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The effect of mechanization level and harvesting system on the thinning cost of Mediterranean softwood plantations

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Highlights

- Whole-tree harvesting is 40–50% cheaper than cut-to-length harvesting.
- Mechanization reduced thinning cost by a factor 4.
- Between 1.5 and 6% of the residual trees were damaged.
- Mechanized cut-to-length harvesting allows controlled biomass release.
- Mechanized whole-tree harvesting is the cheapest option for energy chip production.

Abstract

The study compared motor-manual cut-to-length (CTL) harvesting, motor-manual whole-tree (WT) harvesting, mechanized CTL harvesting and mechanized WT harvesting as applied to the production of energy chips from the second thinning of Mediterranean pine plantations in flat terrain. Mechanization increased productivity between 6 and 20 times, depending on process step. It also allowed reducing thinning cost by a factor 4. Shifting from CTL to WT harvesting resulted in a reduction of harvesting cost between 40 and 50%. Fuel consumption was between 40 and 100% higher for CTL harvesting than for WT harvesting. Mechanization entailed a reduction of fuel consumption between 10 and 40%. Stand damage was generally low, between 1.5 and 6%. Mechanized CTL harvesting resulted in the lowest incidence of wounding, and the difference between mechanized CTL and manual WT harvesting was statistically significant. Soil compaction was absent or very small, depending on treatment. Mechanized thinning may produce larger increases of soil bulk density, compared to motor-manual thinning, but the difference is small, although significant. CTL harvesting leaves a larger amount of biomass on the soil, which relieves possible concerns about soil nutrient depletion. On the other hand, heavy residue loads may increase fire risk especially in sensitive Mediterranean environments.

Keywords logging; biomass; chipping; compaction; stand damage
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1 Introduction

The need for mobilizing increasingly large amounts of energy biomass has revived interest for thinning operations, which cannot offer conventional assortments at competitive cost (Kärhä et al. 2003). In fact, small trees from thinning operations represent an abundant resource (Kinoshita et al. 2009; Malinen et al. 2001), which can be profitably tapped to supplement other biomass streams and prevent harmful competition between new forest energy users and the traditional consumers of wood fibre (Lundmark 2006).

Among the many harvesting systems applied to thinning operations, the most popular are whole-tree (WT) and cut-to-length (CTL) harvesting. Whole-tree harvesting consists of felling trees and extracting them whole (stem, top and branches) to the landing, where they are eventually processed into commercial assortments (Stokes et al. 1989). This system offers the advantage of simplified in-forest handling. First documented in the US (Kammenga 1983), the application of WT harvesting in thinning operations is often associated to whole-tree chipping, and its basic set-up has proven so effective to remain virtually unchanged and appreciated until our days (Mitchell and Gallagher 2007). CTL harvesting in thinning favours a more articulated product strategy, leading to increased value recovery (Harstela 1999). By producing logs directly at the stump site, CTL facilitates wood extraction, potentially decreasing stand damage (Han and Kellogg 2000). What is more, in-stand tree processing results in lower organic matter removals, compared to WT harvesting. That is especially desirable on poorer sites, where organic fertility may represent a serious issue (Jacobson et al. 2000; Smolander et al. 2010). Processing at the stump site allows removing branches and needles, which detract from chip quality. As a result, biomass recovery is lower than for WT harvesting, but product quality is better, which may be rewarded with a higher price (Spinelli and Magagnotti 2010).

Both WT and CTL harvesting can be deployed with different levels of mechanization. In the motor-manual version, trees are felled or felled and processed with chainsaws, and the product is extracted with skidders, forwarders or forestry fitted farm tractors (Kellogg et al. 1993). Motor-manual harvesting is especially suited to self-employed forest owners and small contractors, with limited investment capacity (Lindroos et al. 2005). At the other end of the scale, mechanized WT harvesting is applied with feller-bunchers and grapple skidders, while mechanized CTL harvesting with harvesters and forwarders. The intersection of systems and mechanization levels results in four possible combinations, as follows: motor-manual WT, motor-manual CTL, mechanized WT and mechanized CTL. In all cases, extracted biomass can be chipped at the landing site with a mobile in-woods chipper.

