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ORIGINAL PAPER

The effect of harvesting method on biomass retention and operational efficiency in low-value mountain forests

Raffaele Spinelli[1] · Natascia Magagnotti[1] · Giovanni Aminti[1] · Fabio De Francesco[1] · Carolina Lombardini[1]

Abstract This study determined the biomass retention effects and the technical–financial performance of alternative harvesting practices, applied to mountain sites. The two alternatives were: whole-tree (WT) and tree-length (TL) harvesting. Five cable yarding sites were selected from a larger pool of available sales, and on each site two adjacent and parallel cable corridors were set up, using the same base equipment and crew. For each of the 10 corridors (i.e. 5 sites × 2 corridors), the following data were recorded: biomass retention, product output, time and fuel inputs. Opting for TL harvesting resulted in a large (66 %) and significant increase in biomass retention, which may prove attractive where intensified biomass removal may jeopardize soil fertility and biodiversity. TL harvesting also resulted in a moderate increase (13 %) of total harvesting cost. Furthermore, TL harvesting required 30 % more labour input than WT, which may represent a disadvantage when forest labour is scarce. The increased labour use in TL harvesting occurs mainly at the stump site, where

accident risk is highest. For all these reasons, managers should take their decision very carefully and opt out of more efficient WT harvesting only when the risk derived from increased biomass removal is quite severe.

Keywords Productivity · Cost · Cable yarding · Logging · Coppice

✉ Raffaele Spinelli
spinelli@ivalsa.cnr.it

Natascia Magagnotti
magagnotti@ivalsa.cnr.it

Giovanni Aminti
aminti@ivalsa.cnr.it

Fabio De Francesco
defrancesco@ivalsa.cnr.it

Carolina Lombardini
lombardini@ivalsa.cnr.it

[1] CNR IVALSA, Via Madonna del Piano 10, Sesto Fiorentino, FI, Italy

Introduction

Natural forests cover 40 % of the Alpine landscape and play an important role in supporting local economy (Onida 2009). Alpine forests accomplish many functions at one time, and therefore, they are the object of so-called multi-functional forest management (Brang et al. 2006). In particular, alpine forests have both a productive and a protective function, while producing large amounts of timber, they also prevent soil erosion and shield settlements from avalanches and rock fall (Dorren et al. 2004). The need to guarantee cost-effective wood production and efficient soil protection makes alpine forestry especially complex. Furthermore, the typical access constraints of the Alpine territory often prevent the introduction of modern harvester–forwarder technology, which is a main solution to cost containment in the face of increasing fuel and labour cost (Spinelli and Magagnotti 2011). As a consequence, silvicultural treatment is often delayed and results in a skewed age distribution, because not enough young trees are available for replacing the old ones as they succumb to age and disease (Binder et al. 2004). Excessive ageing contributes to the high vulnerability of Alpine forests in the face of climate change (Seidl et al. 2011). Therefore, it is crucial to optimize forest operations in order to guarantee timely regeneration and maximize forest resiliency.

When slope gradient exceeds 40 %, ground-based harvesting technology cannot offer good results and cable yarding is preferred (Bont and Heinimann 2012). Cable yarding is the most common steep slope harvesting technique world wide, and it is especially popular in the Alps. As a matter of fact, alpine logging companies have a long-standing tradition with yarding. In 2012, there were over 350 cable yarding contractors in alpine Italy alone (Spinelli et al. 2013a). On steep terrain, cable yarding is the cost-effective alternative to building an extensive network of skidding trails and results in a much lower site impact compared with ground-based logging (Bolding and Aust 2011; Spinelli et al. 2010a). On the other hand, cable yarding is inherently expensive because it is normally deployed on difficult sites. For this reason, cable yarding offers lower profit margins compared with ground-based logging (Drews et al. 2001; Spinelli et al. 2015).

Much effort has been applied to increasing the profitability of cable yarding operations (Cavalli 2012). In that regard, a most popular solution consists in whole-tree (WT) extraction, which allows increasing the productivity of both extraction and processing (Ghaffariyan et al. 2009). Once the trees are delivered to the landing, processing becomes faster and safer, due to the easier work conditions (Spinelli et al. 2009). Additionally, processing can be mechanized using machines (i.e. processors) that cannot normally negotiate steep terrain, but can station at the landing and work the trees after extraction. A loader is needed at the landing in any case, for removing the trees from the yarder chute and stacking them to the side. This loader can be used as the base machine for carrying the processor head, so that conversion to mechanized processing may only require the additional investment in a processor head (Wang and Haarlaa 2002). Besides, excavator-based processors are more suited than dedicated units to working under a yarder, due to their 360° rotation capacity and to the possibility of installing a dual processor-grapple head (Spinelli et al. 2010b).

