energies

MDPI

Article

Analysis of the Work Productivity and Costs of a Stationary Chipper Applied to the Harvesting of Olive Tree Pruning for Bio-Energy Production

Alessandro Suardi [1], Francesco Latterini [1,*], Vincenzo Alfano [1], Nadia Palmieri [1], Simone Bergonzoli [2] and Luigi Pari [1]

1 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via della Pascolare 16, 00015 Monterotondo, (RM), Italy; alessandro.suardi@crea.gov.it (A.S.); vincenzo.alfano@crea.gov.it (V.A.); nadia.palmieri@crea.gov.it (N.P.); luigi.pari@crea.gov.it (L.P.)

2 Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Centro di Ricerca Ingegneria e Trasformazioni Agroalimentari, Via Milano, 43, 24047 Treviglio, (BG), Italy; simone.bergonzoli@crea.gov.it

* Correspondence: francesco.latterini@crea.gov.it; Tel.: +39-06-90675248

Received: 6 February 2020; Accepted: 11 March 2020; Published: 14 March 2020

Abstract: Pruning residues could represent an important biomass resources for energy production. Only in Italy it has been estimated that an annual quantity of biomass of over 2600 kt of dry matter could be obtained from olive residues. Several machines developed for pruning harvesting are available in the market, most of which are tractor-driven, while limited knowledge is available on performance, quality of work and costs of harvesting logistics based on stationary chippers. The aim of the present paper is to analyze machine performance of a forestry stationary chipper applied to pruning harvesting for what concerns work productivity, quality of the comminuted product and harvesting operating costs. This system is actually applied by Fiusis Company, an Italian enterprise which manages a biomass power plant exclusively powered by olive trees' pruning residues, and it has never been analyzed in literature. The results obtained showed consistent work productivity, which resulted the highest ever found in olive pruning harvesting systems and equal to 5.23 ± 0.81 $t_{dm}\cdot h^{-1}$. This high work productivity allowed also to obtain a little economic gain from a matter, which is actually considered a problem for olive groves' owners and not a potential source of income. In particular, the use of a stationary chipper seemed very efficient in olive groves with a consistent amount of wooden residues to be processed and with big branches not harvestable by the most common towed pruning harvester. In addition, the stationary chipper has the advantage of avoiding the preliminary raking operation, which results in reduced costs for the farmer.

Keywords: olive groves; pruning; stationary chipper; harvesting system; hog fuel; pruning supply chain

1. Introduction

Fruit orchards cover over 10 million hectares across the EU and are mostly located in Mediterranean areas [1]. All orchards require regular pruning, which is performed at 1–3-year intervals. This operation generates a substantial amount of residues, estimated in the range of 1-5 tons per hectare [2], and an estimated annual quantity of pruning biomass of over 2600 kt of dry matter from the only olive groves in Italy [3] that could represent an important source of biomass for energy production [4]. However, these residues are usually field-burnt or mulched [5–7]. These solutions are not cost-effective [8]. Moreover, field burning causes uncontrolled greenhouse gases (GHG) emissions, and also, mulching, which presents positive aspects like reduced soil erosion and lower soil nutrients depletion, could imply other negative consequences; for example, increased possibility of disease diffusions [9,10].

For this reason, various European projects were focused on activities for the development of an efficient pruning supply chain for energy production [11–14]. One fundamental step in the development of such a supply chain is the identification of cost-effective harvesting technologies. In fact, harvesting is a key stage that influences the product quality, the type of logistics chain and the economic sustainability of the pruning supply chain [15].

Moreover, several agricultural equipment manufacturers developed 75 different models mostly consisting in adaptations of conventional mulchers; other available technologies are chippers, balers or integrated pruning-harvesting technologies [15].

Apart from integrated pruning-harvesting technologies which are still not widespread and not always applicable, other harvesting systems require pruning to be grouped in windrows to optimize biomass-harvesting and reduce losses. For this reason, most available harvesting systems need a preliminary raking operation, carried out by a tractor equipped with a towed rake. Some machines instead have integrated raking systems that are mainly used to compact the windrow and facilitate the pruning collections by the harvester [15]. Raking operations have a consistent influence on costs, biomass quality and biomass losses [16].

An interesting approach to avoid the raking phase is using a stationary chipper (SC). This machinery is typical of forest utilization sector [17–20] but can be applied also in pruning harvesting systems. It represents an interesting choice for fields with a consistent amount of pruning biomass and with big diameter of prunings or when the orchard's field is characterized by slope, which could not be addressed by the majority of self-propelled or towed chippers and balers.

Even if the use of a forestry stationary chipper is uncommon in the normal practice, and according to our knowledge, only one experience has so far been reported in the literature [21], the pruning harvesting system based on stationary chipper is currently used by the Italian firm "Ligna", a subsidiary company of "Fiusis S.r.l." (Calimera, Apulia Region, Italy), which is a 1 MWe biomass power plant in the Municipality of Calimera (Apulia Region, Italy). In Europe, Fiusis and Ligna represent a successful and unique example of a short supply chain (10 km radius) for the production of electricity exclusively obtained from the combustion of local olive tree prunings. Ligna is responsible for procuring the biomass produced by the nine municipalities bordering the Fiusis plant, which transforms it into electricity. The supply of biomass takes place through two types of harvesting systems: four Facma mod. Comby TR200 (Facma srl, Vitorchiano, Lazio Region, Italy) towed shredders for small olive groves (less than 400 trees, corresponding to about 6 ha) and a stationary chipper Caravaggi mod. BIO900 (Caravaggi srl, Pontoglio, Lombardia Region, Italy) for big orchards (more than 400 olive trees) or in slope terrains. The choice of the more adapt harvesting logistic to be used (based on the number of trees) is mainly made by Ligna, according to the results of ten years of experience in the sector. However, unlike pruning harvesting using a towed chipper, few scientific data are available about the harvesting logistic of prunings based on a stationary chipper [15]. This paper analyses the performance, quality of the work and costs of the olive tree pruning harvesting system developed by Fiusis and Ligna and based on the use of a stationary forestry chipper. Although widely used in the forestry sector, the use of a stationary chipper for harvesting and comminuting olive tree prunings is poorly documented, and therefore, the study is innovative and fills a gap in the literature where little information is currently available. Moreover, an economic evaluation of hog fuel production was conducted considering the overall chain, from biomass harvesting to transportation to the power plant. This is another innovative aspect of the present paper. In fact, in literature, there are few studies dealing with hog fuel or wood chips' transport costs and even less considering very short transport distances, such the present case's one.