The goal of this study was to compare these four systems in terms of: 1) productivity; 2) production cost; 3) site impact and 4) residue biomass loads. To our knowledge, no other studies have yet produced such a comprehensive comparison, and especially not in the Mediterranean region, which is characterized by dry climate and mineral soils. In particular, Mediterranean softwoods present a heavy branching, which makes harvesting system especially relevant to soil fertility and fire hazard.

2 Materials

A comparative trial was carried out in a pine plantation located near Pisa, Italy, inside the Regional Park of San Rossore, which encloses a surface of about 3000 ha and is covered for a large part by pine.

Trials were conducted in the second thinning of a 15-hectare tract, consisting of a 21-year-old umbrella pine (*Pinus pinea* L.) plantation, originally planted in rows with 2.5 x 2.5 m spac-

Table 1. Description of the test site.

Placename		San Rossore			
Northing		43°41′33.08″N			
Easting		10°18′30.44″E			
Slope	%	2			
Species		*Pinus pinea* L.			
Age	years	21			
DBH	cm	23.1			
Height	m	10.7			
Operation		2nd thinning			
Criteria		Selection of candidates			
Removal	% trees	35–40			
Mechanization	level	Manual		Mechanized	
System	type	WT	CTL	WT	CTL
Removal	trees ha^{-1}	251^{a}	244^{a}	221^{a}	251^{a}
Removal	t ha^{-1}	51^{a}	29.6^{b}	53.9^{a}	33.5^{b}
Tree size	kg tree^{-1}	203^{a}	122^{b}	244^{a}	133^{b}
Wood moisture content	%	45.8^{a}	47.3^{a}	48.2^{a}	43.5^{a}

Notes: Different letters in superscript indicate that the differences between the mean values presented on the same row are statistically significant at the 5% level according to Scheffe's multiple comparison test; DBH=diameter at breast height; WT=whole-tree harvesting; CTL=cut-to-length harvesting; Tree size=the mass of the mean tree as it is extracted, i.e with top and branches for WT and without top and branches for CTL.

ing. The first thinning was conducted 10 years earlier and removed alternate rows, so that current spacing at the time of second thinning was 5 x 2.5 m. Pine plantations are very common along the Tuscan coastline, where they have been established and managed for many centuries (Barbero et al 1998). The mainstream silvicultural prescription is clear-cutting, followed by replanting or by re-naturalization, if the quality of the hardwood understory is good (Zerbe 2002). Two to four thinnings are performed before the final cut. In the experiment, the local forester marked the trees to be preserved as the final crop (candidate trees) and prescribed the removal of any other trees potentially interfering with their future development (Carrasquinho et al 2010). Selection of removal trees was left to the logger, whose main task was to create enough space around candidate trees. Soil was a loamy sand, developed over a quaternary dune just few kilometres from the present coastline. Site and thinning characteristics are reported in Table 1.

In the motor-manual treatments, trees were felled with two chainsaws (Husqvarna 357XP, 3.2 kW) by two professional operators and skidded to the roadside landing with a forestry-fitted farm tractor (Valtra 6400, 75 kW), equipped with a forestry winch (Fig. 1a). When motor-manual CTL was applied, trees were also delimbed and crosscut into random lengths (4 to 7 m) before skidding, by the same crew and using exactly the same equipment. Minimum top diameter was 3 cm: tops and branches were left inside the plantation. In the mechanized WT harvesting treatment, pine trees were felled and bunched with a 27-t tracked feller buncher (JD759 J, 164 kW) and skidded to the roadside with a rubber-tired grapple skidder (JD460 G, 127 kW). The two machines are shown in Figs. 1b and 1c. Finally, in the mechanized CTL harvesting treatment, trees were felled, delimbed and crosscut to random lengths (4 to 7 m) with a 14-t four-wheel harvester (JD870 B,114 kW), while logs were extracted to roadside with a 10-t capacity forwarder (JD1110 B, 121 kW) (Fig. 1d and 1e). Again, minimum top diameter was 3 cm: tops and branches were left in the forest. None of the extraction machines used tyre chains or bogie tracks. In all cases, whole trees and logs were chipped at the roadside landing with a forwarder-mounted drum chipper (Erjo 12/90), powered by a 370 kW independent engine (Fig. 1f). The technical characteristic of all machines (except for the chainsaws) are presented in Table 2. All teams in each system worked independently, which

Fig. 1. Farm tractor (a); Feller-buncher (b); Skidder (c); Harvester (d); Forwarder (e); Chipper (f).

