Mechanized Harvesting of Eucalypt Coppice for Biomass Production Using High Mechanization Level

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Abstract – Nacrtak

*The main aims of this study were to determine the productivity, profitability and energy balance (output/input) of mechanized harvesting applied to a eucalyptus plantation in central Italy. The study area was located in Rome, at an altitude of 35 m a.s.l., on a flat, even site (average slope gradient 3%). The stand was a eucalypt coppice (*Eucalyptus camaldulensis *Dehnh.) harvested for the first time in 2000. The planting pattern was square with 3 m among stumps (1111 trees ha^{-1}). By 2009, insect (*Phorachantha semipunctata*) attacks had reduced stump density to 592 stumps ha^{-1}. The work system applied was the Whole Tree System (WTS) and the final assortement chips for energy. Machine rates were calculated using coefficients and mathematical formulas extracted from the main methodologies proposed by different authors. Energy balance was estimated with the Gross Energy Requirements (GER) method. In these plantations, mechanized harvesting seems most appropriate: this is demonstrated by the high productivity recorded (PSH_{15} 6.5 $t_{d.w.}$ h^{-1} worker^{-1}) and by the favorable energy balance (output/input 23.8, 95.8% system efficiency). However harvesting cost is still high (44.30 € $t_{f.w.}^{-1}$) and can only be reduced through careful operational planning.*

Keywords: harvester; work productivity; operating costs; energetic balance; chipper; forwarder; forest plantation

1. Introduction – *Uvod*

In Italy, eucalypt was used mainly for windbreaks and reforestation, especially in the South and in the Islands. Large reforestation programs were launched in 1950$_s$ mainly for soil protection purposes in Southern Italy (Calabria and Sicily). Later on, in 1980$_s$ new projects were launched for the production of pulpwood (Mughini 2000). Most popular Eucalypt species were *E. globulus* ssp. *bicostata, E. globulus ssp. globulus, E. occidentalis, E x trabutii, E. camaldulensis and E. viminalis*. The surface of eucalypt plantations is now estimated at 72,000 hectares (54,000 ha pure, 18,000 ha mixed with other species). Yields vary a lot, depending on species and site. For instance, *E. globulus* ssp. *globules* may produce from 10 to 35 m^3 ha^{-1} year^{-1}, whereas *E. occidentalis* will produce between 3 and 8 m^3 ha^{-1} year^{-1} (Gemignani 1988). The outlook for eucalypt plantations in Italy can be summarized in three points:

⇒ naturalization of less productive plantations, especially in Southern Italy;

⇒ intensification of crop modules for industrial plantations, in order to increase both the quality and quantity of production (medium rotation coppice and short rotation coppice for wood chips). This will be done using selected clones;

⇒ rationalized use in agroforestry, where row plantations can offer timber, firewood and wood chips.

Energy crops appear as a promising option for ensuring bioenergy feedstock. The profitability of energy crops is highly dependent on appropriate logistics, harvest planning and crop yield (Vega-Nieva et al. 2008). The greatest potential for cost reduction lies in mechanization, which may increase productivity with the introduction of innovative harvesting equipment. Although stand management research regarding the definition of proper practices is now completed, there is always some potential for further cost reduction (e.g. refinement of yield-response in relationships for various management practices). Many experimental plots are now entering the coppice stage. In many cases, the primary maintenance practice consists of frequent harvesting that rejuvenates the stand and stimulates fast growth. Traditional practices for harvesting fuel wood are labor intensive, which may discourage maintenance causing the deplorable state of abandonment of many coppice stands in industrialized countries (Spinelli et al. 2006). The main aims of this study were to determine the productivity, profitability and energy balance (output/input) of mechanized harvesting applied to eucalyptus plantation in central Italy. In order to estimate the energy balance, we determined: indirect inputs, i.e. the energy used for equipment production; direct inputs, i.e. fuel and oil consumption; and human energy consumption during work; output, i.e. energetic value of total wood fuel produced.

These data were used to determine the economic and energetic sustainability of mechanized harvesting chains. Over these last years, mechanization has been rapidly introduced to forest operations. The Italian harvester and processor fleet now counts over 84 units, and its number doubled in the last five years (Spinelli et al. 2010). Although mechanized harvesting was originally designed and first applied to high forest logging (poplar plantation, coniferous plantation), in recent years it has been employed for harvesting coppice stands. However, the smaller volume of coppice trees implies a lower productivity (Martins et al. 2009). An adequate training of workers and planners is necessary, especially when introducing mechanized harvesting to the sustainable use of forest biomass, as a renewable source of clean energy with reduced greenhouse gases (GHG) emission balance (Picchio et al. 2009).