2. Materials and Methods

2.1. Experimental Field and Prunings' Characteristics

Experimental field was located in the Carpignano Salentino Municipality (Apulia Region, Italy). The experimental field was 2.49 hectares with an average slope of 2% and a planting layout of 12 m × 12 m. The average pruning's diameter, length and weight were 39.75 ± 12.66) mm and 1950 ± 524) mm and 4.13 ± 2.48) kg, respectively. A map of the olive grove is given in Figure 1.

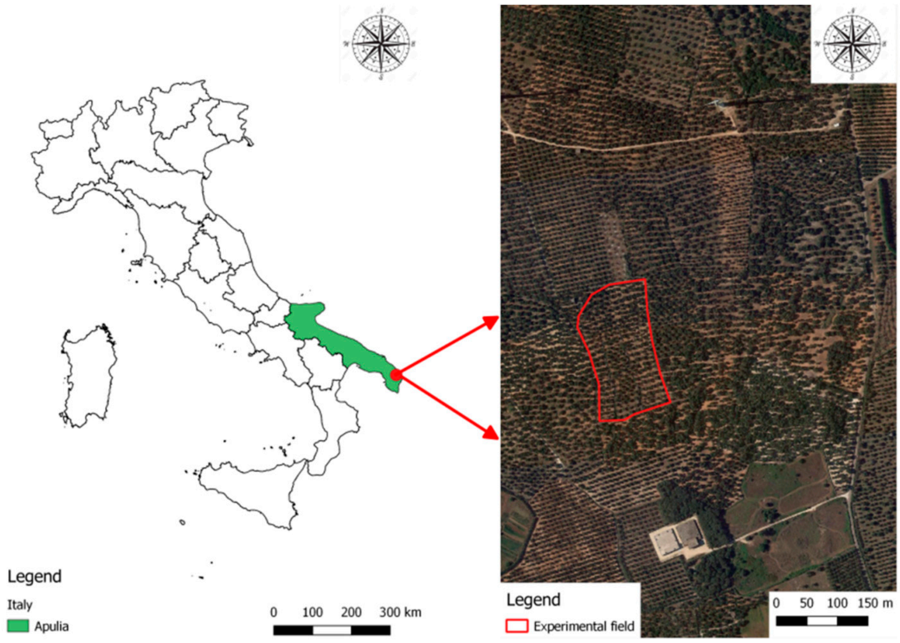

Figure 1. Area and experimental fields location. EPSG: 32633; CRS: WGS84-UTM33T.

The Fiusis plant is located at a distance of 9.3 km from the experimental field.

2.2. Harvesting System Description

As previously written in the Introduction section, the analyzed pruning harvesting system is a nonconventional one. In fact, there was no preliminary raking operation, but instead, the pruning residues were collected and piled on the field side by a 66-kW tractor equipped with fork (Landini model Rex 90 S DT Cab, Argo Tractors SPA, Fabbrico, Emilia-Romagna Region, Italy). Near the pile, a Caravaggi BIO900 chipper is located (Figure 2). This is a stationary chipper 9.65-m-long, 3.90-m-high, and it weighs 10,000 kg. It is powered by a Diesel 129 kW motor. The rotor is 0.78-m-wide, and the machine is able to shred wooden materials up to diameters of 45 cm. The feeding of the chipper was provided by a hydraulic loader Agrisav CAS 1000 (Agri Sav, Savigliano, Piemonte Region, Italy) powered by a 129-kW tractor (same Virtus 140 dt Cab, same Deutz-Fahr, Treviglio, Lombardia Region, Italy). Comminuted biomass is heaped on the pile and then loaded by a 90-kW Manitou 940–120 LSU (Manitou, Ancenis, Loire Atlantique Department, France) lifter into the dumpster of a IVECO Trakker 190T36 (Iveco, Torino, Piemonte Region, Italy) truck in order to be transported to the Fiusis biomass power plant in Calimera Municipality.

2.3. Harvesting System Performance and Quality of the Work Evaluations

Working times were measured according to ASAE S495 DEC99 [22]. Investigated parameters for what concerned work productivity were: theoretical field capacity (ha·h^{-1}), effective field capacity (ha·h^{-1}), material capacity (t_{fm}·h^{-1} and t_{dm}·h^{-1}) and fuel consumption (l·h^{-1} and l·$t_{fm}{}^{-1}$).

Figure 2. Stationary chipper Caravaggi and tractor with uploading equipment.

The field capacity of a farm machine is defined as the rate at which it performs its primary function, for example the number of hectares which can be harvested per time unit. Measurements or estimates of machine capacities are fundamental to plan field operations, power units, labor and also to evaluate machine operating costs. The effective field capacity (EFC) of the machines in the field were calculated by dividing the hectare harvested by the hours of actual field time. Theoretical field capacity (TFC) depends instead only on the full operating width of the machine and the average travel speed of this while operating in the field. It consists in the maximum achievable field capacity which could be obtained at the given field speed when the full operating width of the machine is being used. EFC is generally less than the TFC due to turns and other delays. The ratio of EFC to TFC is defined as machine field efficiency (FE).

FE is expressed as the percentage of a machine TFC actually achieved under real operating conditions. It accounts for failure to utilize the full operating width of the machine (the so called overlapping) and many other time delays which can occurred during harvesting operations. These cover turning, material unloading, traveling, refilling the fuel tank, making adjustments, waiting for trucks and operator rest stops. Delay activities which occur outside the field, like daily service, travel to and from the field and major repairs, are not considered in the field efficiency estimation.

The working capacity of harvesting machines is generally measured by the quantity of materials harvested in the time unit. This capacity is called the machine material capacity (MC), expressed as tons per hour. It is the product of the machine EFC and the average yield of crop per hectare.

