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Mechanical Harvesting Line Setting of Giant Reeds

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Abstract: This study evaluated the possibility of adopting haymaking farming machinery in giant reed (*Arundo donax* L.) harvesting. The test shows the technical and energy aspects of mechanical harvesting using only one specific machine, a shredding machine, designed and developed by an Italian constructor for large biomass herbaceous crops (giant reed, sorghums, switchgrass, *Mischantus*, etc). It is designed for high vegetative growth crops, as it is able to spread products over all soil surfaces or, alternatively, carry out windrowing. Tests were conducted in the south of Italy (Campania region) on the experimental farm Torre Lama in Bellizzi (SA). Biomass was shredded, dried in the field, and baled for use in a logistic chain and storage. The first step was the cutting and shredding of biomass crops with the specific shredder rear-mounted in an agricultural tractor. The biomass then was dried on the field, constantly monitored for moisture content, and finally, baled with a trailed round baler for storage (second step) and used in a specific logistic chain. The test showed good performance of the shredder machine between 1.17 and 1.77 ha h^{-1} with an operative speed between 3.9 and 5. 9 km h^{-1}. To define the hourly production, a high wet production level of 60.70 t ha^{-1} and a low level of 56 t ha^{-1} were used as references. Under the climatic conditions of the experimental test, this harvesting system showed some advantages, such as the possibility of immediate and long-term biomass storage (less than 14% moisture content), the potential alternative use of the biomass, and the reduced resource use compared to that of other ordinary crops growing in the area.

Keywords: giant reed; haymaking; baling; storage; energy

1. Introduction

The fast growth rate, high biomass yield, limited input demand, ability to grow in different soil types and under different climatic conditions, high resistance to pathogens and long drought periods, strong weed competition, and high calorific value [1] are some of the most important characteristics of the giant reed (*Arundo donax* L.), making it one of the main bioenergy crops [2]. Lignocellulose from the giant reed represents a significant source for paper [3], rayon [4], second-generation ethanol and biopolymers [5], biogas production [6], and for the raw materials of biodiesel production [7,8]. Moreover, its good yield coupled with the low level of input needed for its production could provide a positive energy balance. *Arundo donax* is adapted to all soil types and different weather conditions, but it is very important to determine the most appropriate harvesting technique in order to obtain the highest level of biomass possible, together with a low level of moisture during harvesting and a small fine fraction [9]. Several studies have confirmed that the key cost components in the logistic chain of herbaceous crops are transportation, adopted logistics, and field operations, such as biomass

harvesting [10–15]. Until a few years ago, the propagation system was critical; then, mechanized techniques using rhizomes [16] were developed, which reduced the establishment costs [17]. The main bottleneck of this herbaceous crop is the low bulk density, which causes high logistic costs [18], and only the baling technique can reduce the harvest costs [19,20]. Modern baling machines, both round and square balers, can increase the final density, but they require a lower moisture level in the crop [21] to enable longer storage and reduce the fermentation risk. The moisture at harvest time is the main parameter that determines the success of the storage phase, and this problem can be reduced through the infield densification of dried biomass harvested in round or square balers [22,23]. The same test was conducted with a self-propelled forage harvester (SPFH) that chips dry biomass, but the low bulk density of the chipped material and the lack of an efficient compaction field system limits the applicability of this system by raising the harvest costs [18,22]. These parameters allow the immediate use of it as a fuel for thermo valorization, and the low moisture of the biomass prevents the risk of unwanted fermentation during storage, thanks to the improvement of air permeability. A greater moisture content limits the possibility of biomass valorization in solutions of fresh biomass (second-generation ethanol and biogas) [24]. The machine adopted for mowing and shredding the crops is a new commercial machine with a specific rotor for herbaceous crops that comminutes the plants into small pieces, while the harvesting of dry materials is carried out with a trailed round baler, conventionally adopted for haymaking crops. Several studies have provided interesting information about *Arundo donax* compared with other herbaceous crops in terms of its biomass and responses to different harvest technologies, fertilizers, and other cultivation techniques [25–27].

In the southern areas of Italy, the giant reed is a newly introduced energy crop for combustion in thermo valorization plants, and its use has sparked great interest [28]. The bales are classified as high quality if they have a low moisture content and a high bulk density [29].

The aim of this study was to analyze two-steps (shredding and baling) of the harvesting system of *Arundo donax* in southern Italy. We considered two production levels and two different settings of the mechanized harvesting line.

