	14 × 14	14 × 14	10 × 9	7 × 5	7 × 5.5	7 × 5.5	7 × 5.5
Surface area	ha	6.57	1.61	7.04	8.61	12.9	10.2	18.44	0.59	1.74	1.58
Harvest	t	10.6	3.2	49.5	17.8	22.8	11.0	22.8	4.1	20.2	29.2
Moisture content	%	25	35	35	26	30	27	26	43	38	38
Harvest	odt ha^{-1}	1.20	1.30	4.57	1.53	1.24	0.79	0.91	4.03	7.25	11.56
Pruning intensity	kg tree^{-1}	10.1	39.3	137.9	40.6	34.6	9.7	4.3	27.0	44.7	71.2
Interrows: windrow	ratio	1:1	1:1	1:1	1:1	2:1	2:1	2:1	1:1	1:1	1:1

Notes: The operation conducted on site 3 was a stand replacement; the interrows to rows ratio represents two basic cases, namely if the windrows are built on each interrow (ratio 1:1) or if they are built on alternate interrows (ratio 2:1) to obtain a higher concentration of residue.

Table 2
Operational costs.

Machine		Tractor	Header and bin	Self-propelled
Investment	€	150,000	100,000	190,000
Service life	years	8	8	8
Usage	h year^{-1}	1000	600	600
Labour cost	€ h^{-1}	15	15	15
Crew	no	1	0	1
Fixed cost	€ year^{-1}	22,800	15,200	28,880
Variable cost	€ h^{-1}	62.5	8.3	78.2
Total cost	€ h^{-1}	**107**	**42**	**158**

increases in prediction accuracy when used on such simple process chains (Björheden, 2008). Deterministic spreadsheet models have already been used for estimating the cost of agricultural harvesting operations, such as sugar cane harvesting (Salassi and Champagne, 1998).

The model calculates machine costs with the method described by Miyata (1980), on the assumptions shown in Table 2. Labour cost was set to 15 € per scheduled machine hour (SMH), inclusive of indirect salary costs. The calculated operational cost was increased by 25% in order to include administration costs. The spreadsheet model is available for free, and can be requested from the authors at: spinelli@ivalsa.cnr.it.

3. Results

Overall, 69 ha were harvested, producing 191 tonnes of fresh biomass, which corresponds to an average yield of 2.8 t ha^{-1} (1.9 odt ha^{-1}). The concentration of residue showed significant variation, caused by differences in tree density and pruning intensity. Both were consistently higher in the Italian groves, which were relatively new and had been established following the modern specifications of thick industrial olive tree groves. Besides, these stands were pruned at relatively long intervals, in the range of 3–5 years. Residue yield ranged from 1 to 5 and from 4 to 11 odt ha^{-1}, respectively for the Spanish and the Italian plantations. These values are net of harvesting losses, which were not measured, but appeared to be very limited in both cases. The reported amounts of residue are also net of any branch portions with a diameter larger than 5 cm, which had been removed by the farm owners to be used as firewood.

The moisture content of pruning residue was relatively low, generally in the range of 30–35%. The residue obtained from the Spanish groves was significantly drier than that harvested in Italy: that is likely to depend on the longer time elapsed between pruning and harvesting, since the Spanish tests took place in March, whereas the Italian trials were conducted in January.

Time consumption, machine productivity and harvesting cost are reported in Table 3. Productivity varied between 3 and 9 tonnes per scheduled machine hour (SMH), or 2–7 odt SMH^{-1}. Harvesting cost varied from 17 to 52 € t^{-1}, with an average value of 28 € t^{-1}: these values correspond, respectively to 22, 70 and 40 € odt^{-1}. It is also interesting to notice that both machines showed a relatively high mechanical availability, generally equal or higher than 90%. This seem to indicate that both machines are now mature for commercial use, having passed the prototype stage.

The values in the table are not suitable for a direct comparison of the two machines, since the tractor-mounted unit did not actually forward the loads to a central collection point, and it was studied under specific trial conditions, which may have encouraged the operator to keep a more sustained work pace, and especially to cut on rest breaks and other personal delays. Hence, the crucial role of the model described above, which may compensate to a certain extent for such differences. The relationships used to build such model are described in Table 4.