The term »energy analysis« refers to the study of the energy used for the production of a service or a stock. Total energy use includes both the energy directly used during the production process (direct), and the energy stocked in the materials used for the production process (indirect). The Gross Energy Requirements (GER) method is commonly used in energy analyses (IFIAS 1975, Picchio et al. 2009). Although the GER method and the ISO 14040 standard (UNI EN ISO 14040 2006) do not include the assessment of human energy input, man work is of relevant contribution in many production activities, such as forestry activities with low mechanization level. So for a proper comparison between yards with high and low mechanization levels, it will be appropriate to put the human energy input in the energy balance of all forestry yards, even if it represents a low percentage contribution to the total energy inputs. A basic requirement for any bioenergy generation system is that the energy produced (output) must be greater than the inputs of non-renewable energy required to establish and operate the system (Matthews 2001, Picchio et al. 2009).

2. Materials and methods – *Materijal i metode*

The study was carried out in Rome (41°54'32,55'' N, 12°21'32,34'' E). The study area was characterized by mild climate and volcanic substrata (sand 60%; silt 20%; clay 20%). It had an elevation of 35 m a.s.l. and its terrain was even and flat (average slope gradient 3%, maximum 10%).

The stand was a eucalypt coppice (*Eucalyptus camaldulensis* Dehnh.) (Table 1) harvested for the first time in 2000. The plantation was established in 1989; trees were planted according to 3 m square pattern (1111 trees ha^{-1}). By 2009, insect (*Phorachantha semipunctata)* attacks had reduced stump density to 592 stumps ha^{-1}.

Logging was conducted in summer 2009 on a total area of about 2 ha. All area was surveyed with a Trimble Juno ST GPS device. All operations were carried out by the same private Forest Company. The machines used were:

⇒ one harvester John Deere (ex Timberjack) 1270 C with a felling-processing head JD (ex TBJ) 762 C, for felling and bunching the trees;

Table 1 Site characteristics
Tablica 1. *Značajke radilišta*

Place – *Mjesto*	Rome (Italy)
Surface, ha – *Površina,* ha	1.72
Slope gradient, % – *Nagib terena,* %	3
Elevation, m a.s.l. – *Nadmorska visina,* m n. v.	35
Species – *Vrsta drveća*	*E. camaldulensis*
Age in years – *Dob u godinama*	10
Density, stumps/ha – *Gustoća, panjeva/ha*	592
Average DBH, cm – *Prosječni srednji promjer,* cm	12.9
Average height, m – *Prosječna visina,* m	14.3
Average mass, $t_{f.m.}$ – *Prosječna masa,* $t_{f.m.}$	0.329
Average number of shoot per stump *Prosječan broj izbojaka po panju*	3.6
Average mass harvested, $t_{f.m.}ha^{-1}$ *Prosječna masa sječe,* $t_{f.m.}ha^{-1}$	194.768
Wood characteristics, chips – *Značajke drva, ivera*	
Bulk density, kg m^{-3} – *Gustoća,* kg m^{-3}	320
Moisture content, % – *Udio vlage,* %	37.59

⇒ one forest loader OP T80, to assist the harvester in tree bunching;

⇒ one forwarder JD (ex TBJ) 1100 with chipper Erjo for chipping whole trees from bunches;

⇒ one truck DAF CF 85.430 with trailer VIBERTI 7 LOMASS 22 R for chips transport.

There were two forestry operators. The work system applied was the *Whole Tree System* (WTS). Whole trees were chipped at the stump site, and chips were discharged directly into the transportation vehicles, which could easily access the cutover.

The main dendrometric parameters (DBH and tree height) were measured in 2 circular plots randomly selected inside the stand (total surface 5652 m^2). A t test for independent samples was applied to each dendrometric parameter and showed no significant difference between the two plots (DBH n° 309, *p*-value 0.079; height n° 97, *p*-value 0.647). A tree caliper (Silvanus type 1208, accuracy 0.5 cm) was used for measuring the diameter at breast height (DBH) and a tape logger for determining tree height, after felling. After the harvesting, the height of the felled stump was measured in 2 rectangular plots randomly selected (total surface 1200 m^2). A t test showed significant differences between two plots (n° 134, *p*-value 0.0233).

Moisture content and wood density were determined on 30 wood discs (3 cm thick) collected randomly in each plot. The 60 wood discs were immediately weighed with a precision scale (Orma model BC16D) and then taken to the laboratory for determining moisture and wood density, according to the thermo-gravimetric method (UNI EN 13183-1 2003, UNI ISO 3130 1985, UNI ISO 3131 1985, Lo Monaco et al. 2011). Statistical analysis (Kruskal Wallis) showed no significant differences (wood density fresh weight: KW 0.259, *p*-value 0.611; wood density dry weight KW 0.188, *p*-value 0.665) between the two plots.

For the conversion of volume into fresh mass, we used the measured average density of 1.13 kg dm^{-3}. The top and branches were considered to be the 25% of the stump mass. This figure was determined by weighing the stem, the top and the branches of a sample of 60 shoots, randomly selected on 60 different stumps.

The experimental data (felling/bunching and chipping) were recorded for one hectare of plantation. To relate the felling time to tree mass, 110 stumps (396 shoots) were numbered, randomly selected.