2. Material and Methods

2.1. Environmental Aspects of the Experimental Site

The experimental site was located in Bellizzi (SA) at the experimental farm Torre Lama of the University of Naples Federico II (Table 1). The soil in the experimental plots was deep Vertic Luvisol [30], with a texture ranging from clay-loam (topsoil) to sandy clay (subsoil) without gravel. The experiment site was in a Mediterranean climate, where the yearly temperature ranged from 2.6 to 37.5 °C, the annual average rainfall was 651 ($\pm$135) mm, and the evapotranspiration (ET_0) was 1105 ($\pm$14) mm year^{-1} (climatic period 2009–2013) [31].

Table 1. Characteristics of the experimental field and crop management.

Latitude	40°36′50.49″
Longitude	14°55′19.46″
Total area, m^2	7450
Transplant, year	2007
Inter-row spacing, m	1
Plants density, n ha^{-1}	10,000
Shredding date	12/03/2015
Baling date	13/04/2015

2.2. Crop Management

In autumn 2007, the soil was prepared and a deep ripping (60 cm) was made up, followed by soil milling (20 cm), pre-plant fertilization (150 kg ha^{-1} K_2O and 150 kg ha^{-1} P_2O_5). A total of 50 kg N

ha^{-1} from urea was distributed. Giant reed rhizomes were planted on February 2008 at a soil depth of 10–20 cm and a density of 1×1 m.

The characteristics of the investigated crops that were measured before harvesting were as follows: the average and maximum height, plant density, moisture content, average and maximum diameter, and the average weight of the plant and biomass that could be harvested. These data were collected at the 3rd and 4th cropping cycles, because this stage can be considered the ordinary yield stage [12,31]. Tissues from different plant organs (leaves, culms, and rhizomes) were oven-dried at 105 °C until constant weight to determine the dry matter content.

The harvesting operations started from the two long sides of the external plot, always identifying a turning phase for each setting, and continued towards the inside of the experimental field, thus defining the different setting in a precise order.

2.3. Machine Characteristics and Performance

The study on the harvesting of the giant reed took place in March when the biomass of the crop was shredded and spread on the surface of the field. In the first phase, the operations involved cutting, shredding, and spreading without windrowing with the rear mounted shredder. The machine used was a biotriturator produced by the company Nobili S.r.l. (Bologna, Italy), which combines all of the above-mentioned operations. The Windrower Shredder (WS) series was specifically designed and developed for this category of energy crops [30]. It was composed of a main rotor with 40 hammers installed on 8 lines and driven by 5 parallel belts (Figure 1) and it was rear-mounted (Figure 2) using three-point linkage on a four-wheel drive tractor with a 206 kW engine (make: Fendt, model: 828 Vario).

Figure 1. Hammer rotor.

Figure 2. The shredding machine adopted for the tests (Nobili WS 320 BIO).

Before harvesting, some tests were carried out to monitor the performance of the machine in terms of its settings (working speed and rotor speed). In the first two years of development, the test field was divided into two and each part was treated differently. One part was irrigated and fertilized as described; the other only underwent transplant irrigation. In the following years, the plants were treated in the same way without external intervention. However, two levels of production—high and low yield—were characterized. The data were obtained from manual harvesting of a specific sample area of 4 m². For the two yield classifications (high and low), we used two working speeds obtained with the same gear but varying the motor speed from 2200 to 1890 revolutions/minute (r.p.m.) and using two rotor rotational speeds (1170 and 1000 rpm). For each of the eight settings identified by two passages for the entire length of the test field, three replicates were monitored (Figure 3).

The manufacturer of the biotriturator indicated that it was specifically designed and developed for use at a main rotor speed of 1000 rpm; this was applied by setting the power take off of the tractor to this speed.
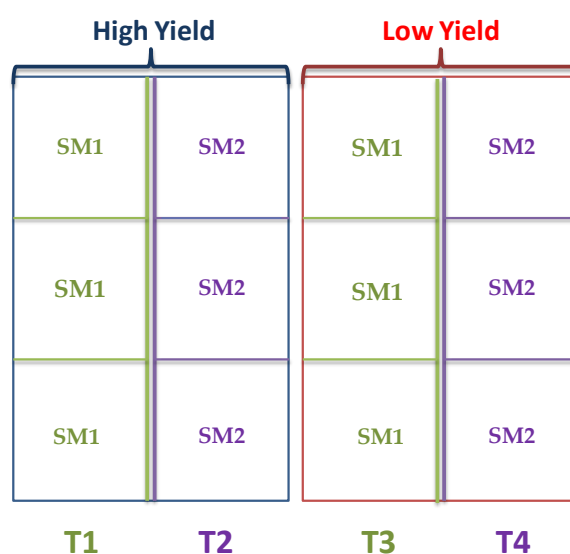

Figure 3. Experimental plot: Treatment 1 (T1)—high yield and setting machine 1 (SM1); Treatment 2 (T2)—high yield and setting machine 2 (SM2); Treatment 3 (T3)—low yield and setting machine 1 (SM1); Treatment 4 (T4)—low yield and setting machine 2 (SM2).

