Options for the Mechanized Processing of Hardwood Trees in Mediterranean Forests

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ABSTRACT

In this study, three different processing options for trees yarded whole at the roadside in a beech thinning operation, typical of the Italian Apennine mountain, were studied. Trees were delimbed, crosscut, and stacked, respectively, by a four-man crew equipped with chainsaws and a hydraulic loader (motor-manual control thesis), by a small stroke harvester head mounted on a light excavator, and by a dedicated 6-wheel harvester. Under the conditions of the study, mechanized processing was less expensive than the motor-manual control thesis, regardless of the specific option. Cost reductions amounted to 27 percent and 38 percent, respectively, for the light processor and the heavy harvester. Annual usage is a crucial factor for the introduction of industrial mechanization: the heavy harvester is preferable to motor-manual processing only when the annual output exceeds 5,000 metric tonnes (t) per year. When this figure grows above 13,000 tonnes per year, it will profitably replace the light processor, not just for monetary gain, but for the inability of the lighter unit to cope with such a heavy workload. On the other hand, the light processor was always less expensive than the motor-manual control, while requiring an additional investment of only (US)$47,000. Therefore, the acquisition of a light processor represents the most viable option, at least for immediate deployment. Its productivity closely matches that of the yarder, allowing for hot-deck (synchronic) operation. All of the options can efficiently process beech trees within the full range of diameters normally obtained from thinning operations, and up to a 30 cm diameter at breast height. As expected, productivity increases with tree size, and even more so for the mechanical units, which normally handle just one or a few trees at a time. Under the conditions of this study, both mechanized options have a potential for bringing processing cost near (US)$10 per tonne, which is half the cost of traditional motor-manual processing.

Keywords: *harvester, processor, logging, firewood, hardwoods*

Introduction

Increased global competition is imposing a growing strain on all commercial activities, including wood harvesting. Forest operations must increase their productivity, while decreasing production costs (Hoesch 2003). In the last decade, this has resulted in a massive effort toward forest mechanization. Harvesters, processors, and forwarders have become widespread in all industrialized countries, far beyond the borders of the Nordic countries where they were first developed and thoroughly studied (Brunberg 1997, Nurminen et al. 2006). Even where motor-manual harvesting techniques are still competitive due to inexpensive labor, there is a general objective to introduce mechanical harvesters in order to streamline production in anticipation of future labor shortages (Spinelli et al. 2001). Today, the use of these machines is no longer limited to gentle terrain (e.g., slope gradient < 25%) and conifer forests, as demonstrated by their massive deployment in the Austrian (Stampfer 1999) and Swiss (Frutig et al. 2007) mountain forests, or in the French (Martin et al. 1996, Cuchet and Morel 2001) and German (Schorr 2000) hardwood stands. Harvesters and forwarders are also very popular in Mediterranean countries, such as Spain, Portugal (Spinelli et al. 2004), and Italy (Cielo and Zanuttini 2004), where they perform much of the harvesting in the industrial pine, eucalypt, and poplar plantations. But, this situation changes abruptly when moving upland to natural hardwood stands, and especially to the oak and beech formations that represent much of the forest cover of the Mediterranean countries (Ciancio and Nocentini 2004).

In these areas the introduction of mechanized harvesting is progressing slower than expected. This might be related to a number of factors, including: the socio-economic conditions of the Mediterranean mountain, characterized by small enterprises with low investment capacity; the limited density of the forest road network; and the strong concern of local foresters for environmental impacts (Gallis 2004). The result is a worrying stagnation of forest activities and a decline of the logging business, as many operations are on the edge of economic survival, and often fill the gaps by resorting to underpaid irregular labor. Such solution is becoming increasingly widespread, but its ethics are debatable and while it could satisfy the requirements of environmental sustainability, it blatantly contradicts all demands for social sustainability. Modernization is badly needed, and operators are increasingly looking for directions concerning the type of units that are best suited to their work environment and the conditions required for a successful deployment.

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International Journal of Forest Engineering 20(1): 39-44.

In central and southern Italy, several operators have become equipped with modern tower yarders, specializing in steep terrain logging. They target mountain forests, where competition is weaker. Poor accessibility discourages potential bidders and yarder operators can outbid traditional animal loggers, where they still exist. Generally, trees are yarded whole to the landing, where they are handled with a hydraulic loader and processed motor-manually. This operational mode is just one step away from a typical yarder-processor operation, but most loggers hesitate, not knowing if current technology can profitably handle their trees. Furthermore, they are torn between different options and ignore which can best suit their own operating conditions.

