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Integrating olive grove maintenance and energy biomass recovery with a single-pass pruning and harvesting machine

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ABSTRACT

In Italy, olive tree groves may offer up to a million tonnes of dry biomass per year as pruning residue. Searching for a cost-effective way to tap this potential, the authors tested a new machine, capable of recovering pruning residue at the same time as pruning. The pre-commercial prototype was tested on four different plots and compared to a simpler tractor-base mechanical pruning unit. The authors conducted detailed time-studies in order to determine machine productivity and residue recovery cost. The integrated machine can treat between 0.2 and 0.6 ha h^{-1}, producing between 0.33 and 1.03 tonnes of fresh residue $hour^{-1}$. Its integrated residue recovery function does not slow the pruning, which actually proceeds faster than with the tractor-base unit, due to the more efficient multiple-disc cutting bar. The marginal cost of residue recovery hovers around 40–45 € fresh $tonne^{-1}$. However, the new machine must not be considered just as a biomass harvester, but rather as a mechanical pruning unit with an integrated biomass recovery function. Its main benefit derives from the capacity of performing a very effective mechanical pruning, and the residue recovery function is a secondary benefit yet unavailable on standard pruning machines. Its deployment must be seen in the context of a general effort to modernize olive grove management and to develop an integrated biomass production system, rather than as a further attempt to build a specialised biomass supply chain.

1. Introduction

Energy biomass can be sourced from existing agricultural residue, which offers a strategic benefit wherever it is impractical to convert cropland to energy crop cultivation [1] and the disposal of such residue is expensive or problematic [2].

Besides, agricultural residue does not accrue any growing costs and could be tapped at a relatively low price, if effective collection systems were deployed. In particular, olive tree pruning residue has already been targeted as a main source of lignocellulosic biomass, especially in the Mediterranean Sea basin, where olive groves cover almost 9 million hectares [3]. 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 tons, net of the amounts already recovered for traditional utilization [4]. Such a massive and concentrated availability would be suitable for industrial utilization, such as co-firing [5] and bioethanol production [6],

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which explains why pruning residue generally plays an important role in any analysis of biomass availability conducted in the Country [7]. In particular, the surface grown with olive trees amounts to over 1 million hectares [8] and generates at least 1 oven dry ton (odt) of pruning residue per hectare and year [9].

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 [10] or about 0.6–0.8 ha per hour [11]. 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. Then, two main alternatives remain available: a) resorting to powerful industrial harvesters with frontal collection devices, which can overcome both the productive and the structural limits of lighter tractor-mounted machines and achieve gross productivities in excess of 5 green tonnes per hour [12] or b) integrating pruning residue collection and processing with some other operation, so that its recovery is obtained at a marginal cost. Ideally, one could integrate pruning and pruning residue collection in a single operation performed with a suitable mechanical unit. In specialised industrial orchards, pruning is the most expensive task after harvesting, and represents between 20 and 40% of the overall management cost [13]. For this very reason, pruning is being mechanized, just like harvesting. The effect is obtained with reciprocating cutter-bars, applied to standard agricultural tractors [14]. This way it is possible to reduce labour consumption from 80 to 15 worker hours per hectare [15]. Furthermore, mechanical pruning does not seem to produce inferior results to manual pruning, whose supposed superiority is merely aesthetic, especially if harvesting is also mechanized [16]. In fact, if harvesting is performed mechanically with tree shakers, then mechanical pruning offers a significant advantage [17].

Recently, the Italian manufacturer Favaretto has developed an integrated harvester (Speedy-cut) capable of performing both pruning and pruning residue harvesting in a single pass. This machine may offer a cost-effective solution to pruning and pruning residue recovery, and has attracted much attention. Therefore, the goal of this study was to determine the performance of this machine with scientific methods, offering reliable estimates for its productivity and cost. Furthermore, the study aimed at determining whether pruning residue collection and processing does slow down the main pruning operation, so that a realistic marginal cost of pruning residue recovery can be calculated.

2. Materials and methods

In its present version, the machine consists of a four-wheel-drive self-propelled carrier, powered by a 150 kW diesel engine. A multiple-disc cutting bar is mounted on a hydraulic boom hinged on the right side of the carrier. The bar is divided in two segments by an articulation, so that its shape can be adjusted to fit the trees and the job. A collection tub is placed under the bar and in front of the machine, to receive the prunings as they are cut. A belt conveyor at the bottom of the tub feeds the prunings to a swinging-hammer grinder placed just under the driver's cab. Removable screens can be placed between the grinder and the bottom of the grinding chamber in order to produce even-sized fragments. Ground residue is then moved to a 5 m^3 tilting bin by a combined auger and ladder conveyor. The bin is placed on the rear end of the machine, so that the load can be easily dumped on the ground or into suitable containers (Figs. 1 and 2).