The results of the preliminary tests were used to assess the level of crushing and the obtainable cutting height at different advanced and rotor speeds. They were considered to be the limit values of crop crushing that could give a maximum length of 100 cm of unshredded material (1000 r.p.m. main rotor) and a minimum working speed (1800 r.p.m. engine speed) that allowed good precision cutting. The machine used to harvest the dry-biomass was a roundbaler (Claas model Rollant 250) trailed by four wheels and driven by agricultural tractor (Valtra model N141). The machine adopted for baling has specific features for the management of different categories of crops, for example, the compression chamber is fixed and composed of multiple parallel roller systems and a specific feeding device. This compression system is adapted for dried and wet biomass, is equipped for tying on both mesh or twine, and is quickly editable by the operator cab. For the test, it was decided to use mesh tying, as this is able to reduce the loss of small particles, especially during the tying phase. It is important to choose the most suitable tying system (on mesh or twine) to suit the characteristics of the biomass crop and influence the baling costs. To determine the round baler efficiency, we recorded the turning times at the field end, and the periodical time losses due to the tying and discharge of bales were also considered.

We assumed that the appropriate performance measure of the investigated machine was the working time according to American Society of Agricultural and Biological Engineers (ASABE) [32,33]. Other references included the Commission International de l'Organisation Scientifique du Travail en

Agriculture (CIOSTA) and the Italian Society of Agricultural Engineering (AIIA) 3A R1 [34]. Based on the classification proposed by the CIOSTA, work times have been classified as follows (the acronyms of times derived from Latin were used). *Tempus operandi* (TO) is the operative time and is given by *tempus efficientiae* (*TE*) that is the effective time and *tempus adiuvandi* (*TA*) that is the accessory time. The equation can be formalized as:

$$TO = TE + TA, \text{ where } TA = TAS + TAV + TAC,$$

where *tempus adiuvandi supplendo* (*TAS*) represents the maintenance time, *tempus adiuvandi vertendo* (*TAV*) represents the turning time, and *tempus adiuvandi curandi* (*TAC*) represents the adjustment time. All of these parameters are expressed in % of *TO*.

Considering that the machine was operating in the field, it was important to determine its *effective field capacity* (*EFC*), which can be expressed as the area capacity (Ca):

$$Ca = TFC \times Ef$$

where *Ca* is the area capacity (ha h^{-1}), *TFC* is the theoretical field capacity:

$$TFC = (S \times W)/10$$

where *S* is the field speed (km h^{-1}), *W* is the implemented working width (m), and *Ef* is the field efficiency (%). The field efficiency is computed as follows:

$$Ef = EFC/TFC \times 100\%.$$

During baling, the working time, performance, and fuel consumption were recorded. Fuel consumption was measured during the experimental trial by starting with a full tank and refilling the tank at the end of the work.

2.4. Quality of Work

At the end of the shredding phase, three replicate plots (7.5 m^2) in the test area were randomly chosen for height-cut and loss evaluation. Forty-five plants per treatment (15 plants per replicate) were measured to determine ground losses. To represent the shredder efficiency, all non-shredded *Arundo donax* plants less than 1 m long remaining on the field after step 1 of harvesting were harvested and weighed.

The drying time of the biomass in the field was evaluated using a completely randomized design. The number of drying days was calculated from shredding to baling. A sample of each replicate was collected randomly on seven different dates, immediately weighed, and sealed in a plastic bag after harvesting. It was then sent for moisture measurement according to DD CEN/TS 14774-2:2004 [35]. After an initial period with quite variable data between the different samples, the drying step showed a loss of moisture that was enough to adjust the minimum value indicated. This was almost stable for two successive sampling intervals. A few days later, when the value was stable, the round baling step began.

At the end of baling, three replicates per treatment (1 × 1 m) were randomly chosen for ground loss evaluation. For the twelve plots (3 replicates × 4 treatments), all ground losses were collected in a plastic bag and weighed.

2.5. Statistical Analysis

Data recorded on the heights of stems and the losses at steps 1 and 2 were analyzed using analysis of variance procedures (free software PAST version 2.12, Øyvind Hammer Natural History Museum, University of Oslo). The shredding stem heights and losses at steps 1 and 2 were used as variables;

the treatments from 1 to 4 were the analyzed factors. Mean separations were performed using the post-hoc Tukey's HSD test at $p \leq 0.05$.

3. Results and Discussion

3.1. Harvesting—Step 1 (Shredding) and 2 (Baling)

At the harvest time, the crop field was uniform and without a laid out area. The plant density was 14.2 ± 0.04 stems m^{-2}, the average plant height was 3.98 ± 0.09 m, and the average diameter was 16 ± 2 mm.