The purpose of this study was to evaluate the performance of different processing solutions when dealing with the trees coming from a typical operation in the Mediterranean mountain. In turn, this would allow determining which options are technically and economically viable, and how they compare under varying work conditions. This is especially important, as no scientific studies are presently available on the processing of mountain hardwoods at yarder landings, where the introduction of effective mechanized processing methods may impact a large number of operations and a vast area across Europe.

Table 1. ~ *Description of the test site.*

General	
Place	Monte Cavallo
Municipality	Granaglione
Province	Bologna
Surface (ha)	2.90
Elevation (m a.s.l.)	1290
Species	*Fagus sylvatica*
Average age (yr)	45
Treatment	Thinning
Type	Selection
Criterion	From below
Intensity (% number)	38
Removal	
Number (trees/ha)	770
DBH (m)	0.137
Height (m)	15.1
Firewood (t/ha)	148.1
Chips (t/ha)	15.2
Chips (% total)	9.3
Wood and site characteristics	
Wood density (kg/m^3)	963
Moisture content (%)	39.8
Slope gradient (%)	65
Terrain class[a] (code)	2.2.5

[a] According to the UK Forestry Commission, 1995.

Materials and Methods

The study was conducted on a beech forest on the Apennine mountain range, south of Bologna in central Italy. The stand was a young high-forest derived from the conversion of an abandoned beech (*Fagus sylvatica* L.) coppice, conducted 15 years earlier. Coppice represents about 50 percent of the Italian forest surface, and beech is the most common species in the mountains from the altitude of approximately 1000 m. Due to poor accessibility, mountain coppice is often abandoned, which justifies the general policy toward its conversion to high forest (Cantiani and Spinelli 1996). This is generally obtained through repeated thinning, aimed at fostering the best specimen while keeping a dense enough cover to prevent stool resprouting.

The plot selected for the study is described in **Table 1** and represents a typical case. The stand was receiving a second thinning aimed at removing over one-third of the original trees. In the motor-manual control thesis, trees were felled and yarded uphill to a forest road, 3.5 m wide, where the yarder was stationed. A four-man crew was deployed with the following tasks: two men were at the harvesting site, felling and hooking the trees; one men was at the yarder, operating the winch and unhooking turns; one man was on a 16-t excavator, picking the trees from the chute and stacking them under the road cut, parallel to the road. Every few hours, yarding was interrupted and the entire crew gathered on the road for processing: the excavator would then break the piles and spread five to seven trees at a time on the road, so that the other three operators could motor-manually delimb, measure, and crosscut them into 2-m-long firewood logs. The excavator would then pick up the logs and stack them by the roadside, ready for collection by the transport units. The work progressed smoothly, as the excavator would alternatively spread trees and stack logs, thus reducing the eventual waiting time. This operational mode is the most common among local operators.

For the purpose of the study, two further options were introduced – a light excavator-mounted processor and a heavy dedicated harvester. The former consisted of an Arbro S 400 stroke harvester head mounted on a 5-tonne JCB 8052 tracked excavator, while the latter was a John Deere 1470 D 6-wheeled harvester equipped with a massive 290 H head. These two machines were rented from the owner or borrowed from the manufacturer only for the purpose and the duration of study, and represented two extremes in the range of options for mechanized processing. Both worked from stacks, as did the motor-manual control option. All of the operators included in the study – mechanized and manual – were experienced professionals, who knew their job and equipment. In order to minimize the effects of different operator adaptation and motivation levels, the study only included operators who were judged to have a high degree of uniformity in motivation and adaptation to the studied machines/systems (Harstela 1988). Both machine operators, as well as the leader of the motor-manual processing crew, were the owners of the respective contracting firms and were paid at a piece rate to keep motivation high. All of the operators had at least 10 years of experience with the type of machine they were using, of which about 2 years with the specific unit object of the study – except for the chainsaws, that were not older than 1 year. They were all in the 35 to 45 years age class – hence comparatively young, yet intellectually mature. On the other hand, no attempt was made to normalize individual performances by means of productivity ratings (e.g., Scott 1973), recognizing that all kinds of normalization or corrections can introduce new sources of errors and uncontrolled variation in the data material (Gullberg 1995).

The use of multiple units for the same treatment was out of the question, not only for its high cost, but also because the processor and the harvester selected for the study were the only two specimens of the respective make and model present in Italy at the time of the study. Since the three treatments present very large technical differences, the authors believe that any difference in the operators' adaptation level to their respective machines may only play a secondary role – given the selection of expert and motivated operators.