Tests with the Favaretto Speedy-cut were conducted at 3 different sites in Central Italy, representative of the main working conditions found in the Italian olive tree groves (Table 1). 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 [18]. Cycle times were defined and split into time elements [19] 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 eventual productivity estimate [20]. In particular, four main elements were identified and separated, namely: pruning-collecting, turning, 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 [21]. 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

Fig. 1 – A picture of the machine at work.

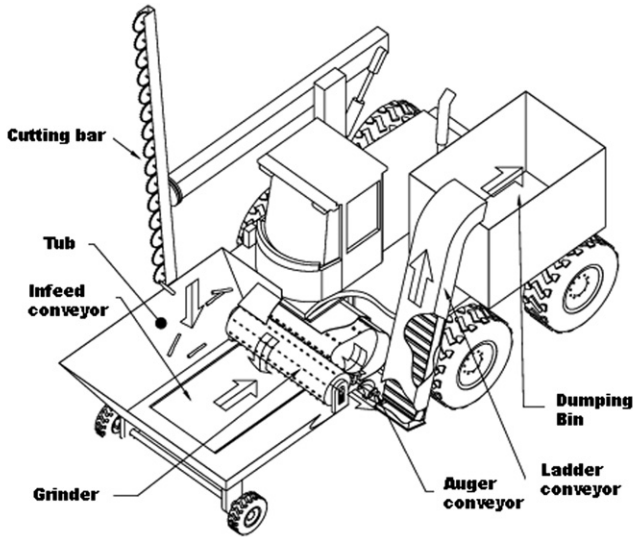

Fig. 2 – Basic machine design.

determination was conducted on twenty 1000 g samples 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, the length of row harvested for each run was measured with a hip-chain and a laser range-finder.

Machine costs were estimated with the method described by Miyata [22], 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 20% in order to include administration and relocation costs. Costs were calculated for both the single-pass harvester and a simple farm tractor equipped with a multiple-disc cutting bar similar to that mounted on the harvester. The latter represents the case where residue is left on the ground for separate recovery, and this option was also tested on plot n° 4, where the machine was made available by a local manufacturer. The data from this additional test were used as a control, in order to determine whether the additional

Table 1 – Description of the test plots.

Plot	n°	1	2	3	4a & 4b
Place name		Botrona	S.Paolina	S.Paolina	P.Pinta
Surface area	ha	0.12	0.45	0.30	0.11 + 0.11
Trees	n.	34	129	86	22
Age	Years	9	14	14	60
Spacing	m	7 × 5	7 × 5	7 × 5	10 × 10
Density	trees ha $^{-1}$	286	286	286	100
Pruning	Intensity	Light	Medium	Heavy	Heavy
Removal	kg tree^{-1}	2.0	7.1	14.9	18.2
Removal	t ha^{-1}	0.6	2.0	4.3	1.8
Moisture content	%	41	41	41	41
Removal	odt ha^{-1}	0.3	1.2	2.5	1.1

Notes: odt = oven-dry tonne.

Table 2 – Operational costs.

Machine		Integrated harvester	Tractor & bar
Investment	€	180000	60000
Service life	Years	10	10
Usage	h year^{-1}	800	800
Labour cost	€ h^{-1}	15	15
Crew	n°	1	1
Fixed cost	€ year^{-1}	19998	6666
Variable cost	€ h^{-1}	39.3	26.4
Total cost	€ h^{-1}	**77.2**	**41.7**

residue recovery function entails a reduction of pruning productivity. Overall, the tests were conducted on 270 trees, distributed among 4 different plots that covered about 1 ha.

Data were statistically analyzed with regression techniques to calculate any significant relationships between pruning-collecting speed and pruning intensity. ANOVA testing was also used to detect statistically significant differences between treatments, and especially between the dedicated pruning harvester and the farm tractor equipped with the multiple-disc cutting bar [23].