The shredding level obtainable in the different machine settings was very heterogeneous, with excessive fragmentation of herbaceous parts such as leaves and simultaneous presence of stem parts longer than 50 cm that were not or partially crushed. The working times and performance characteristics of the first step are reported in Table 2.

Table 2. Working time and performance characteristics of the shredding phase of *Arundo donax* harvesting.

Parameter	T1		T2		T3		T4	
	Values	%	Values	%	Values	%	Values	%
Effective time (*TE*), s	344	90.05	229	89.8	349	91.84	234	92.49
Accessory time (*TA*), s	38	9.95	26	10.2	31	8.16	19	7.51
Turning time (TAV), s	38	9.95	26	10.2	31	8.16	19	7.51
Total, s	382	100	255	100	380	100	253	100
Effective Speed, km h^{-1}	4.33		6.51		4.27		6.37	
Operating Speed, km h^{-1}	3.9		5.84		3.92		5.89	
Effective field capacity (EFC), ha h^{-1}	1.17		1.75		1.18		1.77	
Material capacity, t h^{-1}	35.15		52.66		32.68		49.09	

The favorable conformation of the plots and the reduced time loss for logging positively influenced the performance of the machine with an effective field capacity of over 1.1 ha h^{-1} for the low speed (T1 and T3) and 1.7 ha h^{-1} for the high-speed treatments (T2 and T4). The same result was obtained for both high and low yield areas. The working speeds were always slightly higher than the originally set values for the treatments, because the automatic engine management system permitted different engine settings, i.e., constant speed and/or power take off (PTO) speed. For this test, the engine management was set to a constant PTO speed with a low speed variation caused by a low variation in the engine torque.

Regarding the effective field capacity, the high yield obtained is 60.70 t ha^{-1} and the low one is 56 t ha^{-1}, in terms of material capacity, at a moisture level of 42.51%.

After shredding, the biomass drying in the field was monitored to define the harvest date (baling). The second step was carried out when the biomass moisture was 6.09%—much less than the minimum level of 12–14% cited in reference [36].

In the feeding step, the pick-up of the harvester was able to operate efficiently, and the collection of the larger particles of the chopped yield was regular, as shown in Figure 4.

Figure 4. Baling phase of the high yield treatment (T1 and T2).

As shown in Table 3, the study of the working time demonstrated that the highest efficiency occurred when the tying time was between 14 and 30 s (because at the beginning, the number of wrappings was very low, causing some deformation of the bale). This value is increased as the number of wrappings and the turning times became uniform at 21–25 s. The speed was about 5 km h^{-1} for T2 and T3; however, for thesis 4, it was the highest (6.55 km h^{-1}). Regarding the round bale performance, values were fairly low, but they were still associated with a low biomass moisture content at baling time, about 7 times less moisture than that produced by cutting.

Table 3. Time and performance characteristics for step 2 (baling).

Parameter	T1		T2		T3		T4	
	Value	**%**	**Value**	**%**	**Value**	**%**	**Value**	**%**
Effective time (TE), s	127	58.26	302	78.85	288	75.2	140	68.63
Accessory time (TA), s	91	41.74	81	21.15	95	24.8	64	31.37
Turning time (TAV), s	25	11.47	21	5.48	23	6.01	22	10.78
Maintenance time (TAS), s	66		60		72		42	
Total, s	218	100	383	100	383	100	204	100
Effective Speed, km h^{-1}	5.81		4.89		5.13		6.55	
Operating Speed, km h^{-1}	3.39		3.85		3.85		4.5	
Effective field capacity, ha h^{-1}	0.71		0.81		0.81		0.95	
Material capacity, t h^{-1}	18.5		21.05		19.46		22.76	

During shredding (Table 4), the hourly consumption for chopping remained low for the class of tractor power adopted. However, the engine power was oversized because of the needing to have a tractor with reversible drive system. For this reason, the material consumption was not influenced by yield (high or low).

Table 4. Fuel consumption for shredding (step 1) and baling (step 2).

Machine Setting	Yield	Hourly Consumption, l h^{-1}			Area Consumption, l ha^{-1}				Material Consumption, l t^{-1}			
		Step 1	**Step 2**		**Step 1**		**Step 2**		**Step 1**		**Step 2**	
SM1	high	18	17.5	b	15.3	b	24.7	b	0.51	b	0.95	b
SM2	high	20	19	b	11.4	a	23.4	b	0.38	a	0.9	b
SM1	low	21 n.s	13	a	17.9	b	16	a	0.64	b	0.67	a
SM2	low	22	12	a	12.3	a	12.6	a	0.45	a	0.53	a

Mean separation using Tukey's HSD post-hoc test at $p \leq 0.05$. n.s.—not significant.