The authors then carried out a time-motion study, designed to evaluate machine productivity and to identify the variables that are most likely to affect it, especially tree size (Bergstrand 1991). Each processing cycle was timed individually, using Husky Hunter hand-held field computers running the dedicated Siwork3 time study software (Kofman 1995). Productive time was separated from delay time (Bjorheden et al. 1995), and the diameter of each tree processed in each cycle was recorded and associated with the observation datum. Each cycle contained 5-7, 1, and 1-3 trees, respectively, for the control, the light processor, and the heavy harvester – the latter being capable of multi-tree processing. Tree diameter was then converted into firewood weight, by using the dedicated tariff tables specifically produced for the study site by the University of Bologna, conducting a long-term investigation on the local forests (Magnani 2007). Tariff tables returned dry weight, promptly converted into commercial fresh weight (moisture content 35%) for convenience.

In order to check the statistical significance of the eventual differences, individual observations of each treatment were randomly grouped into data blocks, each containing the time (productive and delay) and the mass (tons) recorded during the processing of 5-7 trees. In turn, block data were converted into an average tree size (total mass divided by number of trees) and an average productivity value (tons/scheduled machine hour [SMH]), so as to obtain three sets of blocks representing the three treatments. Block data were analyzed using the Statview advanced statistics software. Analysis of variance (ANOVA) tests were conducted on the blocks in order to detect significant differences between treatments. A number of different techniques were used, namely Fischer's, Games-Howell's, and Scheffe's. Data reported in this paper were calculated with Scheffe's technique, which is considered more conservative than the others, and more resilient to eventual violations of the normality assumption (SAS 1999). At any rate, the data used for the study showed a normal distribution, which simplified the interpretation of results. In addition, data from individual cycle observations were analyzed per treatment with the regression technique, in order to calculate meaningful relationships between productive time consumption and tree characteristics such as size and form.

Machine costs were calculated with the method described by Miyata (1980), on an estimated annual utilization of 1,000 SMH: this value is half that typically reported for industrial operations (Brinker et al. 2002), and it has been chosen to represent the reality of the Mediterranean high country, dominated by small-scale non-industrial private forestry. Ownership fragmentation is known to dramatically reduce machine utilization, and in general the profitability of forestry (Kittredge et al. 1996). No studies are yet available on the annual utilization of harvesters and processor under the conditions of the Italian mountain, and 1,000 hours has been adopted as a conservative estimate. As a consequence, service life has been proportionally extended to 8 years for the harvester, the processor, and the excavator, and 2 years for the chainsaws. Labor cost was set to (US)$21[1] and $34 per SMH and worker, respectively, for the motor-manual and the mechanized treatments. These values are inclusive of indirect salary costs. The costs of fuel, insurance repair, and service were obtained directly from the operators. The calculated operational cost was increased by 20 percent in order to include relocation and administration costs, the former already capable of representing up to 10 percent of the total machine cost (Väätäinen et al. 2006). This is not a very accurate way of representing relocation and administration costs, but no data are yet available on their exact amount, especially for the conditions of the Mediterranean mountain. Further detail on cost calculation is shown in **Table 2**. The Miyata method was also used to test the effect of annual usage (SMH/yr) on the economic performance of each option: annual usage figures where then converted into annual output (tons/yr) by using the average productivity recorded in the study.

Results and Discussion

Table 3 shows the average productivity recorded for each treatment. The differences were all statistically significant at the 5 percent level (control vs. light, $p = 0.0241$; control vs. heavy, $p < 0.0001$; light vs. heavy, $p < 0.0001$). On the contrary, no significant difference was found for tree size, confirming the assumption of equal test conditions for all treatments, as all operations worked at the roadside from pre-assembled stacks containing trees in the same size range.

[1] Dollar values are U.S. dollars.

Table 2. ~ *Operational costs.*[a]

Treatment	Motor-manual	Light processor	Heavy harvester
Investment (US$)	71,000	113,900	509,200
Service life (yr)	2 to 8[b]	8	8
Usage (hr/yr)	1,000	1,000	1,000
Operator wage (US$/SMH)	21	34	34
Crew (number)	4	1	1
Fixed cost (US$/yr)	11,628	17,031	66,839
Variable cost (US$/SMH)	160.5	49.8	79.3
Total cost (US$/SMH)	142	80	176

[a] Exchange rate: October 15, 2008 – 1 Euro = 1.34 USD

Mechanized processing (per unit) proved less expensive than the motor-manual control, regardless of the specific option. The cost reduction was 27 percent and 38 percent, respectively, for the light processor and the heavy harvester, confirming that even in Mediterranean conditions a very high level of mechanization allows the highest cost reduction. Of course, the quality of mountain road networks is a constraint to the use of heavy machinery, but such constraints can be overcome as demonstrated by the tests, which took the largest John Deere harvester up to a mountain top across winding mountain roads. What is crucial is the possibility to supply such a machine with enough work to pay its high ownership costs. The excellent results shown in **Table 3** depend on an assumed annual output of almost 15,000 tons, which is a reasonable target only for the largest operations.