The time for collecting and comminuting the residue is strongly related to the linear density of the residue, and it is significantly longer for the tractor-mounted unit. These two variables alone can explain over 80% of the variability, and their effect resulted statistically significant at $p < 0.0001$ (ANOVA analysis).

The model also incorporates the average turning times of 34 and 56 s turn^{-1}, respectively for the dedicated machine and the tractor-base unit. Again, the difference resulted statistically significant at the ANOVA testing ($p < 0.0001$).

Forwarding time was calculated by applying to both units the same function developed for the self-propelled machine, since no data were available for the tractor-base unit. Forwarding distance is the main variable affecting time consumption and explains over 80% of its variability.

The average unloading time is 255 and 180 s load^{-1}, respectively for the dedicated machine and the tractor-base unit.

A good estimate of delay times was then used to transform net work time (collecting-comminuting, turning, forwarding and unloading) into scheduled work time. Delays such as mechanical breakdowns and operator rest were recorded during the study and transformed into a delay factor, which is the coefficient needed to extract delay time from net work time (Spinelli and Visser, 2008). The delays recorded for the self-propelled machine were considered more representative of true commercial harvesting conditions, and therefore the 32% delay factor obtained for this unit was also applied to the tractor-base machine.

Fig. 3 shows the relationship between relocation time and distance between the sites, and includes terminal times (respectively "prepare for travel" and "prepare for work"). The relationship appears extremely significant, and can be safely assumed as a good estimator of relocation time within the observed distance limits.

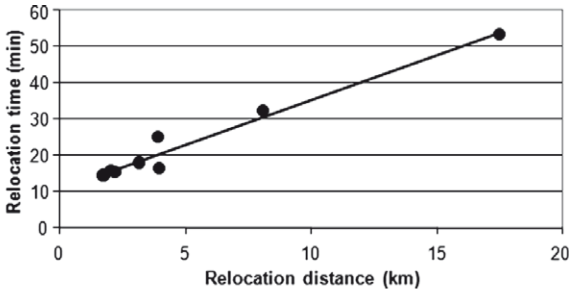
The model also assumes a daily preparation time (refuel, warm-up, cleaning etc.) of 45 min, which was added to the total time consumption. Finally, relocating the operation was also included into the model, using the data recorded for the dedicated unit, which was relocated eight times during the study. No such data were available for the tractor-mounted unit, which was tested on

Table 3
Recorded time consumption, harvesting productivity and harvesting cost.

Machine	#	Self-propelled, Spain							Tractor-mounted, Italy		
Field		1	2	3	4	5	6	7	8	9	10
Collecting-comminuting	s	3233	1496	10,302	3858	3992	2564	7112	1606	7052	8920
Turning	s	892	326	618	595	643	469	680	516	1005	619
Forwarding	s	1028	664	6060	1452	1466	598	3589	0	0	0
Unloading	s	494	368	3359	1159	1481	755	2773	226	1106	1602
Mechanical delays	s	1930	76	4680	457	228	0	1073	76	811	1103
Other delays	s	1107	886	1500	328	945	2219	3405	206	1049	889
Total time consumption	s	8686	3816	26,519	7849	8755	6606	18,631	2630	11,023	13,132
Mass harvested	t	10.6	3.2	49.5	17.8	22.8	11.0	22.8	4.1	20.2	29.2
Surface area	ha	6.57	1.61	7.04	8.61	12.90	10.20	18.44	0.59	1.74	1.58
Mass productivity	$t h^{-1}$	4.4	3.0	6.7	8.2	9.4	6.0	4.4	5.7	6.6	8.0
Area productivity	$ha h^{-1}$	2.7	1.5	1.0	3.9	5.3	5.6	3.6	0.8	0.6	0.4
Hourly cost	Euro h^{-1}	158	158	158	158	158	158	158	149	149	149
Unit cost	Euro t^{-1}	36.1	51.9	23.5	19.3	16.9	26.3	35.9	26.4	22.6	18.6
Incidence of delays	%	35	25	23	10	13	34	24	11	17	15
Mechanical availability	%	78	98	82	94	97	100	94	97	93	92

Table 4
Models for predicting work time consumption, for the two units.