The consumption per unit of area between the two speeds is significantly reduced exceeding 25%. This seems to be an aspect of particular importance if the same homogeneity of shredding is used.

The Nobili WS 320 BIO was used for the management of herbaceous plant biomass. The rotor of this device operated at all working widths with a good shredding efficiency, even though a small component exceeding 50 cm remained. This did not cause problems during the baling phase. The presence of larger particles can also increase the stability of the biomass, reducing the risk of harmful fermentation at moisture levels >15%. The chopped biomass was well spread over the entire working front, although there was often a tendency toward central accumulation, leaving the side edges slightly empty. Although this aspect may limit the efficiency of solar radiation, especially during the biomass drying step, it can simplify the subsequent loading operation by allowing baling pick-up where the operator can be used for machine driving.

During baling (Table 4), the area consumption showed significant reductions from T1 and T2 to T3 and T4. This is difficult to explain because the harvesting differences were rather contained. Similar considerations can be made regarding the consumption per unit of harvesting, where the consumption per ton of yield in the T1 was twice as much as that of T4. The lower power output was probably caused by the higher yield and the increased consumption per unit of harvested product in comparison to the lower yield treatments. The average total fuel consumption for *Arundo donax* harvest in the two steps was $1.25 \, \mathrm{l \, t^{-1}}$, ($0.50 \, \mathrm{l \, t^{-1}}$ shredding and $0.76 \, \mathrm{l \, t^{-1}}$ baling). This is interesting and favorable for the energy aspect of mechanical harvest. Once the setup phase of the harvester finished, no problems with baling were observed thanks to the use of a compression system with the steel parallel rollers of the Rollant 250 model without belts, which could be damaged by sharp surfaces of the stem shredded of *Arundo donax*. Good functionality was verified at the tying system levels. The bales, as shown in Figure 5, were well formed with defined edges and a fairly consistent compression level throughout the profile, especially inside the bales. Once ejected from the compression chamber, the bales were able to maintain their shape and to support storage with other bales.

Figure 5. One of the giant reed bales obtained.

3.2. Quality of Work

The average values for the four treatments for the cutting height and losses during steps 1 and 2 are reported in Table 5. During shredding, the cutting height was statistically different in the four treatments. In particular, the stem height of T2 (on average 13.3 cm) was statistically higher than the others. The losses of the four treatments during steps 1 and 2 were not statistically different.

Table 5. Cutting heights and harvesting losses in steps 1 and 2.

Machine Setting	Yield	Stem Height, cm		Dry Matter Losses t ha^{-1}			
				Step 1		Step 2	
SM1	high	10.5	b	2.65		3.38	
SM2	high	11.6	b	1.46	n.s.	3.10	n.s.
SM1	low	13.3	a	1.35		3.01	
SM2	low	14.4	a	1.35		3.01	

Mean separation using Tukey's HSD post-hoc test at $p \leq 0.05$. n.s.—non-significant.

T1 showed a slight increase in losses of stem particles over one meter in length, but the difference was not statistically significant. There was a loss of biomass that was not harvested (shredded or over-sized). This represents a real loss also due to the difference in the working width between the shredding and baling machines. The cutting height was always greater than 10 cm, which is directly related to the loss of product that did not enter the harvest process (Table 6). The losses for the cutting height were low. They were limited to 1.06 and 1.11 t ha^{-1}, respectively, for high and low yield (Table 6), However, the high speed led to higher loss (1.1 t ha^{-1}) due to the higher cutting difficulty and the propensity to plant lower. The stems confirmed a higher recorded cutting height at higher working speeds: from 11.9 to 12.5 cm (data not shown).

Table 6. Correlations between ground losses and cutting height in relation to the yield.

	Cutting Height, cm	Ground Loss, t ha^{-1}
High speed	12.50	1.11
Low speed	11.90	1.06

This study, which was carried out on giant reed harvesting in two fields at the Torre Lama farm in Bellizzi (Sa), highlighted some peculiarities of the crop and the adopted harvesting system; this system required meticulous management of the two phases, and careful monitoring of the soil and weather conditions was needed before the second phase (baling) to limit losses.

The two-step harvest method showed some advantages, such as immediate biomass storage, 12–14% moisture, allowing long-term storage, better use of farm mechanization, the diversified use of the dried biomass (combustion, second-generation ethanol, etc.), and fuel consumption in line or even less than other herbaceous crops for the Italian area [37]. Fuel consumption for chopping and stacking remained below 1.5 l t^{-1}, and in some cases, there was close to 1 l t^{-1} of dried collected product with values rather similar to those of wheat harvest and equal to 1/3–1/4 of that required for the direct shredding of fresh product performed with SPFH but using machines with less economic engagement always for the management of fresh products [38].