Slope gradient was measured with a clinometer (Meridian MI 4007). Work time was recorded for every single phase, using a chronometric table Minerva equipped with three centesimal chronometers (Anon. 1988, Harstela 1991, Berti et al. 1989, Savelli et al. 2010). In order to calculate outputs in different plots, effective time and delays in the work routine up to 15 min (UT, unavoidable time and AT, avoidable time) (Anon. 1988, Harstela 1991, Picchio et al. 2009) were recorded.

Based on work times, volume and mass, the productivity per worker for the different operations was calculated as: average gross productivity (PHS_{15}), measured on the basis of time consumption, inclusive of all delays up to the maximum event duration of 15 minutes; average net productivity (PHS_0), computed with the exclusion of delays.

The cycle times of the machines were divided into time elements (process steps) that were considered typical of the work.

Harvester time consisted of: *positioning*, beginning when the machine approached the stump and ending when the machine head rested on a tree; *felling*, beginning when the felling cut started and ending when the tree touched the ground; *bunching*, beginning when the tree touched the ground and ending when the tree was dropped onto a bunch. Loader time consisted of bunching the tree that the harvester was not able to pile; beginning when the tree was taken from the loader and ending when the tree was put on the pile.

Chipping time consisted of: *positioning, i.e.* the time necessary for the truck to approach the chipper and park by its side; *chipping, i.e.* the time during which the chipper produced the chips; *moving* the time necessary for the truck and the chipper to approach a bunch of trees. For all operations, *delay* was also recorded, i.e. the time during which the machine was not engaged in any productive work process (e.g. repair and/or maintenance, rest, etc.).

The influence of tree weight on the felling time was estimated by linear regression, calculated with a regression analysis.

Total labor cost (including taxes and all social costs) was 23 € h^{-1} for the harvester operator and the chipper operator, whereas the loader operator cost was 15 € h^{-1}. Stumpage was 15 € t^{-1}. Fuel cost was assumed at July, 2009. Machine rates (Table 2) were estimated using the coefficients and the mathematical formulas already applied by many authors (Miyata 1980, Picchio et al. 2011a, Spinelli et al. 2011). Further details on cost calculation are reported in Table 2.

The energy balance was estimated with the GER method (IFIAS 1975, Picchio et al. 2009). It was used to estimate the direct and indirect input requirements for the machinery used as showed by Picchio et al. 2009. Furthermore, by an indirect method to assess the energy expenditure in forestry operations

Table 2 Principal calculation elements and machine costs
Tablica 2. *Glavne sastavnice izračuna i troškovi strojeva*

Description *Stavka*	Unit of measure *Mjerna jedinica*	**JD 1270 c Advance**	**Chipper Eryo on Forwarder (JD 1100)**	**Loader OP T80**
Purchase price – *Nabavna cijena*	€	380,000	520,000	127,000
Salvage value* – *Preostala vrijednost**	€	84,094	115,076	20,786
Service life – *Vrijeme trajanja*	y	10	10	12
Annual usage – *Godišnja uporaba*	H	1,200	800	600
Power – *Snaga*	kW	173	440(+118)	132
Interest rate – *Kamatna stopa*	%	5	5	5
Fuel consumption – *Potrošnja goriva*	$l\ h^{-1}$	15	35	13
Lubricant consumption – *Potrošnja maziva*	$l\ h^{-1}$	0.6	1.4	0.52
Garage space – *Garažni prostor*	m^2	35	45	23
Labor cost – *Trošak radnika*	€ h^{-1}	23	23	15
Fuel cost – *Trošak goriva*	€ l^{-1}	1.04	1.04	1.04
Lubricant cost – *Trošak maziva*	€ l^{-1}	9	9	9
Fixed Costs – *Fiksni troškovi*	€ h^{-1}	41.56	88.12	24.20
Variable Costs – *Varijabilni troškovi*	€ h^{-1}	66.31	114.93	47.57
Total machine Costs (included labour cost) *Ukupni troškovi stroja s troškom radnika*	€ h^{-1}	107.87	203.05	71.77

(*) The salvage value was calculated by multiplying the purchase price for 0.86^N, where N = service life of the machine
(*) Vrijednost na kraju vremena korištenja izračunata je uvećavanjem nabavne cijene za $0,86^N$, gdje je N = vrijeme korištenja stroja

in situ (Scott and Christie 2004, Christie 2008) human energy consumption was estimated, on the basis of a human heart-rate response during field work. The two workers were assessed for five work day. Minute-to-minute heart rate was recorded using a Polar heart rate monitor during the test in order to calculate the predicted energy expenditure from working heart rate responses on the basis of individual regression equations. This technique has been validated by several authors (Haskell et al. 1992, Scott and Christie 2004, Strath et al. 2001).

To calculate the energy output, the Higher Heating Value (HHV) was determined on 30 chip samples, collected randomly from 10 truck loads (Volpi 1992). Calorimetric tests were conducted with an adiabathic calorimeter (Parr, model 6200) (Canagaratna and Witt 1988). A Kruskal Wallis test suggested limited variability (KW 0.679, *p*-value 0.712). The average HHV of *E. camaldulensis* wood was 20.14 MJ $kg_{d.w.}^{-1}$.