3. Results and discussion

All trees presented one single main stem and were pruned on two sides only. Due to the rectangular design of the plantations, the sides being pruned were those facing the widest of the two inter-rows, so as to offer more space for machine access. Each side was pruned in a separate pass, since the machine had just one pruning bar and could only work the tree row to its right side. However, the bar was articulated, so that topping could be performed at the same time as lateral pruning, and did not require a further pass. The amount of pruning residue showed significant variation, caused by differences in tree age, density and pruning intensity (Table 1). Tree density was consistently higher in the first 3 plots, which had been established following the modern specifications for thick industrial olive tree groves. Here different pruning intensities were applied, yielding from 0.6 to 4 tonnes of fresh biomass per hectare (0.3–2.5 oven-dry tonnes ha^{-1}). These values are net of harvesting losses, which were not measured, but appeared to be very limited. Except for advance speed, no specific adjustments were made to work parameter settings (cutter speed, grinder speed etc.) in order to match pruning intensity. Plot n° 4 was an old grove, established with the wider traditional spacing. Tree density was almost three times smaller than in the industrial orchards, which explains the relatively low residue yield, despite the large amount of branch material harvested from each tree. The moisture content of pruning residue was moderate, despite the harvesting of fresh branches. Residue yield figures are significantly lower than those determined by the same authors for the manual pruning of specialised industrial orchards, normally yielding from 4 to 7 oven-dry tonnes ha^{-1} [12]. Such difference may depend on a generally lighter intensity of mechanical pruning, which does not allow the selective removal of individual large branches. What's more, mechanical pruning was performed on two sides only,

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

Plot	n°	1		2		3		4a		4b	
		Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.
Place name		Botrona		S.Paolina		S.Paolina		P.Pinta		P.Pinta	
Pruning		Light		Medium		Heavy		Heavy		Heavy	
Removal	kg tree^{-1}	2.0		7.1		14.9		18.2		18.2	
Removal	t ha^{-1}	0.6		2.0		4.3		1.8		0.0	
Forward speed	km h^{-1}	2.8	0.4	1.4	0.2	1.2	0.4	1.9	0.4	1.9	0.5
Feeding stops	% Harvest time	0.0	0.0	17.1	8.5	24.4	7.9	4.5	14.5	0	0.0
Turning time	s turn^{-1}	43.8	1.8	63.0	12.0	48.0	7.8	78.0	9.6	33.6	12.0
Bin discharging time*	s discharge^{-1}	133.8	25.8	133.8	25.8	133.8	25.8	133.8	25.8	–	–
Discharges	n ha^{-1}	0.7		2.4		5.0		2.1		–	
Total net time**	Hour ha^{-1}	1.36	0.13	2.3	0.21	3.31	0.91	1.79	0.9	2.19	0.58
Delay time	Hour ha^{-1}	0.34	0.03	0.6	0.05	0.82	0.22	0.44	0.2	0.55	0.14
Total work time	Hour ha^{-1}	1.70	0.17	2.9	0.26	4.13	1.14	2.23	1.1	2.74	0.73
Gross productivity	ha hour^{-1}	0.59		0.35		0.24		0.45		0.36	
Gross productivity	t hour^{-1}	0.33		0.70		1.03		0.82		–	
Biomass cost***	€ t^{-1}	106.1		50.8		34.4		43.5		–	

Notes: *bin discharge time observations from the 4 plots had been pooled, in the assumption that discharge time is not affected by crop characteristics; **Total net time is the sum of pruning-collecting time, turning time and bin discharge time, ***Calculated on the marginal operating cost of the pruning-collecting unit (35.5 € hour^{-1}), equal to the total operating cost of the machine (77.2 € hour^{-1}) minus the operating cost of the tractor with the pruning bar (41.7 € hour^{-1})

instead of four, as when applied manually. On the other hand, the lower intensity and cost of mechanical pruning favour more frequent applications, so that the overall annual yield of residue is likely to remain unchanged at the landscape level.

Time consumption, machine productivity and harvesting cost are reported in Table 3. Productivity varied between 0.2 and 0.6 ha h^{-1}, or between 0.33 and 1.03 tonnes of fresh residue hour^{-1}. These figures are inclusive of all delays, estimated to 25% of the net work time. Observation time was not considered long enough to provide a representative estimate of a typically erratic phenomenon such as the occurrence of delays, and therefore an average delay factor was assumed for all tests [24].