Table 2. Technical charecteristics of the machines in the test.

System		WT	WT	CTL	CTL	WT/CTL	WT/CTL
Mechanization	level	Mechanized	Mechanized	Mechanized	Mechanized	Motor-manual	Both
Machine	type	Feller-buncher	Skidder	Harvester	Forwarder	Tractor	Chipper
Make		John Deere	John Deere	John Deere	John Deere	Valtra	Erjo
Model		759J	460D	870B	1110B	6400	12/90
Power	kW	164	127	114	121	75	370/129
Weight	t	27770	12770	13800	13670	4170	30350
Width	mm	3050	2880	2510	2710	2340	2890
Length	mm	4410	7345	5435	10310	4440	10400
Clearance	mm	759	598	570	605	435	600
Head make		John Deere	-	John Deere	-	-	-
Head model		FR21B	-	746C	-	-	-
Cut capacity	mm	508	-	500	-	-	-

Notes: Chainsaws are not included in the table; Chipper size data refer to the complete forwarder-mounted unit; Chipper power figures are provided for both the chipper engine and the forwarder engine, in this order; WT=whole-tree harvesting, CTL=cut-to-length harvesting.

avoided interaction delays. System balance issues were solved by adjusting the hours spent on site by each team. Chipping was performed about four months after harvesting and extraction, and chips were discharged directly into chip vans. Due to logistical reasons, the four treatments were applied at different times, often with several months passing between individual tests. Overall, felling and extraction were performed between February and July 2012, whereas chipping was conducted in October of the same year.

All machines were operated by experienced professionals, who had run them for at least 5 years. No attempt was made to normalize individual performances by means of productivity ratings (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). On the other hand, the skills of study operators were considered representative of the region and were very similar between them, supporting the comparative character of the study.

3 Methods

Each of the four treatments was replicated on three study plots, for a total of twelve plots. Plot size varied from 2500 to 12 000 m^2, with an average value of 5000 m^2. Individual plot size depended on available block size, and on the need to contain work time within manageable bounds (≤ 3 days per plot). For this reason, motor-manual plots were generally smaller than mechanized plots. The average surface area was 3200 and 7600 m^2 for the motor-manual and the mechanized plots, respectively. Plots were randomly distributed on a very uniform stand, so that the main differences could be safely attributed to treatments.

Product output was determined by accumulating all the biomass extracted from each plot in a separate pile and weighing separately the chips obtained from each pile. When a chipvan received chips from more than one pile, partial loads were weighed by interrupting the chipping operation when the first pile was exhausted and driving the van on a set of portable scales. The operation would then be repeated when the load had been completed with material coming from the second pile. Figures obtained with portable scales were validated by taking all loads to a certified weighbridge available just at the exit of the estate. When needed, partial load figures determined with the portable scales were corrected using the certified weighbridge values. Moisture content was determined according to the European standard CEN/TS 14774-2, on one 500-g chip samples per load. These samples were obtained from the reduction of larger 3 L samples collected at different places within the same load.

Time input was determined with a time-motion study (Magagnotti and Spinelli 2012). Each work 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 (Björheden et al. 1995), in order to calculate appropriate delay factors (Spinelli and Visser 2008) for each machine type. Delay factors were calculated as the average delay to productive time ratio recorded on all three plots for each given machine. Then, individual time input per plot was calculated as the actual productive time recorded on each plot, corrected by the appropriate delay factor. This allowed controlling the effect of delay time, which is typically erratic and may confound results (Spinelli and Visser 2009). Study delays were excluded from the study, but all other delay types were included.

Fuel input was determined by refilling all machine tanks at the end of each working day, and recording the amount of fuel used during that day. This figure was divided by stopwatch hours and prorated to each plot based on the hours actually needed to harvest it.

Stand damage was determined by inspecting all trees left on each plot after harvest, according to the method described by Meng (1978). Wounds with an exposed surface smaller than 10 cm^2 were not recorded, as they had little consequences on tree health or wood quality (Whitney 1991). To describe wound severity, the authors used the total wound surface.