Adoption of WT harvesting offers the additional advantage of higher biomass recovery, because tree tops and branches are also moved to the landing, and they can be recovered for use as energy wood, so as to match the increasing demand generated by the growing bioenergy market (Lundmark 2006; Tyner 2008). In most cases, energy wood production is not the main goal of harvesting, but it represents an additional source of income (Han et al. 2004) or—in the worst case—a cost-effective way for disposing of the forest residues (Spinelli et al. 2009).

However, whole-tree (WT) extraction is coming under increased criticism because of the risk for soil nutrient depletion (Helmisaari et al. 2011), which may result from removing nutrient-rich top and branch material (Lamers et al. 2013). Furthermore, the intensification of biomass removal may alter soil carbon balances (Buchholz et al. 2014) and result in increased greenhouse gas (GHG) emissions (Mika and Keeton 2014). Intensified biomass removal at the time of harvesting may also impact the biodiversity of forest sites (Littlefield and Keeton 2012). However, studies on the long-term effects of WT harvesting are not consistent and report about negative, positive or non-existent effects, thus hinting at a site-specific dose–response (Wall 2012).

As a compromise solution, trees could be delimbed and topped before extraction, but not cut to measure. That would allow reducing inefficient stump-site processing work compared with traditional stump-site processing while increasing biomass retention to mitigate possible adverse effects (Mika and Keeton 2013). This work procedure is known as tree-length (TL) harvesting and is widely used to avoid the accumulation of residues at space-constrained landings (Westbrook et al. 2007). On the other hand, tree-length harvesting is less efficient than whole-tree harvesting and may result in higher harvesting costs. However, comparison studies between the two methods are old, do not include cost and biomass retention at the same time, and were done using ground-based logging (Putnam 1983).

Therefore, the goal of this study was to compare TL and WT harvesting under the conditions of cable yarding, covering biomass retention, labour productivity, energy use, harvesting cost and operation profitability at the same time. The null hypothesis was no significant difference existed between the two methods for any of the above-mentioned aspects.

Materials and methods

A comparative trial was carried out in the Italian Alps, near Lake Como (Fig. 1). For the purpose of the study, five cable yarding sites were selected from a larger pool of available sales (Table 1). Each site represented a separate and homogeneous forest compartment. All sites were characterized by deep brown soil with sandy loam texture, except for site 4 that had a dry, shallow rendzina. The selected sites were meant to represent the main stands available for harvest in the area, and those that are most critical in terms of financial viability and site sensitivity. Young softwood plantations and aged coppice stands require urgent management but offer low return, which does not suit production harvesting. Under these conditions, mechanization and the additional harvest of biomass products are often considered as ways to increase cost-efficiency and make management more attractive. That is why such stand types became priority targets for the study.
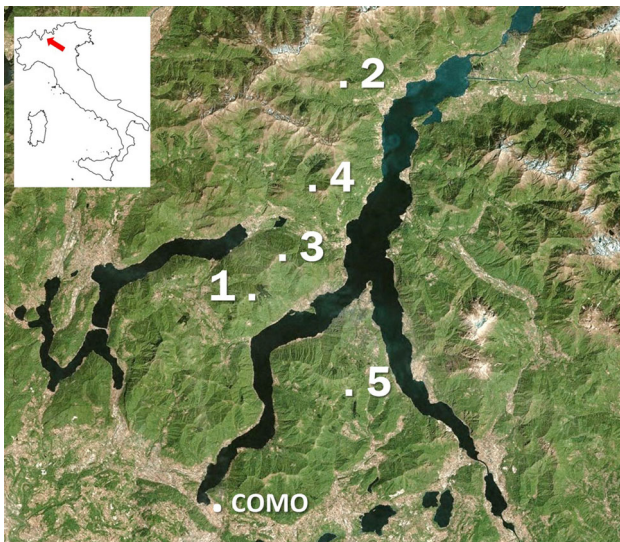
Fig. 1 Location of the test sites

Fig. 2 Typical configuration of a cable yarding operation (site 4, WT)

