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Use, Utilization, Productivity and Fuel Consumption of Purpose-Built and Excavator-Based Harvesters and Processors in Italy

Natascia Magagnotti [1], Luigi Pari [2] and Raffaele Spinelli [1,3,*]

[1] CNR Ivalsa, Via Madonna del Piano 10, I-50019 Sesto Fiorentino (FI), Italy; magagnotti@ivalsa.cnr.it
[2] CRA-ING Via della Pascolare 16, I-00015 Monterotondo Scalo (Roma), Italy; luigi.pari@crea.giv.it
[3] AFORA, University of the Sunshine Coast, Locked Bag 4, Maroochydore, QLD 4558, Australia
* Correspondence: spinelli@ivalsa.cnr.it; Tel.: +39-335-542-9798

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Abstract: Annual use, utilization, productivity and fuel consumption of three purpose-built and three excavator-based harvesters and processors were monitored for one work year. All machines were owned and operated by private contractors and were representative of the Italian machine fleet. Despite challenging mountain terrain, annual use ranged from 675 to 1525 h per year, and production from 3200 to 27,400 m^3 per year. Productivity was lower for excavator-based units, and for machines working under a yarder, due to limited yarder capacity. Purpose-built machines offered higher utilization, productivity and fuel efficiency compared with excavator-based machines. Fuel consumption per m^3 was 2.4 times greater for excavator-based units, compared with purpose-built machines. Excavator-based units offered financial and technical advantages, but their long-term market success will likely depend on future improvements in fuel efficiency, in the face of increasing fuel prices.

Keywords: efficiency; contractors; benchmark; logging

1. Introduction

Mechanized harvesting is performed by specialized machines that fell and process the trees (harvesters) or process already felled trees (processors) into commercial assortments, and by other units (forwarders) that extract these assortments to a landing [1]. Compared with motor-manual operations, mechanized harvesting allows dramatic progress in terms of value recovery [2] labour productivity [3] and operator safety and comfort [4]. Even where motor-manual harvesting techniques are still competitive due to cheap labour, mechanization may increase production capacity and anticipate future labour shortages [5].

For these reasons, harvesters and processors are now common in many countries [6], and not only in Northern Europe where they were first developed and adopted [7,8]. While originally designed for low-land conifer forests, today these machines operate in steep terrain [9,10], hardwood stands [11] and fast-growing plantations [12].

In Italy, mechanized harvesting was introduced at the beginning of the new century [13], and by 2013 the Italian fleet counted over 200 units, including harvesters, processors and forwarders [14]. These machines are used under different and peculiar conditions compared with those encountered further North, and namely steep terrain alpine forests, industrial poplar plantations, close-to-nature forests, coppice stands, and non-industrial private forestry. Despite a relatively difficult work environment, mechanized harvesting technology has enjoyed much success and many logging firms have already purchased their second or third machine [15].

On the other hand, some logging contractors still have some doubts about acquiring a harvester or a processor, mainly due to the high purchase cost of the equipment and the limited investment capacity of their firms [16]. Before they buy, operators would like to obtain reliable information about productivity, actual use potential and fuel consumption, for costing purposes. Productivity references are mostly available for Nordic and Central European conditions, and these figures may not correctly represent the conditions of Southern Europe, where operator training, work environment and technology type can be quite different.

In fact, productivity figures can be derived from published short-term studies lasting a few days; however, these figures can be representative of actual work time only, because short-term studies offer a poor representation of delay incidence, and of long-term productivity in general. This is best gauged through long-term follow-up studies [17]. Besides, long-term follow-up studies are generally immune from the so-called "Hawthorne effect", i.e., the tendency of observed workers to change their behavior as a result of being observed. Even when operators know their performance is being observed, work pace tends to stabilize to normal levels if the observation period is very long and the knowledge of being observed fades into the general background.

Existing literature offers few examples of long-term follow-up studies of harvesters and processors. Most of these studies tap into State company records, due to the general practice of State companies to keep accurate records of their own activities. However, machine use conditions are likely different between large State or private companies and individual small-scale contractors, who still represent the backbone of the forestry contracting sector in many countries, inside and outside Europe. Therefore, data obtained from large companies may not provide an accurate representation of the use pattern, productivity and fuel consumption normally experienced by individual private contractors.