Soil compaction was determined from undisturbed cores, collected before and after harvest. Cores were collected in rings of thin-walled stainless steel tubing, with an internal diameter of 8 cm and a height of 5 cm, corresponding to a volume of 250 cm^3. Rings were pushed into the soil down to a 5-cm depth, after removing the litter layer. Rings were then removed from the soil, for trimming the sample and placing it into a sealed plastic bag. Bags were taken to the laboratory and weighed before and after oven-drying at 105°C for 48 hours. These data were used to calculate the bulk density (BD) and the gravimetric water content of each sample. Researchers collected 40 cores per plot, 20 before and 20 after harvesting. Cores collected after harvesting were obtained from inside the machine tracks. Each core was considered as an individual observation. The depth of the observations seemed to be appropriate, as the main impacts of wood extraction are generally concentrated within the first 10 cm layer (Ampoorter et al. 2009), especially in Mediterranean and sub-Mediterranean soils (Makineci et al. 2007). Unfortunately, soil moisture was only determined at the time of core sampling, about 8 weeks after harvesting.

The amount of retained biomass was determined on forty 1 x 1 m sample plots, randomly spread over the whole experimental area in the number of 20 per harvesting system. Before locating the samples, the sample area was divided in two strata according to residual biomass load, in order to reflect the systematic slash accumulation pattern derived from trafficking every other inter-row.

Machine costs were calculated with the harmonized method developed within the scope of European COST Action FP0902 (Forest Energy Portal 2013). Data about utilization, maintenance and value recovery were obtained directly from the machine owners, and matched published figures (Spinelli et al. 2010; Spinelli et al. 2011a). Main assumption and results are shown in Table 3.

Data were analyzed with the Statview advanced statistics software (SAS 1999). Differences between plot characteristics were tested with the Kruskal-Wallis non-parametric test, because the distribution of data was skewed and it did not met the normality assumption. If this test detected significant differences between treatments, the data pool was tested again with the Scheffe's multiple comparison test, in order to pinpoint differences. Differences between unit cost figures and specific fuel consumption were tested with standard analysis of variance (ANOVA) because the data met all standard assumptions. The analysis of variance allowed to separately gauge the effect

Table 3. Costing assumptions and machine rates.

Unit		Chainsaw	Tractor	Feller	Skidder	Harvester	Forwarder	Chipper
Utilization	%	46	72	81	90	90	90	83
Investment	Euro	1500	55 000	320 000	180 000	300 000	240 000	500 000
Resale	Euro	450	16 500	96 000	54 000	90 000	72 000	150 000
Service life	years	2	10	10	10	10	10	10
Utilization	SMH year^{-1}	1000	1000	1600	1600	1600	1600	1600
Interest rate	%	4	4	4	4	4	4	4
Depreciation	€ year^{-1}	525	3850	22 400	12 600	21 000	16 800	35 000
Interests	€ year^{-1}	50	1507	8768	4932	8220	6576	13 700
Insurance	€ year^{-1}	2500	2500	2500	2500	2500	2500	2500
Fuel	€year^{-1}	2700	4500	47 840	31 408	27 040	27 040	72 800
Lubricant	€ year^{-1}	270	450	4784	3141	2704	2704	7280
Repairs	€ year^{-1}	263	1925	11 200	6300	10 500	8400	17 500
Total	€ SMH^{-1}	6	15	61	38	45	40	93
Crew	n.	2	1	1	1	1	1	1
Labour	€ SMH^{-1}	32	16	20	20	20	20	20
Overheads	€ SMH^{-1}	8	6	16	12	13	12	23
Total rate	€ SMH^{-1}	46	37	97	70	78	72	136

Notes: Cost in Euro (€) as on Sept.18, 2013. 1 € = 1.33 US$; SMH = Scheduled Machine Hours, inclusive of delays; Utilization is the incidence of work time over total work site time: the remaining time is represented by delays. The utilization rates reported in the table were actually measured during the study.

of harvesting system and mechanization level. Again, Scheffe's multiple comparison test was used to pinpoint specific differences between treatments.