The quality of the work of the harvesting system was evaluated also by analyzing the hog fuel quality in terms of bulk density ($kg \cdot m^{-3}$) according to ISO 17828:2015 [23], moisture content (%) according to ISO 18134-2:2017 [24] and particle size distribution analysis (%) according to [25].

Fuel consumption was measured by machine tank refilling until the full level at the end of each plot using a handheld fueling system with a flowmeter to identify the volume of fuel consumed ($l\ ha^{-1}$ or $l\ t^{-1}$ of biomass harvested). Each plot was started with the tank entirely full. The fuel consumed was proportioned to the harvested surface to define the fuel consumed per hectare.

It is valuable to underline that, even though the mentioned above method to estimate the fuel consumption is very common and presents the benefit to result very easy to apply in the field, and sometimes it represents the only method which can be applied, its precision has been questioned in many studies, most of all when the amounts to be measured are minute, and the measurement errors are difficult to evaluate [22].

Bulk density and moisture analysis were conducted according to the methodology proposed by Pari et al. [26]. Particle size distribution (PSD) was instead determined according to the European Standard ISO 17225-4:2014 [27].

2.4. Harvesting Cost Analysis

Operating costs of the harvesting system were analyzed, including transport costs to the Fiusis biomass power plant. The economic analysis was focused on both maintenance and operating costs, according to the parameters measured during the field tests (primary data) or by using standard values provided by the CRPA methodology [28]. Interviews with agro-industry owners and with their usual suppliers have provided further costs items and have validated the data measured during the field tests. The hourly costs for all the equipment tested during the harvesting were calculated according to [28,29] and using the Italian Ministry of Infrastructure and Transport guidelines for transport operation [30]. In particular, for what concerns field operations, the total yearly fixed costs, which were calculated starting from the machine price, were divided for the machineries' annual usage (expressed in hours) to obtain the hourly fixed cost. Hourly variable costs (maintenance, fuel, lubricant and manpower) were estimated using the mentioned-above methodologies. In such ways, we obtained the total hourly costs of the harvesting system. To have costs per surface unit (€·ha^{-1}), instead, the previously calculated total hourly costs were multiplied for the duration of agricultural operations needed for one hectare. Successively, this amount was divided for yield (expressed in t·ha^{-1}) to calculate the cost per biomass unit (€·t^{-1}). In such a way, it was possible to estimate the cost of each operation, i.e., accumulation by tractor with fork, comminuting by stationary chipper and truck load by lifter.

A similar procedure was made for transport costs taking into account maintenance costs and operating ones and considering an average transport speed of 50 km·h^{-1}. Main parameters for the cost analysis are given in Table 1.

Table 1. Main parameters used for the economic analysis of field operations and transport.

Parameters	Unit	Landini Rex 90 S DT Cab	Caravaggi BIO900	Agrisav CAS 1000	Same Virtus 140 dt Cab	Manitou 940–120 LSU	IVECO Trakker 190T36
Investment	€	54,554.00	92,800.00	15,060.00	96,340.00	110,000.00	130,850.00
Service life	yr	10	10	10	10	10	-
Usage	h·yr^{-1}	460	460	460	460	460	-
Labor costs	€·h^{-1}	11.50	11.50	11.50	11.50	11.50	16.66
Crew	n	1	1	1	1	1	1
Load	t	-	-	-	-	-	16.8
Distance to power plant	km	-	-	-	-	-	9.3

3. Results and Discussions

The harvesting system based on the stationary chipper showed a very high harvesting efficiency, because the tractor with fork accumulated the pruning biomass without pauses near the uploading equipment that fed the chipper continuously. In fact, the FE resulted very high and equal to 99% due to an EFC very similar to the TFC. This is a very important aspect, because delay times are instead substantial in pruning harvesting for hog fuel production. As observed also by [21], in the case of the stationary chipping system, its use is nevertheless conditional on the concentration of residues. For this reason, the ability of the tractor driver equipped with a fork to accumulate the material to be chipped continuously without creating idle time for the chipper is a key aspect of achieving high levels of harvesting efficiency. For example, Spinelli et al., dealing with olive-pruning harvesting with a self-propelled harvesting machine, Favaretto Speedy Cut (Favaretto Paolo, Meolo, Veneto Region, Italy), reported that the effective field capacity was more or less 20% lower than the theoretical one [31].

There are not many experiences in literature related to the collection of pruning by a stationary chipper. According to our knowledge, only Borja Velázquez-Mart et al. report results of harvesting pruning by means of a transportable chipper fed by means of a mechanical crane (Jenz AZ 30 D of 74.5 kW (JENZ GmbH Maschinen- und Fahrzeugbau, Petershagen, Nordrhein-Westfalen Region, Germany) and a Ventura Wood-Terminator 7 (Ventura, Aiguaviva, Girona District, Spain) of 60 kW) [21]. According to the reported above paper's results, obtained during the harvesting trials of olive tree-pruning with a stationary chipper, registered a field capacity of 1.75 ha·h^{-1} (0.572 h·ha^{-1}) [21]. This value is higher than those recorded in the present study (Table 2) that, on the other hand, is compatible to the value obtainable by applying the predicting model proposed by [21] to evaluate the field capacity of specific harvesting systems, according to the pruning biomass available in the field. So, for collection systems based on stationary chippers, and with an available biomass of 12.8 $t_{fm} \cdot ha^{-1}$, the model reported by [21] predicts a field capacity of 0.59 $ha \cdot h^{-1}$, which is compatible with the 0.6 $ha \cdot h^{-1}$ obtained in the present study.

Table 2. Results of the performance and work quality of the stationary harvesting Caravaggio mod. BIO 900.