Furthermore, machine use and performance may differ between machine types, and especially between purpose-built machines and excavator-based units. In particular, excavator-based units seem to be poorly represented in the Northern and Central European machine fleets, while they are quite popular in Southern Europe due to their lower investment cost and their higher operational flexibility. The former facilitates penetration of new markets such as the Southern European market, while the latter favors introduction to radically different work chains, such as those encountered in mountain operations or in short-rotation tree farms established on ex-arable land. This is also the case for Italy, where three-quarters of the harvester and processor heads are mounted on adapted excavators, often pre-owned, which indicates the strong interest in minimizing investment cost and the associated financial risk [15]. Very little long-term information is available about these machines, nor can one find any comparison between machine types that could help derive estimates from the figures already available for purpose-built harvesters.

Therefore, the goals of this study were (1) to provide reliable information about machine use (hours per year), utilization (percent of productive time over scheduled time), productivity and fuel efficiency, as typical of individual small-scale private contractors operating in Southern Europe; (2) to detect any significant differences between purpose-built and excavator-based units. While the study was centered on small-scale Italian logging contractors, some of these contractors conducted cross-border business and also operated in the neighboring Austrian and French regions, which may give some more general value to the figures obtained in the process.

2. Materials and Methods

The study involved five logging contractors, of which one was based in Central Italy and four in Northern Italy, where about two-thirds of the Italian harvester and processor fleet is stationed [15]. The company based in Central Italy was one of the early adopters, and had accumulated over 15 years of experience with mechanized harvesting technology, which they had acquired already in the early 2000s.

Six machines were selected for the study, of which three were purpose-built machines and three were excavator-based machines (Figure 1). Two of the purpose-built machines were owned by the same logging company, but they were operated by different drivers. All the selected machines were used for one single shift, which is current practice in Italy.

Figure 1. Example of the purpose-built (**top**) and excavator-based (**bottom**) units in the study. These are respectively unit # 2 and # 6.

The two machine types represented in the study (i.e., purpose-built and excavator-based) reflect different technical choices available to contractors working with mechanized harvesting technology. In general, contractors opt for an excavator-based machine because it is cheaper to acquire and easier to re-sell if the business does not grow as expected, compared with a purpose-built machine. Deployment conditions were similar across the two groups: within each group, two machines out of three were deployed to assist a yarder and worked as processors, whereas one was working independently as a harvester (i.e., machines 3 and 4). The six machines in the study were considered representative of the entire population of harvesters and processors used in Italy, and in much of Southern Europe [15]. Their technical characteristics are described in Table 1, while Figure 2 shows their work areas (e.g., home range).

Table 1. Technical characteristics of the machines in the study.

Unit	#	1	2	3	4	5	6
Machine	**Type**	**Purpose-Built**			**Excavator-Based**		
Base	Make	Skogsjan	Ecolog	John Deere	Liebherr	Daewoo	JCB
Base	Model	495	580	1470	912	225 NLCV	180
Base	kW	165	205	180	80	110	81
Base	Kg	15,500	18,500	19,700	16,000	21,500	20,200
Head	Make	Woody	Woody	Waratah	Valmet	Zoeggeler	Woody
Head	Model	60H	60H	290	965 II	ZBH 70	60H
Age	Years	9	8	6	6	1	3

Each machine was considered as a study unit and was operated by an individual driver, often the main company owner. All drivers were male Italian nationals, aged between 30 and 45 years. They all had at least three years of experience running a harvester or a processor, often the same machine included in the study. The drivers on machines # 3 and 6 were employees working for the machine owner, while all the others were also the main company and machine owners. Each driver agreed to keep a detailed logbook, where he recorded the main work data on a daily basis, for one year. Each daily record included date, location, travel hours, work hours, delay hours, processed volume and fuel used. Travel distance between sites was calculated on maps, and so was the home range of each unit—i.e., the work area explored during one year. Units # 1, 2, 5 and 6 worked in the Alps and negotiated the maturity cut of typical steep-terrain alpine forests, generally consisting of an uneven-aged mix of spruce (*Picea abies* Karst.), fir (*Abies alba* L.) and beech (*Fagus sylvatica* L.), and treated with selection cutting. These machines were associated with a yarder and operated as processors on pre-felled trees. In contrast, units # 3 and 4 negotiated the clear-cutting of mature low-land pine (*Pinus pinaster* L.) and poplar (*Populus x euroamericana* sp.) plantations, and worked as harvesters, felling and processing the trees at the stump site.