Some limits were highlighted such as the high product losses in the ground (>12%, mainly due to the loss of fine fractions), the need for specific machines (both shredders and balers), the prolongation (>10 days) of field drying due to exposure to meteorological events and negative climatic events (e.g., rain), and the execution of repeated passages in the field with machines that were not equipped for the reduction of soil compaction. Regarding economic aspects, bibliography data suggest that it is not always easy to divide the costs between different harvest methodologies. As a consequence, costs are frequently estimated and grouped according to different machine and utilization levels [39]. The application of predictive software and models which, according to requirements and parameters, permit these costs to be defined at different yield levels is also frequent [40,41]. The machine performance, in terms of both working speed and field capacity, agrees with data recorded on sorghum fiber by Bentini and Martelli [19]. The small differences found are due to the different incidences of turning times in the two different treatments.

The total harvest loss for the two phases was 5.33 t ha^{-1} for the high yield area and 4.41 t ha^{-1} for the low yield areas—rather high values for this harvest system mostly due to the high values found in

shredding phase of MS1. In addition, the losses were not distributed equally between the two phases, as shown in Table 7.

Table 7. Total harvest losses t ha$^{-1.}$

	High Yield	Low Yield
Shredding	2.17	1.46
Baling	2.3	2.13
Total	4.47	3.59

All round bales obtained were weighed, and the total biomass production at a moisture content of 6.09% was found to be 22.68 t ha^{-1} for the high input area and 20.64 t ha^{-1} for the low input area, with an average single weight of 333.23 kg. The dry matter (DM) yield for the total harvest area was 27.29 t ha^{-1}. There was considerable loss at a cutting height over 10 cm that showed an additional quantity of product loss of just under 1 t ha^{-1} (Table 6).

The local logistic chains for *Arundo donax* were not considered in the test, and we did not evaluate the economic aspect due to both the small available surface area for the test and the modest annual use of machines that cannot have a positive effect on the hourly cost.

4. Conclusions

The machines adopted in the test allowed the harvesting cycle to be completed with promising results, even when it rained during the drying phase. In particular, they provided good results despite the use of non-specific machine for *Arundo donax*, such as the round-baler developed for forage harvest. The interesting aspect of this experiment was the reduction of biomass loss in the field (less than 13% of the potential DM). These values are even more interesting because the mechanized method tested was less expensive than those tried in previous CREA (Consiglio per la ricerca in agricoltura e l'analisi dell'economia agraria) experiments with a SPFH. From an energetic point of view, the two-stage harvest allowed the containment of fuel consumption per unit of product, and if machines were already present on a farm, there would also be better rationalization of the machinery in terms of annual employment.

In this first test, the round-baler was adopted, and if there is increase interest in the *Arundo donax* biomass harvesting system, the adoption of square baler technology, which is characterized by better performance especially in terms of working capacity, could be necessary. This harvesting system will permit more haymaking farm machines to be used, and in the future, more economic assessments will be needed to determine the most suitable harvesting system and logistics chain.

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References

1. Vasconcelos, G.C.; Gomes, J.C.; Corrêa, L.A. Rendimento de biomassa da Cana-do-Reino (*Arundo donax* L.). *Embrapa Clima Temperado Bol. Pesqui. Desenvolv.* **2007**, *42*, 5–24.
2. Pindozzi, S.; Faugno, S.; Cervelli, E.; Capolupo, A.; Sannino, M.; Boccia, L. Consequence of land use changes into energy crops in Campania region. *J. Agric. Eng.* **2013**, *44*, 467–471. [CrossRef]
3. Ververis, C.; Georghiou, K.; Christodoulakis, N.; Santas, P.; Santas, R. Fiber dimensions, lignin and cellulose content of various plant materials and their suitability for paper production. *Ind. Crops Prod.* **2004**, *19*, 245–254. [CrossRef]

4. Facchini, P. *La Canna Gentile per la Produzione Della Cellulosa Nobile, L'impresa Agricolo-Industriale di Torviscova*; Snia Viscosa: Milano, Italy, 1941.

5. Williams, C.; Biswas, T. *Commercial Potential of Giant Reed for Pulp, Paper and Biofuel Production*; Rural Industries Research and Development Corporation: Kingston, Australia, 2010.