Pruning and collecting proceeded at a rather high speed, ranging between 1.2 and 2.8 km h^{-1}. These figures included the eventual stops necessary to let the grinder "digest" any accumulation of branches: the incidence of such feeding stops was significantly different between the different plots, and seemed related to the amount of residue eventually harvested, being totally absent from the plot with the lowest removal, while highest and most frequent in that with the highest removal (Fig. 3). Overall pruning and collecting speed is related to the intensity of removal, as shown by the regression in Fig. 4. The somewhat low (0.53) coefficient of determination of this regression is explained by the distribution of data for the independent variable, which was not ideal for regression purposes but was forced upon the data pool by

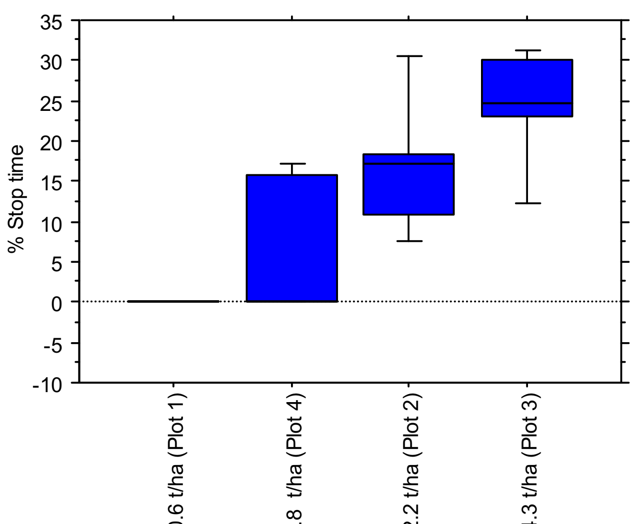
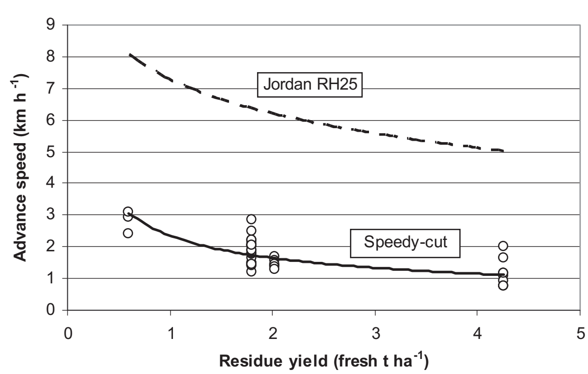


Fig. 3 – Box-plot for the percent incidence of residue feeding stops on the total net harvesting time, excluding turning, bin discharge and delays.



Speed	km h^{-1}	n 39	R^2 0.534	F-Value	42.395
	Coefficient	Std.Error	Std.Coeff.	t-Value	p-Value
Intercept	0.255	0.234	0.255	1.091	0.2823
t ha$^{-0.52}$	2.058	0.316	0.731	6.511	< 0.0001

Fig. 4 – Relationship between pruning-collecting speed (km h^{-1}) and pruning residue yield (fresh tonnes ha^{-1}) and comparison with an industrial residue harvester (Jordan RH25).

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the difficulty of correctly measuring the residue output of each individual row. Nevertheless, the regression explains over 50% of the variability and its general outline is corroborated by the similar findings of previous studies [12,25].