3. Results and discussion – *Rezultati i rasprava*

Harvester delays represented 18.1% of the total work time, and in line with the values reported by Spinelli and Visser (2008) for short-rotation plantations (Fig. 1). Harvester delays were mostly due to the need for sharpening the cutting chain; this is explicable considering the type of wood harvested. Chipping delays had a very small incidence (9%), much lower than reported in previous bibliography (Spinelli and Visser 2009) (Fig. 2). Moving and po-

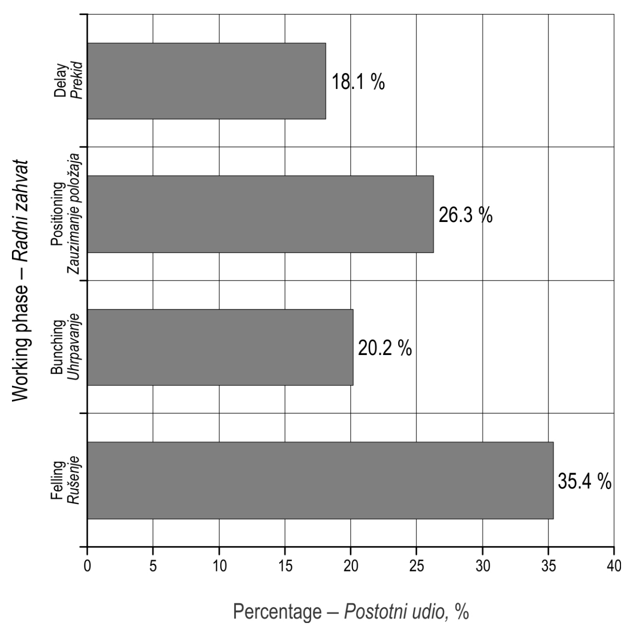

Fig. 1 Harvesting and bunching time analysis, percent incidence of time elements

Slika 1. *Analiza utrošaka vremena sječe i uhrpavanja, postotni udjeli trajanja sastavnica rada*

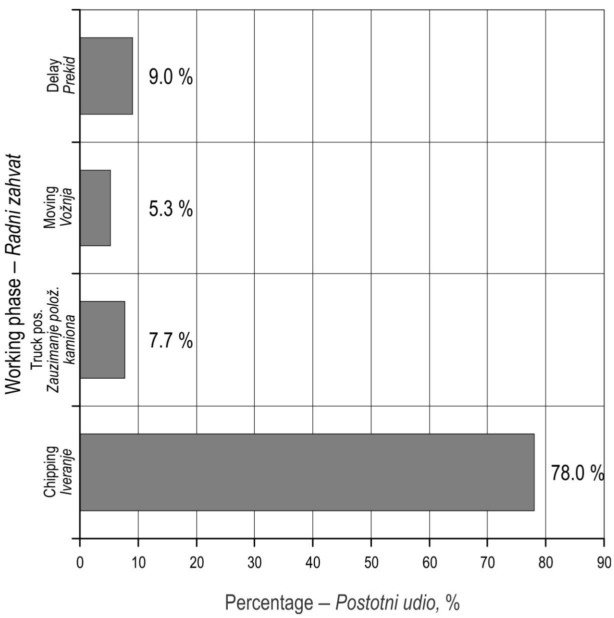

Fig. 2 Chipping time analysis, percent incidence of time elements

Slika 2. *Analiza utrošaka vremena iveranja, postotni udjeli trajanja radnih sastavnica*

sitioning also had a very low incidence, due to the good trafficability of the test area (Fig. 1 and 2).

Productivity (PSH_{15} and PSH_0) of each working phase was good (Table 3). As compared to literature data of felling and bunching operations, it had a higher productivity than a harvester used for felling and processing (Spinelli et al. 2002a), but it had a lower productivity and a higher cost than a proper feller-buncher (Spinelli et al. 2002b). The average gross time only for felling and bunching (average stump fresh mass 0.33 tons) was 1.25 minutes, corresponding to a PSH_{15} per worker of 15.8 fresh t h^{-1}.

Table 3 Productivity of felling-bunching (the work of loader included) and chipping

Tablica 3. *Proizvodnost sječe i uhrpavanja (uključen rad utovarivača) te iveranja*

Operation	PSH_{15} t h^{-1}worker^{-1}	PSH_0 t h^{-1}worker^{-1}	PSH_{15} m^3 h^{-1}worker^{-1}	PSH_0 m^3 h^{-1}worker^{-1}
Felling and bunching *Sječa i uhrpavanje*	15.8	19.3	13.9	17.1
Chipping *Iveranje*	44.7	49.1	39.6	43.5
Total of the yard *Ukupno na radilištu*	11.7	13.9	10.3	12.3

For the regression analysis between dependent variable »gross time (T [min]) for felling and bunching« and independent variable »stump fresh mass (x [t])« 110 stumps were sampled randomly among all the data observed. The regression was expressed by the equation: $T = 0.774 + 1.458\ x$; $R^2 = 0.678$ (Fig. 3). According the regression analysis (Table 4) the model is significant at $p<0.001$.