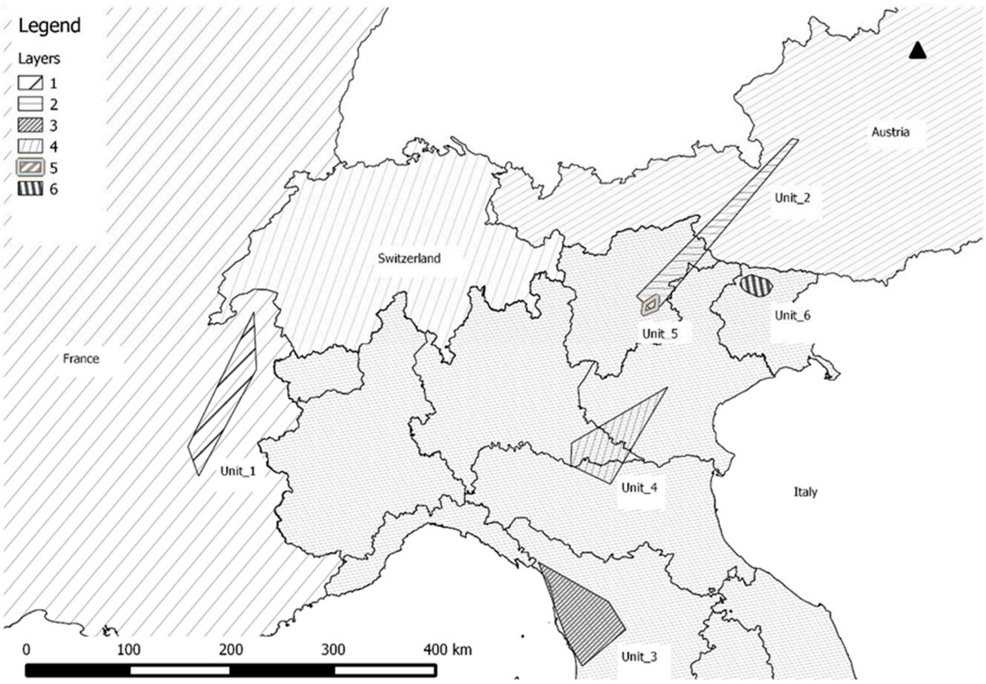

Figure 2. Work area (i.e., home range) explored by the machines during this study (notes: polygons represent the area explored by each study unit, as reported in the legend near each individual polygon).

Daily records were consolidated and analyzed as monthly averages, to smooth extreme differences. This was especially important for fuel consumption, because machines were not refueled every day, which made it difficult to produce exact daily consumption estimates. Furthermore, monthly records were summed into annual totals, offering an immediate view of annual work load.

Data were analyzed with the Statview 5.01 advanced statistics software, in order to check the statistical significance of the eventual differences between unit types—purpose-built vs. excavator-based. The significance of any differences between annual totals was tested with non-parametric techniques, because the data points were few and their distribution violated the normality assumption. In contrast, the significance of any differences resulting from the comparison of monthly averages was tested with a conventional analysis of variance, because the data was normally distributed. The elected significance level was $\alpha < 0.05$.

3. Results

Annual use ranged from 675 to 1525 h (Table 2). Purpose-built machines worked more hours, had a higher percent utilization and produced larger log volumes than excavator-based machines, but these differences had no statistical significance when taken as annual totals. In that case, the only statistically significant difference concerned fuel consumption per cubic meter, which was almost twice as high for excavator-based units compared with purpose-built units (Table 3).

Table 2. Annual totals by test unit.