The tests on plot n. 4 showed that the integrated processing and collection of pruning residue does not determine any significant reduction of pruning speed compared to pruning only, as t-testing for the treatments 4a and 4b returned a *p*-value of 0.36. The average pruning speed of both options was compatible with the data reported for mechanical olive tree pruning in previous studies [13]. On the other hand, the integrated harvester is certainly larger and heavier than a farm tractor and it takes longer to manoeuvre at the end of the row: its turning time is indeed twice as long as that of the tractor (68 s turn^{-1} vs. 33 s turn^{-1}) and the difference resulted significant to t-testing ($p = 0.042$). In any case, the multiple-disc cutting bar model mounted on the harvester is a very effective pruning device, more capable and sophisticated than those generally applied to farm tractors. Its hinged construction and the application to an articulated boom favour accurate adjustment, and allow performing both lateral pruning and topping in one pass. This was not possible with the bar mounted on the farm tractor pruning the trees on plot 4b, which had to make a further pass for topping. That explains the lower productivity of the tractor (0.36 ha h^{-1}) compared to the harvester (0.45 ha h^{-1}), even if the latter took longer to turn and needed to stop and discharge the bin at regular intervals. The use of a better pruning bar is integrated into the price difference between the harvester and the tractor, justifying direct comparison between the two machines. The additional cost of the harvester was fully charged to the residue recovery function, so that recovering and processing of the pruning residue incurred a cost between 34 and 106 € fresh tonne^{-1}. Excluding the cost peak from plot n° 1, the average recovery cost hovers around 40–45 € fresh tonne^{-1}, which is 30–50% higher than the cost incurred for the separate recovery with industrial units [12] and not much lower than that obtained for the separate recovery with light-weight tractor implements [26]. The same Fig. 4 reports a line graph for the advance speed of an industrial shredding-collecting machine (Jordan RH25): the data were obtained from Spinelli and Picchi 2009 [2], and show the significantly higher work pace of the specialised industrial unit. However, the effective application of double-pass recovery is dependent on the accurate windrowing of pruning residue in the inter-rows, which implies manual pruning or the additional pass with a windrower. This considered, an integrated pruning and collecting machine may represent the best option for the recovery of pruning residue when tree pruning is mechanized. Besides, such recovery mode offers the important benefit of avoiding any contamination of the residue, which does not touch the ground but goes directly to the grinder and into the collection bin. In this respect, one may wonder if a grinder is the best solution for the job: its swinging hammers break the residue into irregular elements, which produce bulkier loads and tend to bridge over ports and conveyors [27]. A drum chipper would offer superior product quality [28] and faster processing [29], which could help reducing the incidence of feeding stops, further increasing harvesting speed. Most commercial pruning residue harvesters adopt hammer grinders because they are designed to pick up the residue from the ground, which entails a certain contamination and prevents the use of a chipper. That is not the case with the integrated unit developed by Favaretto, which processes uncontaminated branches as they come off the trees and could be fitted with a more efficient drum chipper. On the other hand, integrated pruning and recovery entails the comminution of fresh residue, preventing any natural drying of the branch material before processing. As a consequence, this harvesting mode offers a relatively wet fuel, which may not store as easily as uncomminuted branches. If the user plant cannot burn it within a short time from harvesting, then one should also account for the cost of active (artificial) drying, or for the dry matter losses caused by intense microbial activity [30].

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.

4. Conclusions

The machine developed by Favaretto is new and original, and carries some interesting potential. Its performance as a residue harvester is inferior to that of industrial pruning residue harvesters, and not much superior to that of small-scale pick-up and process units. Like these, the new machine is sensitive to the density of residue, but it does not allow for its manipulation through concentration on alternate inter-rows, since the biomass is still attached to the tree when the machine starts to work. The minimum threshold for cost-effective deployment is between 1.5 and 2 fresh tonnes of residue per hectare: below this level it may be cheaper to prune the trees and recover the pruning residue in two separate passes. However, the new machine must not be considered just as a biomass harvester, but rather as a mechanical pruning unit with an integrated biomass recovery function. Its main benefit derives from the capacity of performing a very effective mechanical pruning, and the residue recovery function is just a secondary benefit offered by Favaretto and yet unavailable on standard pruning machines. Under the conditions of mechanical pruning, separate residue recovery may entail a significantly higher cost than incurred when recovering pruning residue obtained from manual operations, because the branches lay scattered at the tree base and need to be windrowed before collection. The unit built by Favaretto allows the recovery operation to be performed at a relatively small marginal cost, while preventing any contamination of the biomass. Its deployment must be seen within the context of a general effort to modernize olive grove management and to develop an integrated biomass production system [31], rather than as a further attempt to build a specialised biomass supply chain.

In any case, it must be stressed that the machine observed in this study is just a pre-commercial prototype susceptible of considerable improvement, and that a fully commercial

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version may eventually offer a better performance than reported here. That is very likely, especially if the grinder will be replaced by a chipper, and if the in-feed conveyor is further developed. Work technique could also be refined, in order to boost productivity and reduce downtime. Once a new commercial version is ready, further studies should be organized in order to develop improved estimates for productivity, and especially for delays. At this stage, one should also address the organization and the logistics of the integrated pruning and residue harvesting operation.

In principle, integrated pruning and biomass collection might be extended to a significant portion of the olive orchards grown in the Mediterranean basin, and especially to the new plantations designed for industrial management. Of course, further work should address such important topics as the quality of pruning, fuel consumption, the risk for a erosion and compaction resulting from the use of a relatively heavy machine, and the specific site characteristics allowing for successful deployment.

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