Variable	Unit	Value
Theoretical Field Capacity (TFC)	$ha \cdot h^{-1}$	0.61 ± 0.13
Effective Field Capacity (EFC)	$ha \cdot h^{-1}$	0.60 ± 0.13
Field efficiency (FE)	%	99.0
Yield	$t_{fm} \cdot ha^{-1}$	12.8
Material Capacity (MC)	$t_{fm} \cdot h^{-1}$	7.26 ± 1.13
Material Capacity (MC)	$t_{dm} \cdot h^{-1}$	5.23 ± 0.81
Fuel Consumption	$l \cdot t_{fm}$	3.5 ± 0.40
Fuel Consumption	$l \cdot h^{-1}$	25.1 ± 0.80
Bulk Density	$kg_{fm} \cdot m^{-3}$	246 ± 11
Moisture content	%	28 ± 0.40
d50 value for particle size distribution	mm	9.17
Particle size distribution class	-	P16

Although, an even more important parameter to consider is the material capacity (MC). In fact, the hourly productivity obtained during the test with Caravaggi mod. BIO900 was 7.26 $t_{fm} \cdot h^{-1}$ (5.23 $t_{dm} \cdot h^{-1}$), which is comparable to works in forest systems that were determined by ref [32–34], who reported productivities between 2.5 and 5.5 $t \cdot h^{-1}$ [21]. So, forestry stationary chippers permitted to obtain a high productivity compared to the mobile chippers was also observed by [21]. In fact, previous similar studies showed a material capacity of 6.01 $t_{fm} \cdot h^{-1}$ for a self-propelled SAT-4 (Valoriza Energia-Energy Agency, Villanueva de Algaidas, Andalusia Region, Spain) harvester and 6.77 $t_{fm} \cdot h^{-1}$ for a tractor-mounted Jordan (Jensen Service GmbH, Maasbüll, Schleswig-Holstein, Germany) machine [35]; moreover, only 0.72 $t_{fm} \cdot h^{-1}$ were reported for the Favaretto Speedy Cut [31], and similar values were found for various kinds of towed chippers; in particular: 1.37 $t_{fm} \cdot h^{-1}$ for the Promagri 2000 (Promagri, Casablanca, Casablanca-Settat Region, Morocco); 0.69 $t_{fm} \cdot h^{-1}$ for the Jounes Atila (Jonues I Fills Sl, Lleida, Catalonia Region, Spain); 1.27 $t_{fm} \cdot h^{-1}$ for the Serrat Olipack T1800 (Serrat, Castejón del Puente, Huesca Region, Spain) and 1.38 $t_{fm} \cdot h^{-1}$ for the Berti Picker C180 (Berti, Caldiero, Veneto Region, Italy) [21].

It is obvious that this kind of mechanization chain implies a high fuel consumption per time unit ($l \cdot h^{-1}$). This is because the stationary system employed multiple machines at the same time. On the other hand, thanks to the high work productivity, fuel consumption per biomass unit ($l \cdot {t_{fw}}^{-1}$) was limited and similar, even lower, than other machines for pruning harvesting [36].

For what concerns obtained biomass quality, hog fuel produced by the Caravaggi BIO900 belongs to the particle size class P16 (60% of the product with particles between 3.15 and 16 mm) and a fine fraction class F15 (fine fraction < 15%) Figure 3.

The d50 value (median value of the cumulated distribution curve) is 9.17 mm (Figure 4 and Table 2).

Thus, allowing this kind of hog fuel, for what concerns this parameter, for usage also in small domestic plants and not only in industrial ones [37]. The P16 quality class is not simple to be reached with pruning harvesting, which generally leads to the P31.5 or P45 class [38]. Additionally, bulk density and moisture content showed very interesting results, allowing to reach the A1 and A2 class standards, respectively, according to UNI EN ISO 17225-4 [27].

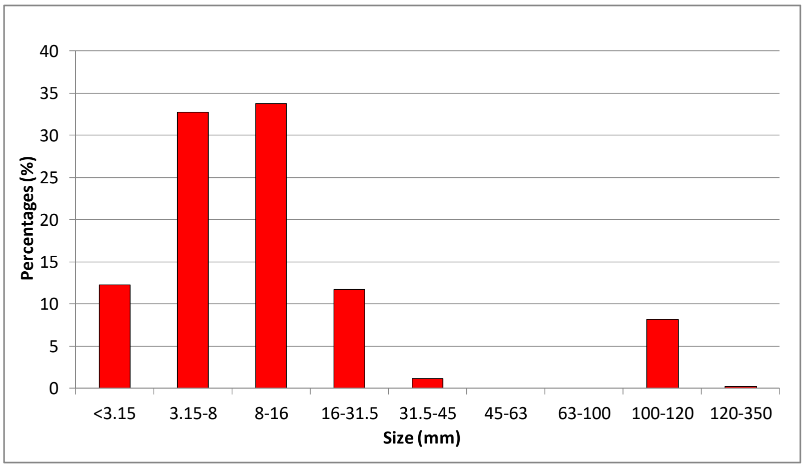

Figure 3. Particle size distribution analysis of the hog fuel produced by the Caravaggi mod. BIO900.

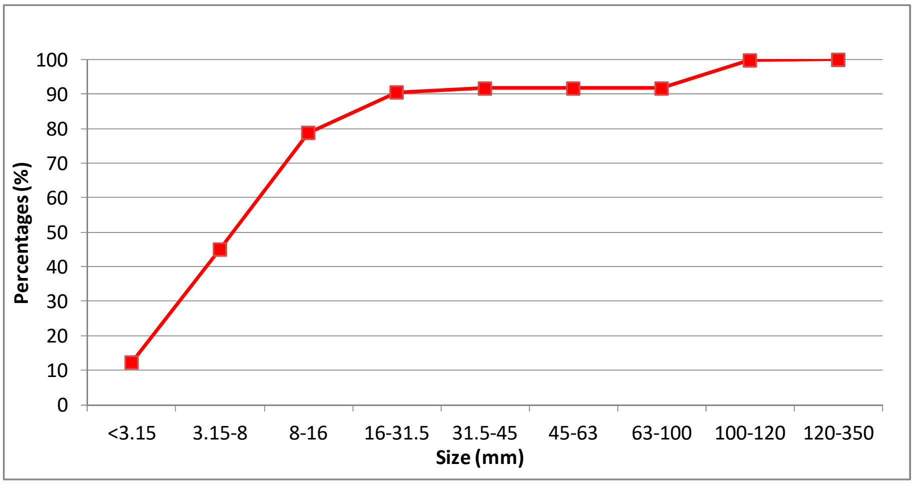

Figure 4. Cumulative distribution curves of the hog fuel produced by the Caravaggi mod. BIO900.