Overall, the test covered 6.47 ha, from which 1558 trees were harvested, yielding 262 tonnes of oven-dry chips. The time study sessions covered a total of 227 observation hours.

4 Results

Table 1 shows the absence of any significant differences between treatments for what concerns the number of trees removed per unit surface and wood moisture content at the time of chipping. In contrast, mass removals (per unit surface and per tree) differed significantly between the WT and CTL treatments, with WT harvesting yielding 66% more biomass than CTL harvesting, regardless of mechanization level.

Felling and extraction productivity were significantly different between treatments, whereas chipping productivity was not (Table 4). Mechanization allowed a dramatic increase of labour productivity. With mechanization, felling-processing productivity increased 8 times, and felling-bunching productivity 20 times. Extraction productivity increased from 6 to 8 times. Shifting from CTL to WT resulted in productivity increases between 40% and 270%, depending on work step and mechanization level. Gains were highest when replacing mechanized felling-processing with mechanized felling-bunching. The table also shows that extraction distances did not differ significantly between treatments, whereas mean payloads did. Larger mechanized units were able to carry larger payloads.

Specific fuel consumption ranged from 4.6 to 10.6 L per tonne of oven-dry chips (Fig. 2). Consumption was between 40 and 100% higher for CTL harvesting than for WT harvesting. Mechanization entailed a reduction of fuel consumption between 10 and 40%. Shifting from mechanized CTL to manual WT harvesting allowed reducing fuel consumption by 19%. Differences were statistically significant between motor-manual CTL harvesting and all other treatments, as well as

Table 4. Productivity by treatment and work phase.

Mechanization		Manual		Mechanized	
System	type	WT	CTL	WT	CTL
Felling	odt SMH^{-1}	0.9^a	0.6^b	18.2^c	4.9^d
Extraction	odt SMH^{-1}	2.3^a	0.6^b	13.5^c	6.9^d
Chipping	odt SMH^{-1}	18.7^a	16.7^a	15.5^a	17.5^a
Extraction distance	m	233^a	140^a	189^a	174^a
Load size	odt	0.410^a	0.212^b	0.958^c	3.845^d

Notes: Different letters in superscript indicate that the differences between the mean values presented on the same row are statistically significant at the 5% level according to Scheffe's multiple comparison test; SMH = Scheduled Machine Hours, inclusive of delays; odt = oven-dry tonnes; WT = whole-tree harvesting, CTL = cut-to-length harvesting.

Table 5. Anova table for the effect of mechanization level and harvesting system on unit cost and fuel consumption.

Thinning cost (€ odt^{-1})					
Effect	DF	SS	η^2	F-Value	P-Value
Mechanization	1	20003	0.71	113.034	<0.0001
System	1	4863	0.17	27.479	0.0008
Interaction	1	1861	0.07	10.515	0.0118
Residual	8	1416	0.05		
Specific fuel consumption (L odt^{-1})					
Effect	DF	SS	η^2	F-Value	P-Value
Mechanization	1	17.452	0.22	13.529	0.0062
System	1	40.853	0.52	31.668	0.0005
Interaction	1	10.155	0.13	7.872	0.0230
Residual	8	10.32	0.13		

Notes: odt = oven-dry tonnes.

between mechanized CTL and mechanized WT harvesting. In contrast, there was no statistically significant difference between the mean fuel consumption incurred by manual WT harvesting and by the two mechanized treatments.

Harvesting cost varied between 19 and 142 € per tonne of oven-dry chips (Fig. 3). Mechanized WT harvesting offered the lowest harvesting cost, allowing a 40% saving over the next best option (mechanized CTL). In both cases, mechanization allowed reducing harvesting cost by a factor 4. Shifting from CTL to WT harvesting resulted in a reduction of harvesting cost between 40 and 50%. All these differences were statistically significant. Table 5 shows the results of the ANOVA, indicating that the effect of mechanization was stronger than the effect of harvesting system for what concerned harvesting cost. The contrary was true for fuel consumption.