The elaboration of experimental data collected for chipping, related to the load of 10 trailer trucks, shows a very good productivity: PSH15 of 44.7 t h^{-1} and a very low level of delay (9.0%), as compared to literature data (Spinelli and Visser 2009, Spinelli and Hartsough 2001). This is mainly due to the good shape of trees and to a good yard organization, but also to the fact that Spinelli and Visser (2009) and Spinelli and Hartsough (2001) included all delay events, including those with the duration longer than 15 minutes.

The average calculated height of felled stumps was 11.4 ± 3 cm ($p<0.05$), a value that indicates the need of lowering the stumps by chainsaw after mechanical harvesting. This is very important for the coppice wood or plantation physiology.

Fig. 4 shows the results of financial calculations. The total production cost was 44.30 € t^{-1}, broken down as follows: 14.42 € t^{-1} for felling, bunching and chipping; 12.83 € t^{-1} for chip transportation (performed with truck and trailer units, over a distance of about 150 km); 2.05 € t^{-1} for the relocation and

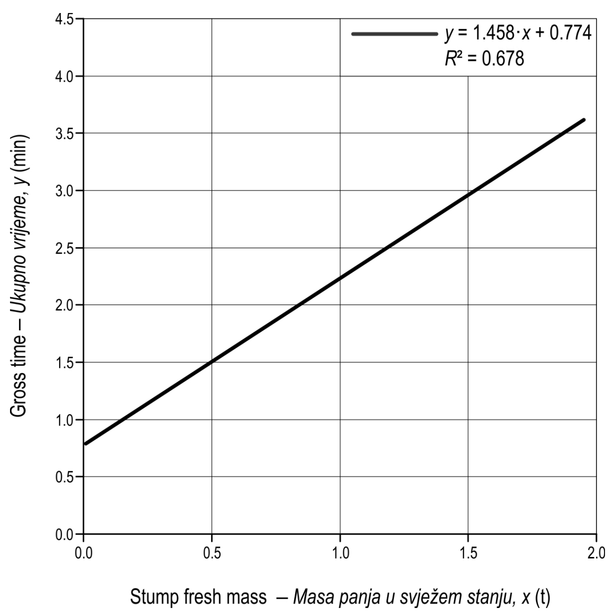

Fig. 3 Variation of gross time only for felling and bunching as a function of the stump fresh mass (from the regression analysis in Tab. 4)

Slika 3. *Odstupanja ukupnih vremena rada pri sječi i uhrpavanju kao funkcija mase panja u svježem stanju (iz regresijske analize u tablici 4)*

Table 4 Regression analysis of felling and bunching time predicted for stump fresh mass
Tablica 4. *Regresijska analiza utrošaka vremena sječe i uhrpavanja predviđanih na osnovi mase svježega panja*

Dependent variable ***Zavisna varijabla***	R^2	**Count** ***Zbroj***	***F*-Value** ***F-vrijednost***	***p*-Value** ***p-vrijednost***
min cycle^{-1}	0.678	108	227.76	<0.0001
Independent variables ***Nezavisne varijable***				
Variable ***Varijabla***	**Unit** ***Jedinica***	**Parameter** ***Parametar***	**Std. Error** ***Stand. pogreška***	***p*-Value** ***p-vrijednost***
Stump fresh mass *Masa svježega panja*	t	1.458	0.0966	<0.0001
Intercept *Ordinata*		0.774	0.0584	<0.0001

transfer of machines; 15 € t^{-1} for the stumpage (compensation to the forest owner). In this case, the relocation unitary cost was calculated dividing the total cost sustained (2,000 €) for the total surface worked by the yard (5 ha), and the result obtained was divided for the tons of fresh biomass harvested per hectare (195 t). The resulting profit for the enterprise is 5.70 € t^{-1}.

The human energy consumption was estimated on the basis of a human heart-rate response during field work. The heart rate was recorded on five work days and the ANOVA test showed no significant differences between the two workers (p<0.05) and between the different operations (p<0.01), and the average value was 87.2 bt min^{-1} ± 1.3. The calculated energy expenditure of working was 0.026 MJ min^{-1} per worker. This value is significantly lower than that reported in other studies (Christie 2008, Picchio et al. 2009, Scott and Christie 2004), but it is clearly explained by the high mechanization used in this yard.