Results of the conducted analysis on work productivity and hog fuel quality are given in Table 2.

Focusing on harvesting systems' costs, a detail of these, not considering the transport operation, is given in Table 3, distinguishing, for each machine, fixed and variable costs. As it is possible to notice, Caravaggi BIO900 is the machine which presented the higher costs among the ones used in the investigated harvesting system.

Table 3. Harvesting systems' costs subdivided into fixed and variable costs for each applied machine.

	Cost Item	Measure Unit	Caravaggi BIO900	Landini Rex 90 S DT Cab	Agrisav CAS 1000	Same Virtus 140 dt Cab	Manitou 940–120 LSU
Fixed costs	Reintegration quote	€·yr^{-1}	7638.91	3644.64	1206.74	6436.28	7360.67
	Interests	€·yr^{-1}	1638.16	1089.92	270.79	1924.76	2195.90
	Shelter	€·yr^{-1}	45.61	14.63	27.50	21.44	28.36
	Insurance	€·yr^{-1}	232.00	136.39	37.65	240.85	275.00
	Miscellaneous expenses	€·yr^{-1}	277.61	151.02	65.15	262.29	303.36
	Total fixed costs per year	€·yr^{-1}	9554.69	4885.58	1542.68	8623.33	9859.93
	Total fixed costs per hour	€·h^{-1}	20.77	10.62	3.35	18.75	21.43
Variable costs	Maintenance	€·h^{-1}	7.41	1.02	1.20	1.81	2.07
	Fuel	€·h^{-1}	7.20	5.04		2.16	3.10
	Lubricant	€·h^{-1}	0.30	0.19		0.24	0.23
	Manpower	€·h^{-1}	11.50	11.50	11.50	11.50	11.15
	Total variable costs per hour	€·h^{-1}	18.91	17.76	12.70	15.71	16.54
	Total costs per year	€·yr^{-1}	18253.80	13053.99	7385.92	15847.68	17469.68
	Total costs per hour	€·h^{-1}	39.68	28.38	16.06	34.45	37.98
	Total costs per hectare	€·ha^{-1}	66.14	47.30	26.76	57.42	32.77
	Total costs per ton	€·t_{fm}^{-1}	5.47	3.92	2.22	4.75	2.71

In Table 4, a comparison of the harvesting systems' costs, without the transport operation, with similar studies is shown [31,32].

Table 4. Pruning harvesting systems' costs (no wood chips' transports included) and comparison with previous studies on similar topics.

Harvesting System	Reference	Initial Investment (€)	Harvesting Cost		
			(€·h^{-1})	(€·ha^{-1})	(€·$t_{fm}{}^{-1}$)
SAT-4	[32]	190,000.00	158.00	67.05	29.99
Jordan	[32]	250,000.00	149.00	263.20	22.53
Favaretto	[31]	180,000.00	77.20	97.87	58.70
Caravaggi	this study	368,754.00	156.55	230.38	19.07

As it is possible to notice in Table 4, this paper's system is the one with the highest amount of initial investment, and this is linked to the multiple machines needed for the implementation of such a harvesting system. Caravaggi, SAT-4 and Jordan systems showed similar hourly costs; instead, the Favaretto Speedy Cut presented a substantially lower one. However, it should be noted that Favaretto carries out the pruning, harvesting and shredding phases in a single operation. It is also important to stress that the mechanical pruning carried out by Favaretto is not always applicable or adapted to all the olive groves.

About costs per hectare, it is possible to see how the Caravaggi and Jordan showed very similar values, which were consistently higher than the Favaretto and SAT-4. On the other hand, the stationary harvesting system analyzed in the present paper showed the lowest cost per fresh material ton.

For what concerns the transport cost, conducted by an IVECO 190T36 truck for a distance of 9.3 km from the experimental field to the Fiusis power plant, authors found a cost of 10.93 €·$t_{fm}{}^{-1}$ (1.175 €·t^{-1} km^{-1}). It is important to underline the substantial influence of the transport on overall harvesting system costs. In fact, the transport of the shredded material from the olive grove to the Fiusis power station (9.3 km) accounted for about 35% of the total costs. The transport costs obtained from this study are in line with the transport costs of hog fuel or wood chips to power plants of 1.08–1.18 €·t^{-1}km^{-1} indicated by a sample of seven wood traders and freelance forestry practitioners working in Central and Southern Italy who were contacted by telephone during the study, as well as the validation obtained by representatives of the Fiusis Plant [39]. Furthermore, during the phone was identified a range of hog fuel prices paid by the power plants, which, in Central and Southern Italy, is actually between 35 and 50 €·t^{-1} for the material conferred to the power plant gate. Considering the overall harvesting system costs (field operations and transport for a 10-km distance), this research showed a value of 30.00 €·$t_{fm}{}^{-1}$. A profitability analysis showed a positive value ranging from 5 to 15 €·$t_{fm}{}^{-1}$ depending on the hog fuel price paid from the power plant to the farmer or agro-forestry enterprise, which harvests pruning residues.

According to the findings of the present paper, in the case of the Fiusis power plant which developed a dedicated business unit for pruning harvesting, it is possible to assert that the cost per ton of biomass using the stationary chipper Caravaggi is equal to 30.00 €·$t_{fm}{}^{-1}$ considering also the transport costs within 10 km. After 27 km, the harvesting and transport costs results become higher than 50 € per ton of biomass, and so, considering the maximum market prices, the operation presents a negative value (Figure 5).

The detail of the harvesting systems' costs for each operation (accumulation of the pruning residues, biomass comminuting, truck load and transport), both considering and not considering transport operation, is given in Figure 6.