Between 1.5 and 15% of the residual trees presented wounds larger than 10 cm^2 (Table 6). However, the 15% figure recorded for motor-manual CTL was considered dubious and excluded from the comparison (see discussion), resulting in an actual wounding frequency range between 1.5 and 6%. Therefore, only three treatments were compared, and namely motor-manual WT, mechanized WT and mechanized CTL. Among them, mechanized CTL resulted in the lowest incidence of wounding, and the difference between mechanized CTL and manual WT was statistically significant. Mechanized WT was in between, with no statistically significant differences with respect to the other two treatments. The differences in wound size had no statistical significance, so

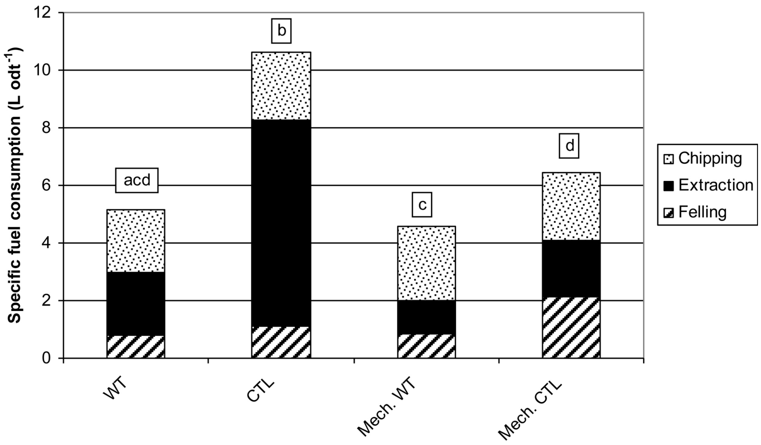

Fig. 2. Specific fuel consumption per unit product by treatment and work phase. Notes: Different letters over different bars indicate that the difference between the mean fuel consumption values are statistically significant at the 5% level according to Scheffe's multiple comparison test; WT = motor-manual whole-tree harvesting; CTL = motor-manual cut-to-length harvesting; Mech. WT = mechanized whole-tree harvesting; Mech CTL = mechanized cut-to-length harvesting; Felling also includes delimbing and crosscutting in the case of CTL harvesting operations.

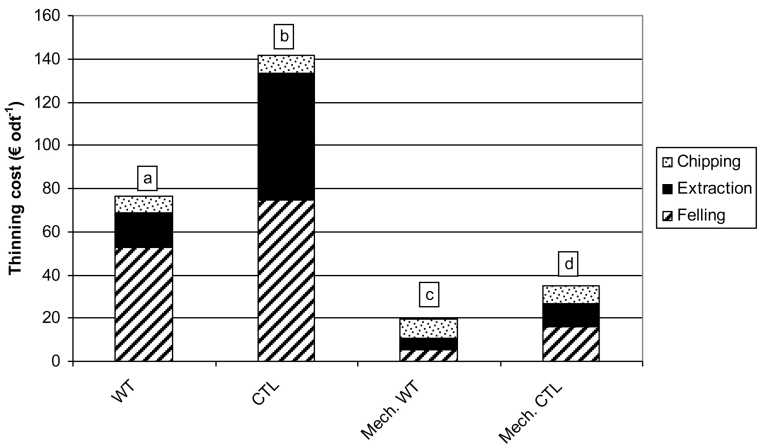

Fig. 3. Thinning cost by treatment and work phase. Notes: Different letters over different bars indicate that the difference between the mean total cost values are statistically significant at the 5% level according to Scheffe's multiple comparison test; WT = motor-manual whole-tree harvesting; CTL = motor-manual cut-to-length harvesting; Mech. WT = mechanized whole-tree harvesting; Mech CTL = mechanized cut-to-length harvesting; Felling also includes delimbing and crosscutting in the case of CTL harvesting operations.

Table 6. Site impact for the four treatments on test.

Mechanization		Manual		Mechanized	
System	type	WT	CTL	WT	CTL
Wounding	% trees	6.0[a]	15.7	2.5[ab]	1.5[b]
Wound size	cm^2	433[a]	407[a]	106[a]	431[a]
Soil density untrafficked	g cm^{-3}	1.30[a]	1.18[a]	1.25[a]	1.21[a]
Soil density trafficked	g cm^{-3}	1.28[a]	1.28[a]	1.28[a]	1.36[a]
Difference	%	–1.2	8.8	2.5	11.9
t test	p-value	0.3462	<0.0001	0.2332	<0.0001

Notes: Different letters in superscript indicate that the differences between the mean values presented on the same row are statistically significant at the 5% level according to Scheffe's multiple comparison test; p-values in the last row refer to the comparison between untrafficked and trafficked soil density within each treatment; WT = whole-tree harvesting, CTL = cut-to-length harvesting.

one could not safely state that any of the treatments caused more severe wounding than the others.