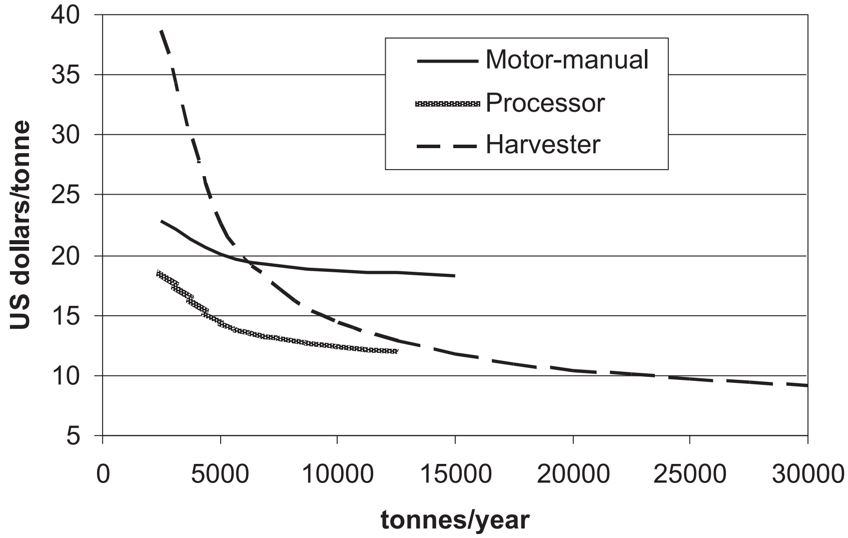

Figure 1. ~ *Processing cost as a function of annual output.*

In order to clarify this point, **Figure 1** shows the relationship between processing cost and annual output for the three processing options considered. Such a relationship is only valid for Mediterranean beech forests, as it was calculated by maintaining the average productivity figures reported in **Table 3** and by changing the annual usage up to a maximum of 2,000 SMH/yr, considered as the reasonable upper limit for operations in the Italian mountain, and the reference value for full-scale industrial operations (Brinker et al. 2002).

Table 3. ~ *Tree size, productivity, and cost: comparison between treatments.*

Treatment	Motor-manual	Light processor	Heavy harvester
Blocks (number)	65	37	70
Observation (hr)	12.1	6.8	5.8
Tree size (t/tree)	0.208	0.213	0.194
Productivity (t/SMH)	7.4	5.8	14.7
Hourly cost (US$/SMH)	142	80	176
Unit cost (US$/t)	19.2	13.8	12.0
Annual cost (t/yr)	7,370	5,760	14,700

[a] Calculated based on working 1,000 SMH/yr.

The figure shows that the light processor always results in lower processing cost than the motor-manual control, with cost savings ranging from 18 to 35 percent. The heavy harvester is preferable to motor-manual processing only when the annual output exceeds 5,000 tons/yr. With annual outputs above 13,000 tonnes per year, the light processor must be replaced by the heavy harvester, not just for a monetary gain, but for the inability of the lighter unit to cope with such a heavy workload. Indeed, at an average productivity of 5.8 t/SMH, the light processor cannot handle more than 12,500 tonnes in a 2,000 SMH year. On the contrary, the heavy harvester can process up to 30,000 tonnes a year, at a unit cost below $9/t[1], which makes it the ideal choice for industrial operations – especially large-scale contractors. Still, it must be seen how fast the typical small-scale mountain operation can evolve toward specialized industrial contracting: presently the light processor option seems the most viable, at least for immediate deployment. The heavy harvester option is definitely more ambitious, and it may take some time before gaining a role in the Mediterranean mountain.

The limited productivity of the light processor may turn into an asset, as it matches quite well with the recorded yarder output of 6.7 t/SMH – excluding set up and dismantle time. Therefore, the light processor could work along with the yarder, replacing the 16-tonne excavator normally detached to assist it. The light processor could pick up the trees at the yarder chute, processing them or stacking them in roadside surge piles, when the yarder pace is too fast for the processor. Stacked trees could then be processed during the waiting time relative to yarder dismantle and set up. Assuming a yarder cost of $127/SMH and an excavator cost of $62/SMH (Spinelli and Magagnotti 2008), the yarding and stacking cost is equal to $28/t, to which processing adds at least an additional $12/t (the least expensive option: heavy harvester working from stacks). On the other hand, hot-deck processing with the light processor means a yarding cost of $19/t ($127/SMH divided by 6.7 t/SMH) and an additional processing cost of $13/t (**Table 3**), which sums to $32/t, i.e., 18 percent less than the cold-deck option.