As it is possible to notice in Figure 6a, the majority of the costs are imputable to biomass comminuting, but also, the transport operation, as already mentioned, has a consistent impact on the overall costs of the harvesting system (Figure 6b). In detail, 47.30 €·ha^{-1} (3.92 €·$t_{fm}{}^{-1}$) was necessary for pruning residue accumulations by tractor with an amount of 66.14 €·ha^{-1} (5.47 €·$t_{fm}{}^{-1}$) was found for biomass comminuting, and a value 32.77 €·ha^{-1} (2.71 €·$t_{fm}$$^{-1}$) was estimated for truck load by the Manitou lifter.

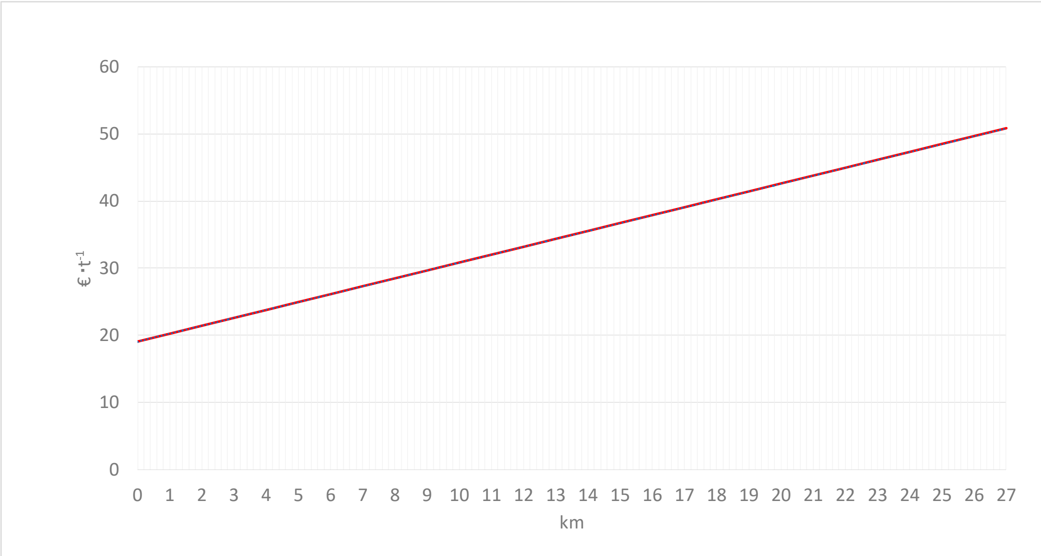

Figure 5. Economic thresholds of the transport of the pruning comminuted product of the Caravaggi mod. BIO900 in Italy (Calimera, LE).

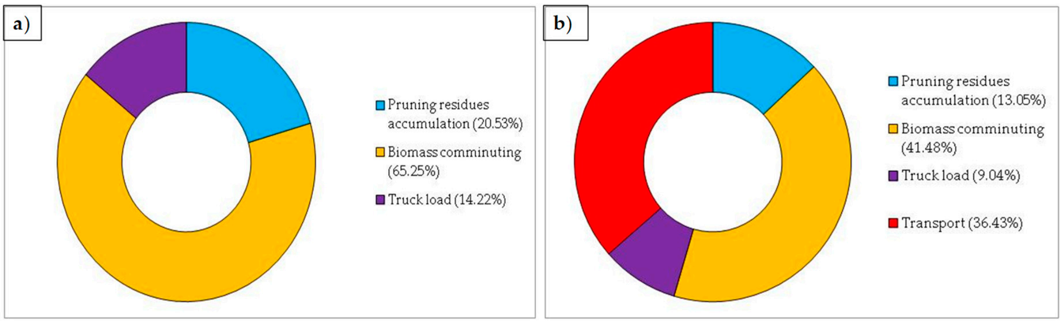

Figure 6. (**a**) Percentage of the total costs for field operations. (**b**) Percentage of the total costs considering also transport operation.

A very important consideration to be done evaluating this study's results is the influence of biomass yield on the economic performances of the harvesting system. Considering the high per hectare costs of the Caravaggi system, obviously linked to the multiple machines needed, a substantial amount of pruning residues to be processed is necessary in order to obtain the economic balance of the harvesting system. In particular, the Caravaggi system needs 4.61 t_{fm}·ha^{-1} considering the best scenario (maximum hog fuel price of 50 €·$t_{fm}$$^{-1}$) and even 6.58 t_{fm}·ha^{-1} considering the worst scenario (minimum hog fuel price of 35 €·$t_{fm}$$^{-1}$). With a biomass yield lower than these values, the investigated harvesting system seemed to be not profitable. Such important amounts of pruning residues are quite frequent in the study area, because olive groves are, in large part, age-old (often secular) trees in which pruning operation is carried out generally every two years. Obviously, this aspect has a strong influence on the logistic of pruning harvesting, and accurate planning is needed to allow for the continuous biomass supply for the power plant. On the other hand, this is an important consideration to be done in the optic of using such harvesting systems in a different context.

However, the investigated harvesting system showed very interesting performances for what concerns work productivity and, so, costs and biomass quality. In particular, the use of a stationary chipper, together with a tractor with fork for pruning residues bunching, seems very feasible for pruning harvesting in olive groves characterized by a considerable amount of biomass to be processed and also located on a hilly situation (slope higher than 20%) not easily affordable by towed shredders, towed chippers or integrated harvester. Moreover, this system allowed to avoid a raking operation.

Finally, there is an important consideration to be done on the harvesting system, which could lead to an additional improvement of its efficiency. This consists of the possibility of conveying comminuted material from the stationary chipper directly into the truck dumpster, instead of discharging it on the ground and then loading it with a Manitou lifter. This could allow, from the one hand, to avoid an operation, so reducing costs and improving the overall work productivity of the harvesting chain, and, on the second hand, it would also improve biomass quality, limiting soil contamination of the comminuted material and, so, reducing the hog fuel's ash content. In any case, future dedicated studies would be necessary to verify the feasibility of the proposed improvement

4. Conclusions

Summarizing, the use of a stationary chipper as a pruning harvesting system seemed to be a very interesting solution; in particular, in olive groves characterized by consistent biomass yields and considerable slopes. This system showed very high work productivity if compared to other similar studies on different machines and harvesting systems. This elevated productivity allowed to obtain a low hog fuel production cost, referred to as the biomass unit (€·$t_{fm}{}^{-1}$). Transport cost from the field to the nearest power plant strongly influenced overall costs, consisting of more than one-third of the total cost. Notwithstanding this, the investigated harvesting systems seemed to be feasible in the study area context, allowing to obtain also a little economic gain from the materials, which is actually considered a problem and not a possible resource.