Only the CTL treatments caused a significant increase of soil bulk density, which is indicative of soil compaction. However, such increase was very low, ranging from 8 to 10% of the original value. The density increase recorded for the mechanized CTL treatment was significantly higher than for the manual CTL treatment (p-value = 0.0032).

After harvesting, the amount of biomass released in the stand as forest residue amounted to 4.6 (standard error = 1.3) and 34.0 (standard error = 1.3) oven-dry tonnes per hectare for the WT and the CTL treatments, respectively. This difference was highly significant (p-value < 0.0001 according to the Mann-Whitney test). Summing the amounts of biomass removed and released for the two harvesting systems gave consistent results, confirming the general validity of our estimates.

5 Discussion

The comparison presented in this study is truly innovative because at the same time a) it is conducted under typical Mediterranean conditions, b) it includes different mechanization levels and c) it concurrently explores productivity, financial performance, site impact and biomass release. However, this study not is the first one to compare the performance of WT and CTL harvesting. In the early 1990s, the appearance of commercial CTL technology prompted a number of comparison studies in North America. In following years, system comparison studies have been produced sporadically but regularly, both in North America and in Europe. As a consequence, we now have a relatively large body of references for checking our results.

The better financial performance of WT harvesting is matched by several papers, which report cost savings between 20 and 40% (Adebayo 2007; Spinelli et al. 2009; Bisson et al. 2013). However, other studies report of no significant cost difference between the two systems (Lanford and Stokes 1996; Benjamin et al. 2012). That can be explained with the fact that the latter studies compared the two systems when applied to the production of pulpwood logs, which made delimbing and crosscutting necessary for both systems. In that case, WT harvesting did not avoid delimbing and crosscutting, as occurred in our study. Cost seems to depend more on the number of process steps than on their sequence, unless a different sequence allows increasing the level of mechanization. In general, the financial advantages of WT harvesting are maximized if the system allows multi-tree harvesting (Oikari et al. 2010) and process simplification (Spinelli and Magagnotti 2010). Anyway, no study has ever suggested that WT harvesting may incur a higher production cost than CTL harvesting, for the same level of mechanization and when producing chips. In the specific case of this study, the heavy branching of umbrella pine trees may have hindered delimbing, thus increasing the gap between the two systems.

Concerning mechanization, the results of our study may deserve some comments. It is clear that mechanization introduces substantial cost reductions, but the differences we observed were twice as large as reported in previous studies (Laitila 2008; Spinelli and Magagnotti 2011). Such result may partly depend on different operator proficiency. While all operators in the study were trained professionals, motor-manual crews were more flexible and performed many different forestry jobs depending on opportunity. In contrast, mechanized operators were much more specialised in their respective tasks, and therefore they were more likely to achieve top performance in their individual jobs. Further evidence of different operational capacity is offered by the use of a winch rather than a forestry trailer for extracting logs, under the motor-manual CTL treatment. A forestry trailer would have been more appropriate, but the company did not have one available and decided to use their simple winch instead. On the other hand, different specialization is an inherent characteristic of the two mechanization levels, which is becoming more pronounced as mechanization develops, and specialized logging companies abandon motor-manual technology.

The selection thinning of Mediterranean forests often results in a higher damage frequency than recorded in our experiment. This can range between 14% (Picchio et al. 2011) and 20 % (Tsioras and Liamas 2010) of the residual stand. Previous studies confirm that CTL harvesting may result in lower residual stand damage compared to WT harvesting (Camp 2002; Lanford and Stokes 1995; Waters et al. 2004), and that mechanized operations may cause less damage than motor-manual operations (Koŝir 2008). Easy handling is the key to stand damage reduction. Whole trees are unwieldy, which increases the potential for hitting the residual stand. Handling is made much easier after size reduction at the stump site, as occurs with CTL harvesting. The better performance of mechanized operations is explained by the higher capacity of mechanical equipment for controlled tree handling (Magagnotti et al. 2012).