On each site, two adjacent and parallel cable corridors were set up, using the same base equipment and crew. The distance between the centres of the two corridors varied between 30 and 40 m. On one of the paired corridors, TL harvesting was applied: trees were motor-manually felled, topped and coarsely delimbed, then yarded as full length stems, and finally crosscut and stacked at the landing using a chainsaw and an excavator with a grapple saw. Minimum topping diameter was 10 cm for conifers and 5 cm for hardwoods. On the other corridor, WT harvesting was applied: trees were motor-manually felled, yarded whole and mechanically processed at the landing, using an excavator-based processor (Fig. 2). Paired corridors had

approximately the same length and removal intensity, as confirmed by a preliminary timber cruise. In any case, the stand types targeted by this study were very homogenous (even-aged monospecific plantations, or even-aged coppice), with minimum differentiation occurring within the compartments themselves. Corridor length varied between sites, ranging from 150 to 400 m. The mean corridor length was 270 m, with no significant differences between treatments. Product removal varied between 0.3 and 2 m^3 per metre of corridor, with small differences between treatments, but a clear stratification between conifer and broadleaf stands (0.46 and 1.52 m^3 per metre of corridor, respectively; $p = 0.01$).

Table 1 Description of the test sites

Site	#	1	2	3	4	5
Placename		Colonno	Gravedona	Ossuccio	Grandola	Lasnigo
Surface	ha	2.00	4.46	4.30	3.96	1.40
Altitude	m a.s.l.	1250	1300	1325	950	800
Slope gradient	%	48	50	42	60	70
Species		Spruce	Spruce	Beech	Beech	Mix h.wood
Management		Plantation	Plantation	Coppice	Coppice	Coppice
Treatment		Gap cut	Gap cut	Selection cut	Selection cut	Selection cut
Age	Years	60	51	50	50	30
Stocking	$m^3\ ha^{-1}$	428	173	238	165	156
Stocking	Trees ha^{-1}	800	425	785	600	578
Removal	$m^3\ ha^{-1}$	428	67	123	123	78
Removal	Trees ha^{-1}	800	251	567	450	382
Harvest intensity	% Volume	100	39	52	74	50
Harvest intensity	% Trees	100	59	72	75	66
Harvest tree	m^3	0.535	0.268	0.217	0.273	0.204

Spruce = Norway spruce, (*Picea abies* Karst.); beech = *Fagus sylvatica* L.; Mix h.wood = hornbeam (*Ostrya carpinifolia* Scop.) and Chestnut (*Castanea sativa* L.); stocking = pre-harvest inventory

Different machines and crews worked at different sites, although technology levels were quite similar (Table 2). In particular, felling (and the eventual processing) was performed with professional chainsaws in the 60 cm^3 engine displacement class; extraction was performed with medium-sized tower yarders, with a skyline capacity of approximately 600 m (all yarders were set up in a standing skyline configuration); landing work was conducted alternatively with light excavators in the 8-ton class (TL harvesting) or medium-sized excavators in the 18-ton class (WT harvesting), the former equipped with a grapple saw, the latter with a 50-cm capacity roller-type processor. All machines were operated by experienced professionals, who had run them for several years. The skills of study operators were considered representative of the region and were fairly similar between them.

For each of the 10 corridors (i.e. 5 sites × 2 corridors), the following data were recorded: biomass retention, product output, time and fuel inputs. Each corridor represented one repetition in the experiment, so that each treatment was replicated 5 times.

Biomass retention was determined on ten to fifteen 1 × 1 m sample plots per corridor, using an improved version of the protocol developed by the Australian Forest Operations Research Alliance at the University of the Sunshine Coast (Ghaffariyan et al. 2011). Before locating the plots, the sampled area was divided in two strata according to residual biomass load, in order to increase the accuracy of sampling and reduce the number of needed sample plots. After that, 50 sample plots per corridor were located systematically on the terrain, and each of them was attributed to one of the strata. From the original 50 plots, 20 plots were selected randomly, reflecting the proportion between the strata. All the residue available on each of the 20 selected plots was weighed, separately for its main components, and namely: (a) branches with a large-end diameter >3 cm, (b) branches with a large-end diameter between 1 and 3 cm, and (c) branches with a large-end diameter <1 cm, foliage and cones (the latter for conifers only). The total weight of the biomass found on each plot was entered in a dedicated calculator, which computed the variance for the plots in each stratum. Based on that, the calculator provided the additional number of plots to be sampled, in order to obtain the desired accuracy (15 % in this case). Furthermore, five 500-g samples per corridor and component were collected in order to determine moisture content with the gravimetric method, according to European standard CEN/TS 14774-2. That allowed estimating biomass retention as dry mass. Sample plots were located after harvest only, and therefore the estimated biomass loads included the biomass already on the forest floor before harvest.