Concerning energy inputs, a comparison was conducted between the results of this study and those of similar studies, where the same mechanization level was applied, and in this case it showed similar results (cf. Yoshioka et al. 2005). However, the comparison conducted between the results of this study and others in similar studies, where intermediate mechanization level was applied (Baldini et al. 2007), showed different results. The input for mechanized harvesting was 0.8 GJ $t_{d.w.}^{-1}$ (Table 5) vs. 1.5 GJ $t_{d.w.}^{-1}$ for

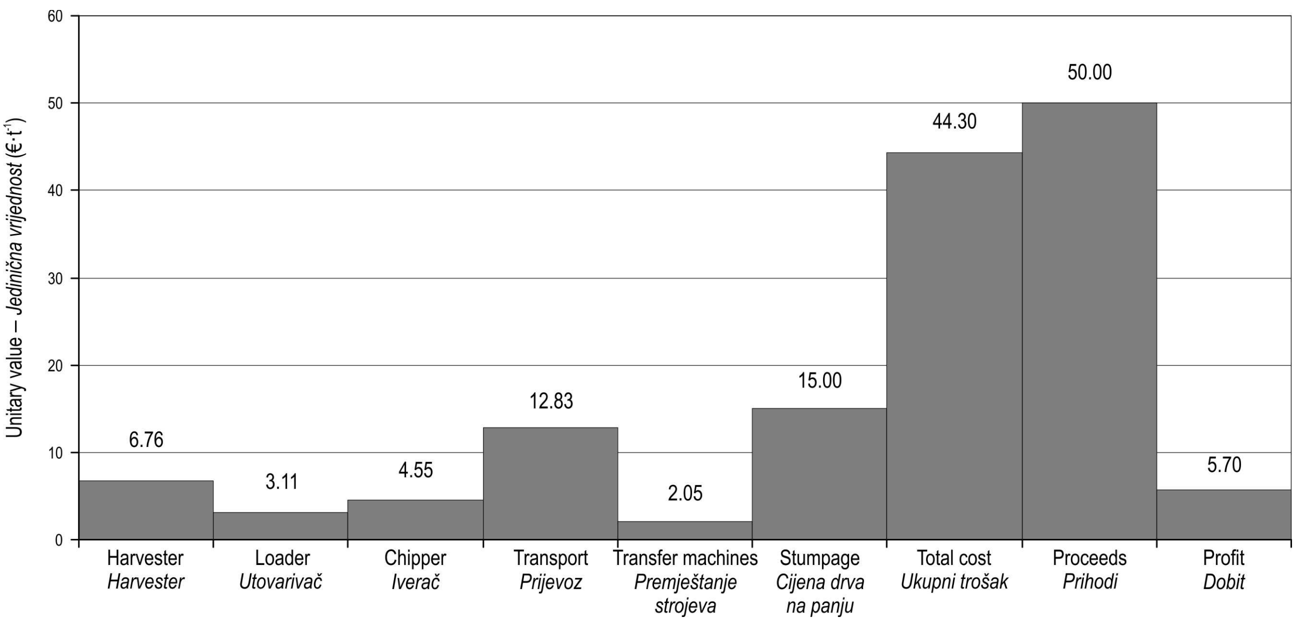

Fig. 4 Financial budget of the mechanized forest yard
Slika 4. *Financijski proračun mehanizacije radilišta*

Table 5 Total energy value of outputs and inputs (GJ ha^{-1}) for all work steps, transport included

Tablica 5. *Ukupna vrijednost izlazne i ulazne energije (GJ ha^{-1}) za sve sastavnice rada s uključenim transportom*

Output *Izlaz*	Machines & Tool Input *Ulaz strojeva i alata*		Human Input *Ulaz radnika*	Total Input *Ukupni ulaz*
	Direct *Neposredni*	Indirect *Posredni*		
2,565.8	95.2	12.7	0.2	108.1

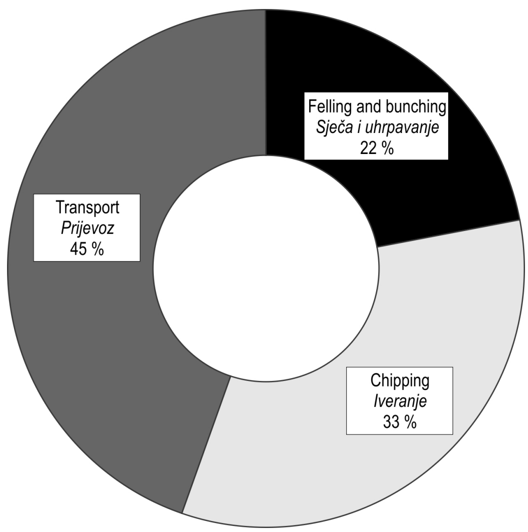

Fig. 5 Percent incidence of work steps on total energy use
Slika 5. *Postotni udjeli radnih zahvata u ukupnoj energetskoj potrošnji*

intermediate mechanization. This obviously affects the energy balance (output/input ratio), which is 23.8 for mechanized harvesting and 12.9 for intermediate mechanization. The calculated detail data of energy indirect input requirements for machinery were: harvester 2.37 GJ ha^{-1} (19%); loader 1.28 GJ ha^{-1} (10%); forwarder with chipper 2.11 GJ ha^{-1} (17%); truck with trail 6.94 GJ ha^{-1} (54%).

Fig. 5 shows the incidence of single work phases on total energy input. Truck transport had the highest incidence (45% or 379 MJ $t_{d.w.}^{-1}$), as also found in other studies (Baldini et al. 2007, Picchio et al. 2009), than chipping (33% or 283 MJ $t_{d.w.}^{-1}$) and finally felling and bunching (22% or 185 MJ $t_{d.w.}^{-1}$).