That is also true for our study, if we accept removing the data obtained for the motor-manual CTL treatment. Stand damage for this treatment was unusually high, and we assumed that it was the result of post-harvest mulching, occurred before data collection. With motor-manual CTL harvesting, tops and branches were left in windrows, to the side of the extraction trails. As a result, slash was not trampled by the tractor and remained quite thick, interfering with the recreational use of the forest. For this reason, the forest manager decided to mulch the slash windrows in the motor-manual CTL plots immediately after harvest. That was not necessary for all other treatments, because branches were either removed and chipped or crushed to the ground by the harvester and forwarder team. Mulching involved further in-stand traffic and the projection of wood particles at relatively high speeds, with a significant potential for tree damage. When mulching is necessary, its cost should be added to total harvesting cost, which would further expand the gap between mechanization levels and harvesting systems.

Post-harvest traffic occurred on alternate inter-rows and did not interfere with the measurement of soil bulk density, because the inter-rows trafficked by the extraction units were those left free from slash. However, harvesting occurred at different times for the two harvesting systems, which prevents us from making any conclusive statements about their relative performance with respect to soil compaction. Different soil moisture content at the time of harvest may explain why one system (CTL) resulted in a significant increase of soil bulk density while the other (WT) did not. On the other hand, motor-manual and mechanized variations of the same system were tested at about the same time, which supports the validity of comparisons between mechanization levels. Apparently, mechanization does not increase the soil impact of WT harvesting, but it does result in higher compaction when CTL harvesting is applied. This result can be explained in several ways. It is possible that soil moisture at the time of WT harvesting was so low that neither motor-manual harvesting nor mechanized harvesting had any effect on soil bulk density. Furthermore. Mechanized WT harvesting was performed by a tracked swing-to-tree feller-buncher and a grapple skidder, both of which would exert a relatively low ground pressure. Mechanized CTL equipment was heavier and had a smaller ground contact area, resulting in higher ground pressure and potentially heavier soil impact, especially if soil moisture content was near critical levels.

In any case, the post-harvest increase in soil bulk density recorded for CTL harvesting is much below the values found in literature, which range between 15 and 30 % (Froehlich et al. 1986). That is explained by the resistance of sandy soils to compaction (Wästerlund 1985), especially when their initial density is near the 1.4 g cm^{-3} threshold (Powers et al. 2005). Mediterranean pine plantations seem less susceptible to disturbance than similar hardwood stands (Gondard et al. 2003).

Obviously, the release of organic matter is much higher for CTL than for WT harvesting, which relieves possible concerns about soil nutrient depletion and consequent growth losses (Nord-Larsen 2002). On the other hand, heavy residue loads may increase fire risk especially in sensitive Mediterranean environments (Graham et al. 1999). In this respect, mechanized CTL harvesting is the best option, because it allows releasing relatively large amounts of slash while crushing it to the soil as the result of trampling.

Finally, readers must notice that product quality is very different for the two harvesting systems. WT harvesting offers whole-tree chips, which contain a larger proportion of needles and twigs compared to the chips obtained from CTL harvesting. In this study, we did not determine chip quality in terms of ash and fiber content, or particle size distribution. Therefore, we cannot make any conclusive statements about chip quality. However, whole-tree chips are likely less suitable for use in small-scale residential heating systems, which may entail a lower sale price (Spinelli et al. 2011b)

6 Conclusions

The results of this study can be extended to similar stands, characterized by simple even-aged structure and growing on flat terrain. Under these conditions, both mechanized treatments achieve high productivity and low harvesting cost, when producing forest chips. In contrast, motor-manual harvesting is too expensive for cost-effective thinning, regardless of harvesting system. WT harvesting allows a dramatic reduction of harvesting cost, as long as it allows simplifying the harvesting process. Fuel consumption is also lower for WT harvesting, compared to CTL harvesting. WT harvesting offers higher product yields, but a higher risk for soil nutrient depletion. All treatments result in very low site impact. If soil fertility is not a problem, mechanized WT harvesting is the preferable option.

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