Collecting-comminuting time (s m^{-1})	Coefficient	*n* 215 Std. error	R^2 0.818 Std. coeff.	*F*-value *t*-Value	315.359 *p*-Value
Intercept	2.530	0.065	2.530	39.063	<0.0001
Residue density (kg $m^{-1})^2$	0.015	0.002	0.867	6.958	<0.0001
Residue density (kg m^{-1})	−0.347	0.028	−1.613	−12.333	<0.0001
Tractor-mounted dummy	−0.305	0.066	−0.165	−4.624	<0.0001
Turning time (s $turn^{-1}$)	*n*	Mean	Std. error	Min	Max
Tractor-mounted	38	93.763	6.779	20	229
Self-propelled	154	56.082	3.357	10	296
Forwarding time (s m^{-1})		*n* 81	R^2 0.824	*F*-value	182.513
	Coefficient	Std. error	Std. coeff.	*t*-Value	*p*-Value
Intercept	22.982	11.431	22.982	2.010	0.0478
Two-way distance (m)^2	0.620	0.076	1.159	8.183	<0.0001
Two-way distance (m)	$-1.946E^{-4}$	$-1.015E^{-4}$	−0.272	−1.918	0.0588
Unloading time (s $load^{-1}$)	*n*	Mean	Std. error	Min	Max
Tractor-mounted	10	180.060	22.998	72	317
Self-propelled	38	255.716	11.561	118	473



Relocation	time (s)	n9	R^2 0.968	F-Value	208.632
	Coefficient	Std.Error	Std.Coeff.	t-Value	p-Value
Intercept	636.017	70.937	636.017	8.966	< 0.0001
km	148.409	10.275	0.984	14.444	< 0.0001

Fig. 3. Relationship between relocation time and relocation distance.

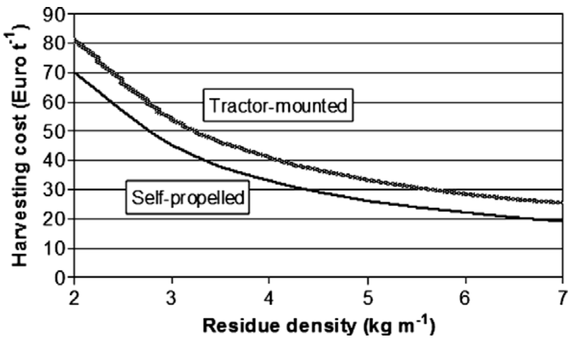


Fig. 4. Relationship between the linear density of the residue and the harvesting cost (dumped at roadside).

different fields in the same farm, and was never relocated during the study. It was therefore decided to use the same function for both operations, on the assumption that both had similar road travel capacities, due to their large mass and heavy implements.

The model was used to analyze the sensitivity of harvesting cost to meaningful work and economic conditions. The cost is intended for the residue dumped at the roadside, eventually into roll-on roll-off containers. Fig. 4 shows the relationship between residue density and cost, calculated for the average row length, moving distance and relocation distance of 300 m, 400 m and 5 km, respectively, on 10 ha fields. The machine rates used for the calculation are those indicated in Table 2. Residue density has a strong impact on harvesting cost: if its value increases from 3 to 4 kg m^{-1}, the harvesting cost will drop by about 25%. Further increases will entail comparably smaller cost reduction, but always in the range of 15–20%.

The tractor-mounted unit has a lower productivity compared to the dedicate self-propelled machine, but it offers the advantage of

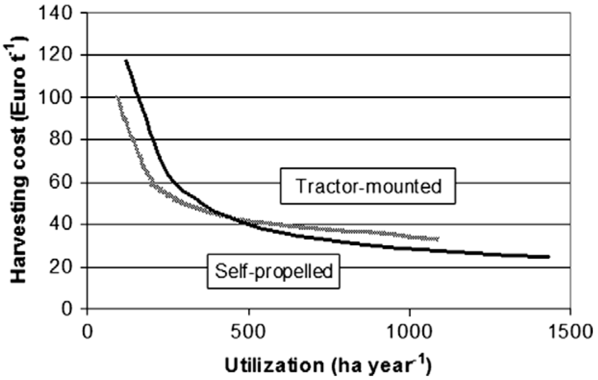


Fig. 5. Relationship between annual utilization and harvesting cost (dumped at roadside).