Unit	**#**	**1**	**2**	**3**	**4**	**5**	**6**
Machine	**Type**	**Purpose-Built**			**Excavator-Based**		
Use							
Work	h year^{-1}	792	813	1260	604	366	701
Delays	h year^{-1}	229	371	265	648	309	314
Total time	h year^{-1}	1021	1184	1525	1253	675	1015
Utilization	%	78	69	83	48	54	69
Work days	n° year^{-1}	123	123	162	152	88	140
Work days	h day^{-1}	8.3	9.6	9.4	8.3	7.7	7.3
Idling	month year^{-1}	1	0	0	0	4	2
Productivity and consumption							
Fuel	L year^{-1}	7807	6851	19,279	10,803	5465	9170
Volume	m^3 year^{-1}	10,533	10,337	27,432	10,487	3191	4146
Productivity	m^3 pmh^{-1}	13.3	12.7	21.8	17.4	8.7	5.9
Productivity	m^3 smh^{-1}	10.3	8.7	18.0	8.4	4.7	4.1
Fuel use	L pmh^{-1}	9.9	8.4	15.3	17.9	14.9	13.1
Fuel use	L m^{-3}	0.74	0.66	0.70	1.03	1.71	2.21

Notes: Utilization = productive time/scheduled time; pmh = productive machine hours, excluding delays; smh = scheduled machine hours, including delays (same here as total time).

The area explored by the different units showed a large variation, ranging between 52 and 1571 km^2, while the number of relocation trips per year varied from 3 to 10. Purpose-built units travelled for longer distances compared with excavator-based units. Most machines experienced some seasonal stop, which was generally very short except for unit 5. In fact, the two machines that performed both felling and processing in low-land forests experienced no prolonged seasonal stops, which were recorded only for machines working alongside a yarder, possibly because these machines operated on mountain forests where snow could impose prolonged seasonal interruptions of harvesting activities.

Table 3. Medians of the annual records by machine type.

Machine	Type	Purpose-Built	Excavator-Based	*p*-Value	DF
Total hours	h year^{-1}	1184	1015	0.2752	6
Utilization	%	78	54	0.1266	6
Work day	d year^{-1}	123	140	0.8273	6
Fuel	L year^{-1}	7806	9170	0.8273	6
Volume	m^3 year^{-1}	10,533	4146	0.1266	6
Productivity	m^3 h^{-1}	13.3	8.7	0.2752	6
Fuel use	L pmh^{-1}	9.8	14.9	0.2752	6
Fuel use	L m^{-3}	0.70	1.71	0.0495	6

Notes: Utilization = productive time/scheduled time; pmh = productive machine hours, excluding delays; DF = degrees of freedom.

The analysis of monthly averages confirmed the main findings that already emerged from the analysis of the annual means, offering further insights into working hours, utilization, productivity and fuel use (Table 4).

Table 4. Means of the monthly totals by machine type.

Machine	Type	Purpose-Built	Excavator-Based	*p*-Value	DF	Eta^2
Work	h month^{-1}	86	56	0.0003	59	0.27
Delays	h month^{-1}	26	42	0.0156	59	MW
Total time	h month^{-1}	112	98	0.1897	59	0.03
Work days	n° month^{-1}	12	13	0.7042	59	0.00
Work days	h day^{-1}	9.2	7.7	<0.0001	59	0.59
Utilization	%	77.1	58.9	<0.0001	59	MW
Product	m^3	1490	584	<0.0001	59	MW
Productivity	m^3 h^{-1}	17	11	0.0004	59	MW
Fuel use	L month^{-1}	1043	846	0.1716	59	0.03
Fuel use	L h^{-1}	12	15	0.0002	59	0.29
Fuel use	L m^{-3}	0.72	1.70	<0.0001	59	MW
Relocation	km month^{-1}	104	28	0.9814	47	MW
Relocation	trips month^{-1}	0.50	0.72	0.4432	47	MW
Max distance	km	126.6	30.2	0.9243	41	MW

Notes: DF = degrees of freedom; Eta^2 = Effect size for parametric tests, or type of non-parametric test used (MW = Mann–Whitney); Utilization = productive time/scheduled time.

Monthly records offered higher resolution, and the higher number of data points allowed significant differences to be disclosed between machine types with regard to use, utilization, production, productivity and fuel use. Operators used purpose-built machines more intensely, which generally turned out to be more efficient than excavator-based units in terms of productivity, fuel use and utilization. As an average, the utilization of purpose-built machines was 18 percentage points higher than that of excavator-based machines (i.e., 30% more in relative terms). Furthermore, the mean productivity of purpose-built machines was 50% higher than that of excavator-based machines, while fuel consumption per hour was 20% lower: as a result, mean fuel consumption per cubic meter was half as high as that recorded for excavator-based machines. Productivity was also dependent on work organization: machines that worked independently (i.e., units 3 and 4) were 60% to 100% more productive than machines that worked under a yarder and were limited by yarder output.