6. Dragoni, F.; Ragaglini, G.; Corneli, E. Giant reed (*Arundo donax* L.) for biogas production: Land use saving and nitrogen utilisation efficiency compared with arable crops. *Ital. J. Agron.* **2015**, *10*, 192–201. [CrossRef]

7. Pirozzi, D.; Fiorentino, N.; Impagliazzo, A.; Sannino, F.; Yousuf, A.; Fagnano, M. Lipid production from *Arundo donax* growth under different agronomical conditions. *Renew. Energy* **2015**, *77*, 456–462. [CrossRef]

8. Pirozzi, D.; Yousuf, A.; Fagnano, M.; Mori, M.; Fiorentino, N.; Impagliazzo, A. Lipids production by yeast grown on giant reed biomass. *J. Biotechnol.* **2010**, *150*, 167–168. [CrossRef]

9. Assirelli, A.; Civitarese, V.; Caracciolo, G.; Sannino, M.; Crimaldi, M.; Faugno, S. Double-pass harvesting system on giant reed in south Italy. In Proceedings of the 26th EUBCE European Biomass Conference and Exhibition, Copenhagen, Denmark, 14–18 May 2018; pp. 305–308.

10. Hanegraaf, M.C.; Biowinga, E.E.; van der Bijl, G. Assessing the ecological and economic sustainability of energy crops. *Biomass Bioenergy* **1998**, *15*, 345–355. [CrossRef]

11. Angelini, L.G.; Ceccarini, L.; Bonari, E. Biomass yield and energy balance of giant reed (*Arundo donax* L.) cropped in central Italy as related to different management practices. *Eur. J. Agron.* **2005**, *22*, 375–389. [CrossRef]

12. Angelini, L.G.; Ceccarini, L.; Di Nasso, N.N.O.; Bonari, E. Comparison of *Arundo donax* L. and *Miscantus x giganteus* in a long-term field experiment in central Italy: Analysis of productive characteristics and energy balance. *Biomass Bioenergy* **2009**, *33*, 635–643. [CrossRef]

13. Lewandowsky, I.; Scurlock, J.M.O.; Lindvall, E.; Christou, M. The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. *Biomass Bioenergy* **2003**, *25*, 335–361. [CrossRef]

14. Faugno, S.; Civitarese, V.; Assirelli, A.; Sperandio, G.; Saulino, L.; Crimaldi, M.; Sannino, M. Chip quality as a function of harvesting methodology. *Chem. Eng. Trans.* **2017**, *58*, 271–276.

15. Faugno, S.; Quacquarelli, I.; Civitarese, V.; Crimaldi, M.; Sannino, M.; Ricciardiello, G.; Caracciolo, G.; Assirelli, A. Two steps *Arundo donax* L. harvesting in south Italy. *Chem. Eng. Trans.* **2017**, *58*, 265–270.

16. Ceotto, E.; Di Candilo, M. Shoot cuttings propagation of giant reed (*Arundo donax* L.) in water and moist soil: The path forward? *Biomass Bioenergy* **2010**, *34*, 1614–1623. [CrossRef]

17. Assirelli, A.; Santangelo, E.; Spinelli, R.; Acampora, A.; Croce, S.; Civitarese, V.; Pari, L. Mechanization of Rizhome Extraction in Giant Reed (*Arundo donax* L.) Nurseries. *Appl. Eng. Agric.* **2013**, *29*, 489–494.

18. Pari, L.; Suardi, A.; Giannini, E.; Civitarese, V. Strategie per meccanizzare la raccolta di canna comune. *L'Informatore Agrar.* **2009**, *29*, 22–25.

19. Bentini, M.; Martelli, R. Prototype for the harvesting of cultivated herbaceous energy crops, an economic and technical evaluation. *Biomass Bioenergy* **2013**, *57*, 229–237. [CrossRef]

20. Pari, L.; Curt, M.D.; Sanchez, J.; Santangelo, E. Economic and Energy analysis of different systems for giant reed (*Arundo donax* L.) harvesting in Italy and in Spain. *Ind. Crops Prod.* **2016**, *84*, 176–188. [CrossRef]

21. Assirelli, A.; Croce, S.; Acampora, A.; Civitarese, V.; Suardi, A.; Santangelo, E.; Pari, L. An innovative System for conditioning Biomass Sorghum [*Sorghum bicolor* (L.) Moench.]. *Trans. ASABE* **2013**, *56*, 829–837.

22. Acampora, A.; Assirelli, A.; Croce, S.; Gallucci, F.; Pari, L. Prove di raccolta di Arundo trinciato fresco e affienato. *L'Informatore Agrar.* **2014**, *11*, 20–23.

23. Civitarese, V.; Assirelli, A.; Sperandio, G.; Caracciolo, G.; Faugno, S.; Sannino, M.; Crimaldi, M. Biomass quality of different species after storage. In Proceedings of the 26th EUBCE European Biomass Conference and Exhibition, Copenhagen, Denmark, 14–18 May 2018; pp. 342–345.