Focusing on obtained the hog fuel quality, it is possible to notice good performances for the investigated parameters (moisture, bulk density and particle size distribution), which reached elevated quality standards. A deeper study on hog fuel quality, taking into consideration also chemical composition, ash content and heating value, is however needed to evaluate hog fuel quality and assessing its possible usage.

Author Contributions: Conceptualization, F.L., A.S. and L.P.; methodology, A.S. and V.A.; validation, N.P. and L.P., data curation, A.S., V.A. and S.B.; writing—original draft preparation, F.L.; writing—review and editing, A.S. and N.P.; supervision, A.S. and L.P. and funding acquisition, L.P. All authors have read and agreed to the published version of the manuscript.

Funding: The work was performed in the framework of the European project AGROinLOG "Demonstration of innovative integrated biomass logistics centres for the Agro-industry sector in Europe". This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 727961.

Acknowledgments: The authors wish to thank the employees of FIUSIS Company (Calimera, LE, Italy) for the authorization to conduct the tests and for their assistance in performing them and their professionality and availability.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses or interpretation of data; in the writing of the manuscript or in the decision to publish the results.

Abbreviations

GHG	greenhouse gases
SC	stationary chipper
TFC	theoretical field capacity (ha·h^{-1})
EFC	effective field capacity (ha·h^{-1})
FC	field efficiency %
MC	material capacity (t·h^{-1})
PSD	particle size distribution
WT	working time
B	biomass

References

1. Picchi, G.; Lombardini, C.; Pari, L.; Spinelli, R. Physical and chemical characteristics of renewable fuel obtained from pruning residues. *J. Clean. Prod.* **2018**, *171*, 457–463. [CrossRef]
2. Magagnotti, N.; Pari, L.; Picchi, G.; Spinelli, R. Technology alternatives for tapping the pruning residue resource. *Bioresour. Technol.* **2013**, *128*, 697–702. [CrossRef] [PubMed]
3. Pari, L.; Alfano, V.; Garcia-Galindo, D.; Suardi, A.; Santangelo, E. Pruning biomass potential in Italy related to crop characteristics, agricultural practices and agro-climatic conditions. *Energies* **2018**, *11*, 1365. [CrossRef]
4. Lu, L.; Tang, Y.; Xie, J.; Yuan, Y. The role of marginal agricultural land-based mulberry planting in biomass energy production. *Renew. Energy* **2009**, *34*, 1789–1794. [CrossRef]
5. Gonçalves, C.; Evtyugina, M.; Alves, C.; Monteiro, C.; Pio, C.; Tomé, M. Organic particulate emissions from field burning of garden and agriculture residues. *Atmos. Res.* **2011**, *101*, 666–680. [CrossRef]
6. Pergola, M.; Persiani, A.; Pastore, V.; Palese, A.M.; Arous, A.; Celano, G. A comprehensive Life Cycle Assessment (LCA) of three apricot orchard systems located in Metapontino area (Southern Italy). *J. Clean. Prod.* **2017**, *142*, 4059–4071. [CrossRef]
7. García-Galindo, D.; López, E.; Gómez, M.; Sebastián, F.; Gebresenbet, G.; Jirjis, R.; Kern, J.; Germer, S.; Pari, L.; Suardi, A.; et al. Europruning project: Summary of final results. In Proceedings of the 24th European Biomass Conference and Exhibition, Amsterdam, The Netherlands, 6–9 June 2016; pp. 89–102.
8. Spinelli, R.; Lombardini, C.; Pari, L.; Sadauskiene, L. An alternative to field burning of pruning residues in mountain vineyards. *Ecol. Eng.* **2014**, *70*, 212–216. [CrossRef]
9. Avraamides, M.; Fatta, D. Resource consumption and emissions from olive oil production: A life cycle inventory case study in Cyprus. *J. Clean. Prod.* **2008**, *16*, 809–821. [CrossRef]
10. Jacometti, M.A.; Wratten, S.D.; Walter, M. Management of understorey to reduce the primary inoculum of Botrytis cinerea: Enhancing ecosystem services in vineyards. *Biol. Control.* **2007**, *40*, 57–64. [CrossRef]
11. Summaries ofAGROinLOG (Demonstration of Innovative Integrated Biomass Logistics Centres for the Agro-Industry Sector in Europe) project, Ref Number: 727961. Available online: https://cordis.europa.eu/project/rcn/205975_en.html. (accessed on 13 December 2019).
12. Khawaja, C.; Janssen, R.; Kindler, A.; Solar, T.; Engelmann, K.; López, E.; García-galindo, D.; Poutrin, C. *Triggering the Creation of Biomass Logistic Centres by the Agro-Industry Handbook for Agro-Industries Interested in Starting a New Activity as Biomass Logistic Centre: The Basic Demand of Information*; FAO: Rome, Italy, 2015.
13. Khawaja, C.; Janssen, C. *D4.3a of the SUCELLOG Project—Summary of the Current Situation of Tschiggerl Agrar GmbH and Feasibility Study. SUCELLOG Project, Triggering the Creation of Biomass Logistic Centres by the Agro-Industry*; Sucellog: Zaragoza, Spain, 2015.
14. Up_running Take-Off for Sustainable Supply of Woody Biomass from Agrarian Pruning and Plantation Removal. H2020-LCE-2015, 2015-2016. Ref number: 691748. Available online: http://www.up-running.eu/. (accessed on 13 December 2019).
15. Pari, L.; Suardi, A.; Santangelo, E.; García-Galindo, D.; Scarfone, A.; Alfano, V. Current and innovative technologies for pruning harvesting: A review. *Biomass Bioenergy* **2017**, *107*, 398–410. [CrossRef]
16. Acampora, A.; Croce, S.; Assirelli, A.; Del Giudice, A.; Spinelli, R.; Suardi, A.; Pari, L. Product contamination and harvesting losses from mechanized recovery of olive tree pruning residues for energy use. *Renew. Energy* **2013**, *53*, 350–353. [CrossRef]
17. Spinelli, R.; Cavallo, E.; Eliasson, L.; Facello, A. Comparing the efficiency of drum and disc chippers. *Silva Fenn.* **2013**, *47*, 1–11. [CrossRef]
18. Spinelli, R.; Hartsough, B.R.; Magagnotti, N. Testing mobile chippers for chip size distribution. *Int. J. Eng.* **2005**, *16*, 29–35. [CrossRef]
19. Nati, C.; Spinelli, R.; Fabbri, P. Wood chips size distribution in relation to blade wear and screen use. *Biomass Bioenergy* **2010**, *34*, 583–587. [CrossRef]
20. Civitarese, V.; Del Giudice, A.; Suardi, A.; Santangelo, E.; Pari, L. Study on the effect of a new rotor designed for chipping short rotation woody crops. *Croat. J. For. Eng. J. Theory Appl. For. Eng.* **2015**, *36*, 101–108.
21. Velázquez-Martí, B.; Fernández-González, E.; Callejón-Ferre, Á.J.; Estornell-Cremades, J. Mechanized methods for harvesting residual biomass from Mediterranean fruit tree cultivations. *Sci. Agric.* **2012**, *69*, 180–188. [CrossRef]