Table 2 Machinery used for the tests and estimated machine cost figures

Sites		All	1	2, 4	3, 5	All, TL	All, WT
Machine	Type	Chainsaw	Yarder	Yarder	Yarder	Excavator	Excavator
	Make	Husqvarna	Greifenberg	Valentini	Konrad	Komatsu	Liebherr
	Model	562 XP	TG700	V600/1000	Endmast	PC75	A900C
	Carriage	–	CRG15	HSK2002	Woodliner	–	–
Attachment	Type	–	–	–	–	Grapple saw	Processor
	Make	–	–	–	–	Hultdins	Konrad
	Model	–	–	–	–	Supersaw	Woody 50
Investment	€	1000	150,000	300,000	160,000	90,000	220,000
Resale (20 %)	€	200	30,000	60,000	32,000	18,000	44,000
Service life	Years	2	10	10	10	10	10
Utilization	h year^{-1}	800	800	800	800	800	800
Interest rate	%	4	4	4	4	4	4
Depreciation	€ year^{-1}	400	12,000	24,000	12,800	7200	17,600
Interests	€ year^{-1}	32	3840	7680	4096	2304	5632
Insurance	€ year^{-1}	32	3840	7680	4096	2304	5632
Fuel	€ odt^{-1}	Estimated case by case based on the results in Table 3					
Lube	€ odt^{-1}	10 % of fuel cost					
Repairs	€ year^{-1}	400	6000	12,000	6400	3600	8800
Labour	€ odt^{-1}	Estimated case by case based on the results in Table 3					
Total	€ year^{-1}	864	25,680	51,360	27,392	15,408	37,664
Total	€ h^{-1}	1.1	32.1	64.2	34.2	19.3	47.1

The total cost in this table refers to investment and maintenance only, and it does not include fuel, lubricants, labour and 25 % overheads

Product output was determined by accumulating all the biomass extracted from each corridor in separate piles divided by assortment type, and then weighing the wood in each pile on a certified weighbridge (firewood and chips) or scaling it with calliper and measuring tape (timber). In all cases, 5 sample discs were collected from each pile, in order to determine wood density and moisture content—the latter with the gravimetric method, as above.

Time input was determined through time sheets, compiled daily by the foreman. Each daily record contained the hours and minutes worked by each crew member, separately for the following activities: stump-site work, extraction, landing-site work. Stump-site work included felling under the WT treatment, or felling, delimbing and topping under the TL treatment. Landing-site work included delimbing, topping, crosscutting and stacking under the WT treatment, or crosscutting and stacking under the TL treatment. The incidence of delays was determined through work sampling, conducted at random intervals along the study (Spinelli et al. 2013b). Mean load size was calculated by dividing the total amount of wood extracted during the study by the number of turns, as recorded on the time sheets.

Fuel input was determined by recording all fuel refills for each machine.

Machine costs were calculated with the harmonized method developed within the scope of European COST Action FP0902 (Ackerman et al. 2014). Data about utilization, maintenance and value recovery were obtained directly from the machine owners, and matched published figures (Spinelli et al. 2011a). These data were used to estimate investment cost and maintenance cost (Table 2), whereas labour, fuel and lubricant cost were obtained directly from the daily time sheets.

Product price was obtained from the local forester, and was equal to 55 € m^{-3} of timber, 70 € per fresh tonne of firewood and 32 € per fresh tonne of chipwood, before chipping. After accounting for moisture content (varying between 22 and 42 %) and wood density, prices converted into 128, 127 and 64 € per dry tonne, for timber, firewood and chipwood, respectively. These prices were valid for the wood stacked at landing, before transportation to the user plant.

Energy use was estimated as the sum of direct and indirect energy inputs. Direct energy inputs were calculated by multiplying the total weight of chainsaw fuel, diesel and lubricants by 55.3, 51.5 and 83.7 MJ kg^{-1} respectively (Spinelli and Magagnotti 2011). The indirect consumption represented by machine manufacturing, repair and maintenance was estimated as 30 % of direct energy use (Mikkola and Ahokas 2010). The energy input derived from manual labour was estimated at 1.8 MJ h^{-1} (Christie 2008). Energy output was estimated as 19 and 20 MJ per

kg of dry matter for broadleaf and conifer trees, respectively (Spinelli et al. 2011b).