24. Corno, L.; Lonati, S.; Cantaluppi, E.; Pilu, R.; Tosca, A.; Adani, F. Arundo ottima specie da biogas grazie alle altissime rese. *L'Informatore Agrar.* **2014**, *5*, 21–24.

25. Di Nasso, N.N.O.; Angelini, L.G.; Bonari, E. Influence of fertilization and harvest time on fuel quality of giant reed (*Arundo donax* L.) in central Italy. *Eur. J. Agron.* **2010**, *32*, 219–227. [CrossRef]

26. Christou, M.; Mardikis, M.; Alexopoulou, E. Alexopoulou, Giant reed (*Arundo donax* L.) network. Improvement, productivity and biomass quality. In Proceedings of the 1st World Conference Biomass for Energy and Industry, Sevilla, Spain, 5–9 June 2000; pp. 1803–1806.

27. Yitao, L.; Qingxi, L.; Boping, T.; Caixia, S.; Jing, W.; Aili, M. Experimental research on the mechanical physical parameters of bottom stalk of the *Arundo donax* L. in harvesting period. *Trans. Chin. Soc. Agric. Eng.* **2007**, *23*, 124–129.

28. Dahl, J.; Obernberger, I. Evaluation of the combustion characteristics of four perennial energy crops (*Arundo donx, Cynara cardunculus, Miscanthus x giganteus and Panicum virgatum*). In Proceedings of the Second World Biomass Conference, Biomass for Energy, Industry and Climate Protection, Rome, Italy, 10–14 May 2004; pp. 1265–1270.

29. Cundiff, J.S. Simulation of five large round bale harvesting systems for biomass. *Bioresour. Technol.* **1996**, *56*, 77–82. [CrossRef]

30. ISSS Working Group, RB. *World Reference Base for Soil Resources: Introduction*; Deckers, J.A., Nachtergaele, F.O., Spaargaren, O.C., Eds.; International Society of Soil Science (ISSS), International Soil Reference and Information Centre (ISRIC), and Food and Agriculture Organization (FAO), Acco: Leuven, Belgium, 1998; p. 165. [CrossRef]

31. Fagnano, M.; Impagliazzo, A.; Mori, M.; Fiorentino, N. Agronomic and environmental impacts of giant reed (*Arundo donax* L.): Results from a long-term field experiment in hilly areas subject to soil erosion. *Bioenergy Res.* **2015**, *8*, 415–422. [CrossRef]

32. ASAE. *Agricultural Machinery Management*; Standard ASAE EP 496.3; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2007.

33. ASAE. *Agricultural Machinery Management*; Standard ASAE EP 497.7; American Society of Agricultural and Biological Engineers: St. Joseph, MI, USA, 2011.

34. Bodria, L.; Pellizzi, G.; Piccarolo, P. *Meccanica Agraria*; Il Sole 24 Ore Edagricole: Bologna, Italy, 2006; Volume 2.

35. BSI. *DD CEN/TS 14774-2:2004: Solid Biofuels: Methods for the Determination of Moisture Content; Oven Dry Method; Total Moisture; Simplified Method*; British Standards Insitute: London, UK, 2004.

36. Curt, M.D.; Sanz, M.; Mosquera, F.; Mauri, P.V.; Plaza, A.; Aguado, P.L.; Fernández, J. Harvest mechanization of *Arundo donax* L. in Spain. In Proceedings of the 21st EUBCE European Biomass Conference and Exhibition, Copenaghen, Denmark, 3–7 June 2013; pp. 302–307.

37. Bentini, M.; Caliceti, M.; Zucchelli, M. Development of a prototype implement for *Arundo donax* L. harvesting for combustion purpose. In Proceedings of the 16th EUBCE European Biomass Conference & Exibition-From Research to Industry and Markets, Valencia, Spain, 2–6 June 2008; pp. 523–526.

38. Demaldè, R.; Assirelli, A. Krone Big X 850, produttiva e potente. MAD - Macchine Agricole Domani. *L'Informatore Agrario* **2012**, *9*, 26–32.

39. Assirelli, A.; Pignedoli, S. Costo di esercizio delle macchine agricole. *Cent. Ric. Prod. Anim.* **2005**, *5*, 1–10.

40. Lyncaras, V.; Schneider, U.A. Multi-farm economic analysis of perennial energy crops in Central Greece, taking into account the CAP reform. *Biomass Bioenergy* **2011**, *35*, 700–715.

41. Pignedoli, S.; Bettati, T.; Assirelli, A. Colture no food, un software aiuta a stimare costi e ricavi. *Agricoltura* **2008**, *2*, 104–105.