Furthermore, analysis of monthly records disclosed seasonal trends, which were different for different machine types. In general, all machines experienced a lull in activities at the end of winter (February) and at the peak of summer (August), which can be justified by the combination of climatic factors and calendar holidays, especially for August. However, peaks and lulls were very different, with excavator-based units experiencing deeper and longer drops than purpose-built units (Figure 3).

As an average, excavator-based machines were deployed on much smaller jobs than purpose-built machines, which may have contributed to their lower utilization. In fact, the two machine types seem to underline different use patterns, with excavator-based machines apparently targeting smaller jobs within a smaller distance from each other, and purpose-built machines accepting longer relocation distances (three times longer) in order to acquire significantly larger jobs (three times larger). This is confirmed by the area covered by the contractors, which averaged 3400 km^2 for purpose-built machines and 1300 km^2 for excavator-based machines.

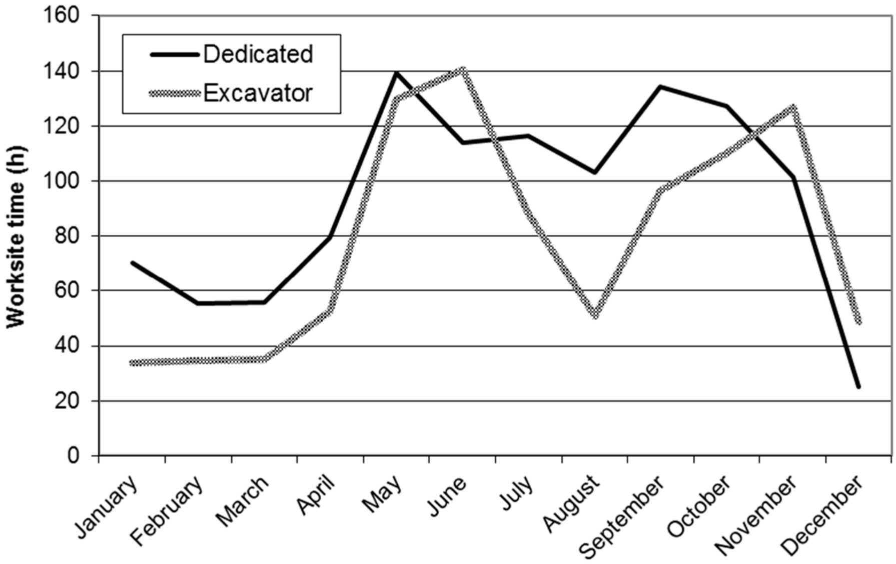

Figure 3. Total working hours per month and per machine type (mean of three samples for each type).

4. Discussion

First of all, it is important to state upfront the limitations of the study: (a) the use of a small and widely variable sample and (b) the reliance on company records, with the inherent variability derived from the different recording practices adopted by different companies. Obtaining detailed, long-term records from small-scale private contractors is rather difficult, because many contractors keep partial records only, and they are often unwilling to share data that may be considered sensitive. Therefore, the small sample size is a justified limitation, and its negative effect has been contained by selecting representative cases based on a detailed knowledge of the sector, which was obtained from three previous surveys of Italian contractors [14–16]. These surveys produced a detailed picture of the contracting sector in Italy, as well as a list of contractors that was used for extracting representative samples. Concerning the variability of individual records, this limitation may have affected the resolution of the data more than its reliability, because this study extracted only basic figures that were accounted for in a common way by all contractors, such as place names, worked volumes, fuel inputs and time inputs. If at all, variability could have affected the estimates for work hours, because different operators may have labelled different tasks under different headings, potentially attributing some delay time to work time or vice versa. However, all operators were carefully instructed about what pertained to work time and what pertained to delay time, and it is unlikely that they made major errors.