Also due to the large amount of biomass harvested, the average output/input ratio was twice as high as the literature data (8.6–11.7, Baldini et al. 2007) available for the harvesting of eucalypt plantations, with intermediate mechanization. Higher values (36–48, Picchio et al. 2009) were also reported, but they were obtained in other forest types (*Quercus cerris* L. coppice).

The percentage energy efficiency (i.e 100*(output – input)/output) was high and on average 95.8% ± 0.3. This value was similar to those reported in other studies (about 91% Baldini et al. 2007, about 97% Picchio et al. 2009).

4. Conclusions – *Zaključci*

Mechanized harvesting allowed a substantial increase of the operational productivity recorded for any single work step: felling/bunching, extraction and chipping. Comparison with other two felling studies (Baldini et al. 2007, Martins et al. 2009) reflecting different mechanization levels with escalating investment requirements, confirmed the excellent performance of the harvester John Deere 1270, with a JD 762 C harvester head. However, it had a lower productivity and a higher cost than a proper feller-buncher (Spinelli et al. 2002b) but the harvester was a machine more multipurpose and versatile, and therefore preferred by Italian forestry companies that work in different agroforestry systems.

Mechanization resulted in a dramatic reduction of felling costs: moreover, it strongly enhanced operator comfort and safety (Bell 2002).

In this kind of plantations, mechanization is most appropriate, as demonstrated by high productivity recorded in our study (PSH_{15} 6.5 $t_{d.w.}$ h^{-1}worker^{-1}) and by the very favorable energy balance (output/input 23.8 and 95.8% system efficiency). These performances far exceed those reported for intermediate mechanization, still very popular in Italy. However, harvesting cost is still high (44.30 € $t_{f.w.}^{-1}$, Fig. 4) and could be reduced only through careful work planning. The cost of harvesting (6.76 € t^{-1}) would certainly have been lower if it was a proper feller-buncher; the machine has a lower hourly rate and can ensure higher productivity. The unusual use of harvester was

Table 6 Energy efficiency, labor use and operational productivity (PSH_{15} e PSH_0)

Tablica 6. *Energetska učinkovitost, korisnost rada i operativna proizvodnost (PSH_{15} e PSH_0)*

Output/Input *Izlaz/ulaz*	System efficiency *Učinkovitost sustava*	Man work time *Vrijeme rada radnika*	PSH_{15}	PSH_{15}	PSH_0	PSH_0
	%	min $t_{d.w.}^{-1}$	$t_{d.w.}$ h^{-1} worker^{-1}	m^3 h^{-1} worker^{-1}	$t_{d.w.}$ h^{-1} worker^{-1}	m^3 h^{-1} worker^{-1}
23.8	95.8	23.12	6.5	10.3	7.6	12.3

determined by the fact that the dedicated CTL machine was nearby for the poplar plantation logging.

Furthermore, Italian forestry is still confronted with a lack of trained forest workers, which may slow down the transition towards mechanized harvesting.

As confirmed by many previous studies (e.g. Baldini et al. 2007, Picchio et al. 2009), this study also shows the urgent need to minimize the costs and energy inputs related to transportation, which can be obtained by developing local markets for energy biomass, thus reducing transportation distance. The cost of chipping was particularly low, due to the power of the machine used and the efficient work system adopted. Field chipping excludes the extraction operation, which often results in long waiting delays for the chipper.

The damages to soil and topsoil have not been discussed in this study. The surveys and studies about this yard are still running and they will be the subject of a forthcoming work. In fact, as mentioned by other authors (Picchio et al. 2011), the research on damage caused by forest operations to the remaining trees and/or to the regeneration in forest stands started at the beginning of the twentieth century and its importance has been rising with the increasing use of mechanized wood harvesting.

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Sažetak

Visoko mehanizirano pridobivanje šumske biomase iz eukaliptusovih panjača

*Glavni su ciljevi ove studije bili utvrđivanje proizvodnosti, isplativosti i energetske bilance (izlaz/ulaz) strojne sječe primijenjene na eukaliptusovim plantažama u središnjoj Italiji. Da bi se procijenila energetska bilanca, određeni su: posredni ulazi, tj. energija korištena za proizvodnju; neposredni ulazi, tj. potrošnja goriva, maziva i potrošnja energije radnika tijekom posla; izlaz, tj. energetska vrijednost ukupno proizvedenoga drva. Površine pod eukaliptusovim plantažama danas po procjenama zauzimaju oko 72 000 hektara (54 000 ha čiste, a 18 000 ha mješovite sastojine). Istraživano je u okolici Rima, na nadmorskoj visini od 35 m, u ravničnom predjelu (prosječan je nagib terena 3 %). Sastojina je bila panjača eukaliptusa (*Eukaliptus camaldulensis *Dehnh.) posječena prvi put 2000. godine. Prostorni je raspored panjeva bio kvadratičan s 3 m između panjeva (1111 panjeva po hektaru). Od 2009. napadi kukaca (*Phorachantha semipunctata*) smanjili su gustoću panjeva na 592 panja po hektaru.*