Finally, **Table 4** shows the equations that relate machine productivity to tree characteristics. It must be noted that the delay rates indicated in the tables are quite low, since they are the actual delay rates recorded in the study. These may not accurately represent the delay rates experienced over a longer period, and corrections might be made by applying appropriate delay factors (Spinelli and Visser 2008). The authors, however, preferred to stick to the original delay data, in order to avoid the introduction of artificial elements, in a study whose primary goal is to compare alternatives. Readers can then decide whether to use the equations in **Table 4** with the original delay factor, or with a different delay factor as suggested by their own experience or by

Table 4. ~ *Relationships between time consumption and tree characteristics.*

		R^2	F-value	Observation
Motor-manual control				
Productive time per tree	= 3.66 + 735.84 t/tree	0.670	128.05	65
Delays per tree	= 10% of Net time			
Light processor				
Productive time per tree	= 16.41 + 600.03 t/tree	0.632	300.96	177
Accessory time per cycle	= 37.6% of Net time			
Delays per cycle	= 15.8% of Net + Accessory time			
Heavy harvester				
Productive time per cycle	= 24.66 + 134.44 t/cycle + 30.89 t/cycle * form	0.621	281.61	347
Accessory time per cycle	= 14.1% of Net time			
Delays per cycle	= 20.9% of Net + Accessory time			
Tonnes per cycle	= 0.08 + 0.80 t/tree	0.525	382.96	349

[a] All times in 1/100 of minute; form is a tree form index with the following values: 1= almost no branches; 2 = average; and 3 = forked or malformed.

recent literature. Regardless, the equations in **Table 4** have high statistical significance and a good coefficient of determination. They show that all of the systems can efficiently process beech trees within the full range of diameters normally obtained from thinning operations, and up to a 30 cm diameter at breast height (DBH) (**Fig. 2**). As expected, productivity increases with tree size, and even more so for the mechanical units, which normally handle just one or few trees at a time. The motor-manual method is less sensitive to tree diameter, because it is applied in such a way as to allow for multiple tree processing. But, both mechanized options have a potential for bringing processing cost near the $10/t limit, whereas the motor-manual control cannot push such cost much below the $20/t threshold.

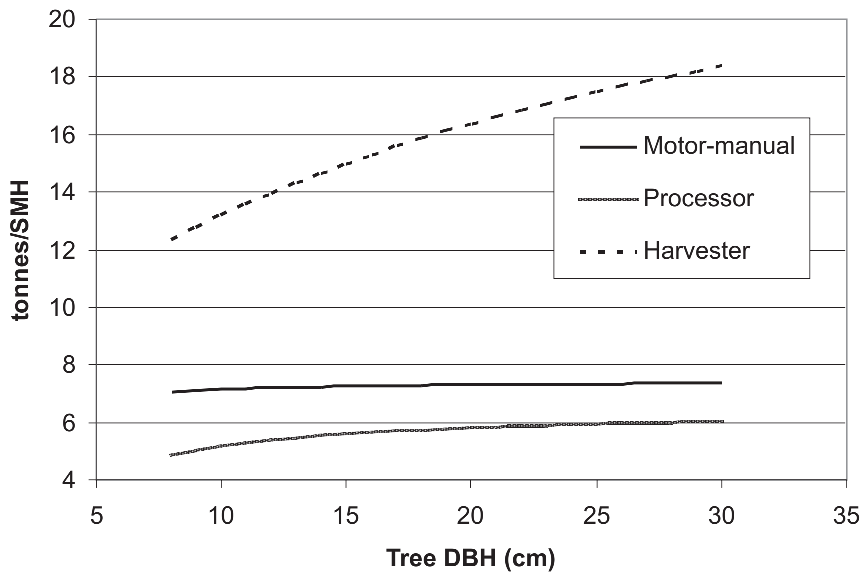

Figure 2. ~ *Processing productivity as a function of tree size.*

Despite the constraints imposed by rugged terrain, fragmented ownership, and close-to-nature forestry, mechanized processing may have a significant potential in the Mediterranean high country. Even when used with comparatively low intensity, it may determine a significant reduction of the harvesting cost, while opening the way to further optimization measures. The financial benefits of mechanized work may cause a progressive replacement of manual work to the advantage of improved job safety and comfort.

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