In any case, this is one of the very few studies representing small-scale private contractors. Most other available studies tap into the records of State companies, which often benefit from a formal support infrastructure and long-term operational planning. This may explain the much larger annual use figures recorded specifically for State companies in Austria and Germany (Table 5). If the difference was just a national one, then the European surveys recently conducted by Malinen et al. [18] and by Spinelli et al. [19] would not report use figures that are so close to those reported in this study. At the same time, similarity with the figures already available for the general pool of Italian harvesters and processors indicates the selection of a representative sample, despite its small size [15]. Further corroboration comes from the analysis of the utilization figures presented in this study: these are generally comparable with those reported in the existing relevant literature, which fall in the bracket between 50% and 80% [20,21].

Productivity is affected by many factors besides machine characteristics, such as tree size and form, operator experience, assortment length and number, branch diameter and management objectives [22–25]. Given the limited detail included in a long-term study, it is difficult to thoroughly discuss the similarities and the differences between the figures obtained from this study and those reported in the general literature on the subject. However, the figures in this study are generally compatible with those indicated in the literature, and they match quite well the Italian productivity standards for harvesters and processors [26]. This said, readers must be aware that direct comparison can be deceiving, because most of the existing productivity figures are obtained from short-term time study sessions, not from long-term company records. The fact that the latter match quite well a productivity standard derived from a compilation of short-term time studies bodes well for the capacity of time studies to reflect actual long-term performance, at least when more individual study sessions are consolidated into a cluster and analyzed as a group.

Concerning productivity, this study shows that purpose-built machines regularly outperform excavator-based units. The reason for the superiority of purpose-built machines is likely in the adoption of a specialized design and a much larger engine. While it may be difficult to separate the effects of design and power, it is worth recalling that the purpose-built machines in this study are twice as powerful as excavator-based machines, and that must have a strong impact on performance. In any case, readers must be aware that the figures in this report represent one element in a more complex supply chain and are likely affected by deployment conditions, which are not described in much detail in the records. Therefore, it may be difficult to produce a detailed productivity analysis from this study, but such analysis was never one of the goals of the project. However, this study clearly discriminates between units used independently from other machines and units routinely used in association with a yarder. The inevitably lower productivity and utilization of the latter raises the question about what processor one would best detach to serve a yarder. Obviously, high productivity is not a primary requirement, because this machine will not be able to express its full potential. On the other hand, a smaller, cheaper and less productive machine may be unable to handle the large trees associated with mountain operations—the only trees that can justify the higher cost of yarding [27]. One solution is to task the processor with additional duties, such as fleeting, stacking, loading and general landing management. That is already implemented by most operators. Readers will notice that all units deployed at yarder operations in this survey (i.e., 1, 2, 5 and 6) carry Konrad or Zoeggeler heads, which can effectively double as log grapples. This is not casual: all processors that worked under a yarder did perform additional duties, such as fleeting and stacking. However, this measure does not seem to fully offset the higher productive potential of the processor, and additional solutions must be considered.

Like productivity, fuel consumption is affected by machine and work type, as well as by operator skills and technique [28]. Again, the range of fuel consumption figures reported in the existing literature is wide enough that the results of this study are fully corroborated. Investigations conducted on purpose-built harvesters operating under similar conditions in neighboring Austria indicate a mean fuel consumption of 15.6 L h^{-1}, with a range between 10 and 24 L h^{-1} [20]. More importantly, the present study highlights a sharp difference between purpose-built and excavator-based machines and points at the potential fuel savings that could be accrued if excavator-based machines could be improved, or replaced with purpose-built units. The lower fuel consumption incurred by purpose-built harvesters is the result of a sophisticated machine control system designed to adjust power output to power demand in real time. Theoretically, excavators are equipped with similar systems but the connection between a processor head and an excavator that was not originally designed to receive it does not allow the same optimization level as achieved by integrated machines built specifically for this task. Extending such benefits to excavator-based machines would require that some excavator manufacturer finally decided to invest time and money into developing specific harvester capability options for one or more of their excavator models, or that a separate manufacturer—possibly the same building the harvester head—developed an effective adaptation kit comprising both hardware and software. The latter solution has already been attempted in the past, and some harvester head manufacturers have developed such kits, but that is often a one-sided effort that has received little support from excavator manufacturers and has produced limited benefits. Manufacturers should keep in mind that contractors are very much concerned with fuel consumption because they cannot control fuel price, and surveys have already shown that fuel-efficiency is a main driver when purchasing new machines [29]. Therefore, the development of fuel-efficient excavator-based processors should represent a strategic goal for excavator manufacturers, and for those companies that build processor heads designed for fitting to an excavator. Otherwise, the increase of fuel price may erode their market shares, in favor of those companies that sell purpose-built units.