Data were analysed with the Statview advanced statistics software (SAS 1999). Differences between treatments (i.e. harvesting methods) were tested with the Wilcoxon signed rank test, which is a robust nonparametric test designed for conducting paired comparisons when the distribution of data does not meet the normality assumption. However, the per cent distribution data for the logging residue components (i.e. branches >3 cm, branches 1–3 cm etc.) were normalized using the logit transformation and then tested with a standard analysis of variance for checking the significance of any differences between treatments, as indicated by the interaction factor "component x treatment" (Eliasson et al. 2015). A different and simpler approach was adopted for the distribution of different product assortments. In that case, the significance of any differences between the distributions recorded for different methods at the same sites was tested with the Pearson's Chi-Square (χ^2) test. In all analyses, the elected significance level was $\alpha < 0.05$.

Overall, the test covered 16.12 ha, which yielded 1075 tonnes of dry wood. Harvesting such a large amount of biomass required 2793 man hours, 3172 L of diesel fuel and 329 L of petrol mix. Work sampling sessions covered a total of 106 worksite hours.

Results

Post-harvest biomass retention varied between 20 and 90 tonnes of dry matter per hectare, depending on site and treatment (Fig. 3). There were no differences between conifer and broadleaf sites. In contrast, there was a clear stratification between sites with lower removals (i.e. sites 2 and 5) and sites with larger removals (i.e. sites 1, 3 and 4), and between harvest methods. As an average, adoption of the TL method resulted in a 66 % increase in biomass retention. To say it another way, WT harvesting removed 40 % of the residues that would be left on site if the TL method had been adopted. This difference was significant for $p = 0.04$. Of course, the exact differences between the two methods varied with stand type and were lower in broadleaf stands, where topping diameter was smaller because large branches were converted into firewood. In those cases, large branches were left attached to the stem and taken to the landing, regardless of harvesting method.

On an average, half of the residue mass left on site consisted of branches with a butt diameter larger than 3 cm. The rest was equally distributed between branches with a diameter between 1 and 3 cm, and smaller branches, foliage and cones. The component breakdown of harvesting residues differed remarkably between sites, but no
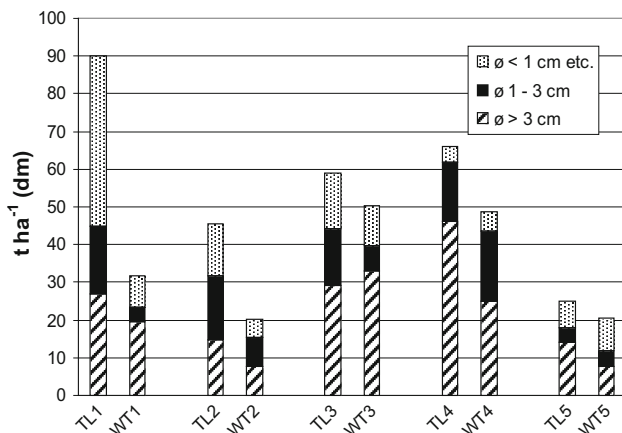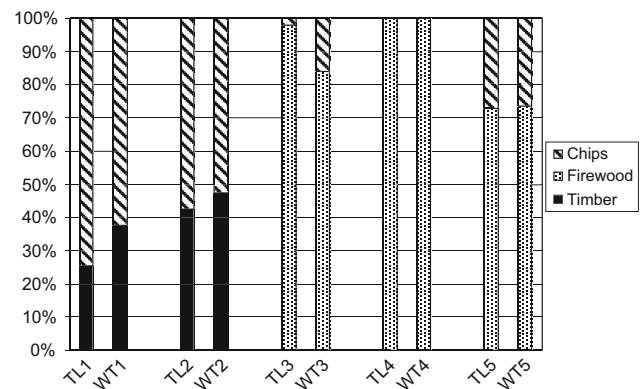
Fig. 3 Biomass retention by site, harvesting method and biomass component. *Note* the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.); Ø butt diameter, *dm* dry matter

significant trends could be detected. Harvesting method had no effect on component breakdown ($DF = 30$, ANOVA $p > 0.05$).