22. ASAE. *ASAE S495 Uniform Terminology for Agricultural Machinery Managemen*; American Society of Agricultural Engineers: St. Joseph, MI, USA, 2000; pp. 342–343.
23. ISO 17828:2015. Solid biofuels — Determination of bulk density. Available online: https://www.iso.org/obp/ui/#iso:std:iso:17828:en (accessed on 13 December 2019).
24. ISO 18134-2:2017. Solid biofuels — Determination of moisture content — Oven dry method — Part 2: Total moisture — Simplified method. Available online: https://www.iso.org/obp/ui/#iso:std:iso:18134:-2:ed-2:v1:en (accessed on 13 December 2019).
25. Eija, A.; Markus, H.; Jaana, L.-L.; Jaana, K. Properties of indigenous fuels in Finland. *VTT Technol.* **2016**, 30–32.
26. Pari, L.; Suardi, A.; Del Giudice, A.; Scarfone, A.; Santangelo, E. Influence of chipping system on chipper performance and wood chip particle size obtained from peach prunings. *Biomass Bioenergy* **2018**, *112*, 121–127. [CrossRef]
27. UNI EN ISO 17225-4:2014. Solid Biofuels - Fuel Specifications and Classes - Part 4: Graded Wood Chips. Available online: https://www.iso.org/obp/ui/#iso:std:iso:17225:-4:ed-1:v1:en (accessed on 13 December 2019).
28. Assirelli, A.; Pignedoli, S. Costo di esercizio delle macchine agricole. *Rice Prod. Anim.* **2005**, *5*, 1–10.
29. ASAE. *EP496.2 Agricultural Machinery Management*; American Society of Agricultural Engineers: St. Joseph, MI, USA, 2000; pp. 344–349.
30. Ministero delle Infrastrutture e dei Trasporti (Ministry of Infrastructure and Transport). *Linee Guida Per La Valutazione Degli Investimenti in Opere Pubbliche, Nei Settori Di Competenza Del Ministero Delle Infrastrutture e Dei Trasporti (Guidelines for the Evaluation of Investments in Public Works, in the Areas of Competence of the Ministry*; Ministero Delle Infrastrutture e Dei Trasporti: Rome, Italy, 2014.
31. Spinelli, R.; Magagnotti, N.; Nati, C.; Cantini, C.; Sani, G.; Picchi, G.; Biocca, M. Integrating olive grove maintenance and energy biomass recovery with a single-pass pruning and harvesting machine. *Biomass Bioenergy* **2011**, *35*, 808–813. [CrossRef]
32. Cuchet, E.; Roux, P.; Spinelli, R. Performance of a logging residue bundler in the temperate forests of France. *Biomass Bioenergy* **2004**, *27*, 31–39. [CrossRef]
33. Yoshioka, T.; Hirata, S.; Matsumura, Y.; Sakanishi, K. Woody biomass resources and conversion in Japan: The current situation and projections to 2010 and 2050. *Biomass Bioenergy* **2005**, *29*, 336–346. [CrossRef]
34. Johansson, J.; Liss, J.-E.; Gullberg, T.; Björheden, R. Transport and handling of forest energy bundles—Advantages and problems. *Biomass Bioenergy* **2006**, *30*, 334–341. [CrossRef]
35. Spinelli, R.; Picchi, G. Industrial harvesting of olive tree pruning residue for energy biomass. *Bioresour. Technol.* **2010**, *101*, 730–735. [CrossRef]
36. Velázquez-Martí, B.; Fernández-González, E. Analysis of the process of biomass harvesting with collecting-chippers fed by pick up headers in plantations of olive trees. *Biosyst. Eng.* **2009**, *104*, 184–190. [CrossRef]
37. Krajnc, N.; Jemec, T.; Rogelja, T.; Mattioli, D.; Schmatzberger, S.; Luttmann, A.; Oršanič, T.H.; Kunst, M.; Kezdy, P.; Michele, L.; et al. Steps in Setting Up Wood Biomass Production Chains in Protected Areas; Bioeuparks project: 2015. Available online: https://slideplayer.com/slide/8879362/ (accessed on 13 December 2019).
38. Pari, L.; Suardi, A.; Frąckowak, P.; Adamczyk, F.; Szaroleta, M.; Santangelo, E.; Bergonzoli, S.; Del Giudice, A.; Dyjakon, A. Two innovative prototypes for collecting pruning biomass: Early performance tests and assessment of the work quality. *Biomass Bioenergy* **2018**, *117*, 96–101. [CrossRef]
39. Latterini, F.; Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria (CREA), Rome, Italy. Personal Comunication, 2019.