Another important question is the extent to which these results can be generalized, and whether they could be used to represent Italy alone, or could be extended to other countries as well. It is true that Italian forestry presents peculiar conditions in terms of extreme ownership fragmentation, conservative silviculture, low product value, and poor integration between forest management and wood industry—all of which affect the progress of mechanized harvesting, when they do not limit it [16]. That is the main reason why the Italian harvester and processor fleet is still much smaller than in the neighboring alpine countries, such as Austria [30] France [31] or Germany [32]. On the other hand, mechanized harvesting has made rapid and significant inroads in Italian forestry over the last few years [14] as the old generations of foresters and loggers are being replaced by new young professionals who are not ready to accept the same taxing work conditions that their elders had to cope with [33]. Therefore, Italian forestry may soon become intensely mechanized, which would justify the attempt to establish benchmark figures for the Italian case alone, even if the work conditions encountered in Italy could not be assimilated to those of any other countries. This said, the case of Italy seems to be a classic example of modernization, where logging is transitioning from a traditional small-scale business to an industrial activity. In that case, results obtained in Italy could be extended to other countries where forestry is experiencing the same transition.

Table 5. Annual utilization of purpose-built harvesters in some European Countries.

Hours Year^{-1}	Country	Population	Source
1184	Italy	Private contractors	This study
1328	Italy	Private contractors	Spinelli et al., 2010 [15]
1439	Europe	General	Spinelli et al., 2011 [19]
1323	Western Europe	General	Malinen et al., 2016 [18]
2042	Austria	State forests	Holzleitner et al., 2011 [20]
1560	Austria	General	Pröll 2005 [30]
1750	Germany	State forests	Forbrig 2000 [34]
1900	Germany	State forests	Denninger 2002 [35]
2036	Germany	General	Findeisen 2002 [36]
1865	Germany	General	Nicks and Forbrig 2002 [37]
1300	Germany	General	Drewes and Jacke 2005 [38]

While producing a benchmark, one should also define its characteristics. In particular, the question is whether the reference figures produced with this study represent best practice or ordinary practice—which are conceptually different. If one has obtained these figures from a representative sample of contractors, then the resulting benchmark must refer to ordinary practice. Otherwise, it should have been obtained from the top operators in the general contractor pool. On the other hand, mechanization is still adopted by a minority of contractors, who generally represent an elite: therefore, the benchmark figures estimated in this study approach best practice, at least for Italian forestry.

The same "natural selection" principle may apply to the differences found between excavator-based and purpose-built machines. The latter are generally adopted by the largest and most skillful contractors, who may have a higher level of professionalism compared with the contractors resorting to cheaper excavator-based units. Therefore, part of the efficiency difference between machine types might result from a combination of machine and operator characteristics, both of which have a strong effect on performance. Even if that were the case, there would still be no reason to try to separate the two effect types, because they would be inherently associated and an eventual separation would not achieve any practical purpose.

5. Conclusions

This study offers reference figures that can be used for benchmarking the performance of harvesters and processors used in Italy, or under work conditions that can be assimilated with those encountered there. These figures are quite reliable, due to the selection of a representative sample and to the long duration of the study itself. Furthermore, these figures are consistent with the results of previous studies, conducted on the same subject with different methods. This corroborates the estimates obtained from the study, and supports confidence in its results. The study also describes the substantial difference between purpose-built harvesters and excavator-based units, in terms of use intensity, productivity and fuel efficiency. Shifting from excavator-based units to purpose-built machines would allow a dramatic reduction of fuel consumption, and the long-term market success of excavator-based technology will likely depend on the ability to increase their fuel efficiency. Since excavator-based units may offer specific financial and technical benefits, there is scope for new research aiming to reduce their fuel consumption. The findings of this research will be useful to contractors who are considering shifting from manual to mechanized harvesting, for increased productivity, safety and comfort.

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