operational flexibility, since the tractor can be used for other tasks when no pruning residue is available for harvesting. It is therefore interesting to determine a break-even utilization point, beyond which a dedicated unit is a better choice. To this purpose, the model was used to calculate the harvesting cost as a function of annual utilization. The calculation was conducted under the assumptions already used for calculating the graphs in Fig. 4, and for a residue density of 4 kg m^{-1}, which is a conservative mean value obtained from the tests. It was also assumed that the total utilization of the farm tractor-base never went below 1000 h $year^{-1}$. The result of this exercise is reported in Fig. 5, showing that the tractor-mounted unit is the most economic choice when the annual harvest does not exceed 450 ha.

4. Discussion

Harvesting productivity is directly proportional to the linear density of the residue, which is a common occurrence and has already been documented in other studies (Spinelli et al., 2009). This may justify the concentration of residue, if its actual surface density is below the minimum levels for economic harvesting. In olive tree pruning, an effective strategy consists in laying the residue on alternate interrows, thus bunching all the prunings obtained from two rows onto the same interrow. This strategy had been applied to fields 5, 6 and 7, resulting in an estimated harvesting cost reduction of about 20 € t^{-1}.

Technically, the tractor-mounted unit cannot compete with the self-propelled machine, which harvests at a faster pace, turns more quickly and tows a bin with twice the capacity of that carried by the tractor. Given the cost of its large-size tractor, the tractor-base unit is only marginally cheaper to operate than the self-propelled harvester. However, the farm tractor can be used for tasks other than pruning residue harvesting when the demand for biomass is low or the harvesting season is over. Therefore the tractor-base unit is a better choice when there are no guarantees of a very intense utilization all along the machine's service life. Of course, the tractor-mounted unit is still an industrial machine that calls for a rather intense utilization level, although not as intense as that imposed by the specialised self-propelled harvester. The simple model developed in this study may help prospective users calculating their own break-even utilization levels.

The comminuting devices used on the two machines are different, and produce different results. The disc chipper used by the tractor-mounted unit cuts the residue into comparatively small and even-shaped particles, thus offering a fuel of superior quality. On the contrary, the swinging-hammer grinder of the self-propelled harvester crushes the residue and breaks it into irregular, often stringy, elements. Although large plants can easily accept the material produced by the self-propelled harvester, its use into small-size boilers will probably require further refining. Besides, large and irregular particle size may entail a lower bulk density of the load as the particles will tend to structure and bridge (Daugberg-Jensen et al., 2004): in turn, this may reduce the efficiency of subsequent transport and raise its cost.

On the other hand, the moisture content of pruning residue is relatively low, in the range of 30–35%, which makes for a very good fuel, generally superior to the wetter chips obtained from forest residue, whose moisture content can be lowered only with considerable effort (Nurmi and Hillebrand, 2007).

The costs indicated in this study and those returned by the model developed in its course refer to the residue harvested, processed and forwarded to the roadside, and do not include transportation to the user plant. However, so-called "farm gate" cost often represents about 70% of the total delivered cost of residue fuel (Panichelli and Gnansounou, 2008), and the transport cost is easier to estimate using market prices. Furthermore, both units can unload the product directly into roll-on roll-off containers left at the roadside, thus contributing to reduce transport cost.

The study did not determine the amount of product losses, which were visually estimated and considered too limited to deserve specific attention. However, there is a certain amount of losses and the technical recovery yields reported in the study may be increased, although slightly. What is most important, is that the little residue left on the field does not hinder soil cultivation and machine traffic, which is the primary goal of pruning residue management operations.

5. Conclusion

The new industrial technologies analyzed in this study represent a dramatic improvement over the small-size units previously available, and offers a drastic cost reduction, harvesting the pruning residues at an average cost of 40 € odt^{-1}. The introduction of industrial technology is probably the only option for commercial pruning residue harvesting, in the absence of specific subsidies and under the current fuel wood price conditions. However, small-size units can still play an important role in those groves where steep terrain and/or irregular spacing prevent the access to industrial harvesting units.

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