Značajke gospodarenja eukaliptusovim plantažama u Italiji su:

⇒ *povratak autohtonoj šumskoj vegetaciji na područjima pod nisko proizvodnim plantažama, posebno u južnoj Italiji*

⇒ *poboljšanje sastojina industrijskih plantaža radi povećanja kakvoće i količine proizvodnje (sastojine srednjih i kratkih ophodnji namijenjenih proizvodnji drvnoga iverja); navedeno se namjerava postići selekcijom klonova*

⇒ *racionalizirana uporaba proizvoda u tzv. poljskom šumarstvu (eng. agroforestry), gdje plantaže mogu proizvoditi i tehničke drvne sortimente, ogrjevno drvo i drvni iver.*

Primijenjena je stablovna metoda izradbe i krajnji je proizvod bio drvni iver za energiju. Nasadi za proizvodnju energije dobar su izbor pri osiguravanju sirovine za bioenergane. Isplativost energetskih nasada uvelike je ovisna o odgovarajućoj logistici, planiranju proizvodnje i prinosa. Troškovi strojnoga rada bili su izračunati pomoću koeficijenata i matematičkih formula preuzetih iz vodećih metodologija koje su predložili razni autori. Ti su podaci bili upotrijebljeni za određivanje ekonomske i energetske održivosti strojne sječe. Prošlih godina mehanizacija se brzo uvodila u šumske operacije. Pravilna je izobrazba radnika i planskoga osoblja nužna, posebno kada se uvodi strojna sječa za održivo korištenje šumske biomase kao obnovljivoga izvora energije uz smanjivanje emisije stakleničkih plinova. Energetska je bilanca bila procijenjena metodom GER (eng. Gross Energy Requirements). Metoda GER također je primijenjena za procjenu neposrednih i posrednih inputa za uoptrijebljene strojeve. Nadalje, kod posredne metode procjene utrošaka energije u šumarskim operacijama u sastojini bila je procijenjena potrošnja energije radnika *prema otkucajima srca tijekom rada. Dva su radnika bila praćena svakoga radnoga dana. Pri dolasku na posao odabrani su radnici bili opremljeni s Polarovim mjeračem otkucaja srca. Za izračun izlazne energije veća ogrjevna vrijednost (HHV) bila je određena na 30 uzoraka drvnoga iverja, koje se skupljalo nasumično s 10 kamionskih tovara. Kalorimetrični su testovi bili izvedeni s adijabatskim kalorimetrom (Parr, model 6200). Prosječna viša ogrjevna vrijednost eukaliptusa bila je 20,14 MJ* $kg_{d.w.}^{-1}$. *Tijekom radnoga vremena prekidi rada harvestera bili su 18,1 % ukupnoga radnoga vremena, prekidi rada pri iveranju zauzimali su manje vrijednosti (9 %), kao i premještanje i zauzimanje položaja zbog dobre kretnosti na istraživanom području. U tim je plantažama strojna sječa omogućila bitno povećanje operativne proizvodnosti zabilježene za svaku sastavnicu radnoga procesa: rušenje/uhrpavanje, izvoženje i iveranje, što je pokazano visokom zabilježenom proizvodnošću (*PSH_{15} *= 6,5 td.w.*h^{-1}*radnik*$^{-1}$*) i povoljnom energetskom bilancom (izlaz/ulaz = 23,8; 95,8 % učinkovitosti sustava). Takva djelotvornost premašuje onu zabilježenu kod sustava niže razine mehaniziranosti koji su i dalje vrlo popularni u Italiji. Cijena sječe (6,76 €* t^{-1}*) svakako bi bila niža u slučaju da je korišten feler bančer (eng. feller buncher) koji ima niže troškove po satu rada i koji može osigurati višu proizvodnost. Neobična uporaba harvestera u tom slučaju bila je određena činjenicom da je stroj bio u blizini i da je radio na pridobivanju drva iz topolovih plantaža. U svakom je slučaju cijena sječe visoka (44,30 € TF.w.*$^{-1}$*) i može se smanjiti samo pažljivim operativnim planiranjem. Prosječna je visina panjeva bila 11,4 ± 3 cm* ($p<0,05$)*, odnosno to je vrijednost koja upućuje na potrebu dodatnoga skraćivanja panjeva uporabom motorne pile lančanice nakon strojne sječe. To je vrlo važno za fiziologiju panjača ili plantaža. Trošak je iveranja bio iznimno nizak zbog velike snage korištenoga stroja i učinkovitoga sustava rada. Iveranje u sastojini isključuje privlačenje drva, što često rezultira dužim zastojima pri radu iverača. Štete na tlu i na površinskom sloju tla nisu detaljno analizirane u ovom radu. Istraživanje i proučavanje toga radilišta i dalje je u tijeku te će biti predmet budućih analiza.*

Ključne riječi: harvester, proizvodnost rada, operativni troškovi, energetska bilanca, iverač, forvarder, šumske plantaže

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