Biomass retention trends were mirrored by biomass removals that were significantly lower for TL harvesting, compared with WT harvesting (Table 3). WT harvesting allowed an average increase in biomass recovery of 23 %, and this difference was statistically significant ($p = 0.04$). Product characteristics varied with stand type. Both conifer stands yielded a variable mix of timber and wood chips, the latter representing always more than 50 % of the total harvest (Fig. 4). Contrary to expectations, the proportion of timber was higher under the WT treatment, but this trend was deprived of statistical significance ($n = 30$, $\chi^2 = 3.309$, $p = 0.07$). Firewood represented between 75 and 100 % of the harvest obtained from hardwood stands. The rest consisted of wood chips. No timber was obtained from these stands, and harvesting method choice had no visible effect on product breakdown.

Total time consumption varied between 1.51 and 3.58 worker hours per dry tonne (Fig. 5). Mean values were 2.27 and 2.98 worker hours per tonne dry matter for WT and TL harvesting, respectively. Therefore, shifting from WT harvesting to TL harvesting resulted in an average increase in total time consumption of 31 %, and this difference was statistically significant (Table 3). In particular, TL harvesting required 63 % more stump-site work, 27 % more extraction work and 1 % less landing-site work, compared with WT harvesting. However, only the stump-site work time difference was statistically significant. In contrast, the recorded extraction time difference can be suggestive of the higher extraction efficiency of WT harvesting, but offers no conclusive evidence for it. In any case, extraction was the most time-consuming activity,

Fig. 4 Product assortment breakdown by site and harvesting method. *Note* the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.)
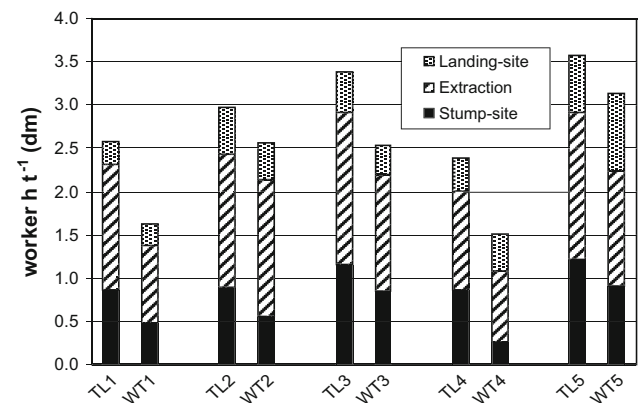
Fig. 5 Time consumption per unit product by site, harvesting method and activity. *Note* the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.)

requiring between 42 and 62 % of the total work time per unit product. Yarder set up and dismantle took between 11 and 26 % (mean = 20 %) of total extraction time, with no clear differences between treatments. Yarder load varied from 0.3 to 0.6 tonnes dry matter per turn and was 30 % larger for the WT treatment. This difference was statistically significant (Table 2).

Fuel use was higher for TL harvesting compared to WT harvesting, but the difference was statistically significant for petrol mix (i.e. chainsaw fuel) only, not for diesel fuel. TL harvesting showed a significantly higher energy consumption (+14 %) per unit product and a significantly less favourable energy balance (−20 %), compared with WT harvesting. In both cases, the energy output–input ratio was very high and larger than 100 (Table 3).

Total harvesting cost varied from 55 to 125 € t^{-1} dry matter (Fig. 6), with large variations between sites and

treatments. Average harvesting cost was 94 and 106 € t^{-1} dry matter for WT and TL harvesting, respectively (Table 3). Favouring TL over WT harvesting incurred a 13 % cost increase, but the difference lacked statistical significance. This may derive from the confounding effect of the test conducted at Site 5, where WT harvesting did result in a higher cost compared with TL harvesting. In any case, fuel cost represented a very small proportion of total cost, varying from 3 to 6 %. As an average, capital cost represented 44 and 51 % of TL and WT harvesting cost, respectively. Conversely, labour cost represented 52 and 45 % of TL and WT harvesting cost, respectively. These differences between harvesting methods were statistically significant.

Harvesting revenues varied between 80 and 127 € t^{-1} dry matter, with an average value of 107 € t^{-1} dry matter (Table 3). Profits ranged from −40 to 41 € per dry tonne (Fig. 7). Losses were incurred on the two sites with the smallest removals (i.e. sites 2 and 5). Harvesting method had a no impact on revenues and a relatively small impact on profits. In neither case was the effect of harvesting method significant.

Discussion

Many papers already contain detailed figures for biomass retention under different operational scenarios (Thiffault et al. 2014; Kizha and Han 2015). However, very few of them offer comprehensive information about the effect of variable retention levels on operational planning and financial viability. This study fills the gap by determining both the biomass retention effects and the financial performance of alternative harvesting practices. In essence, it
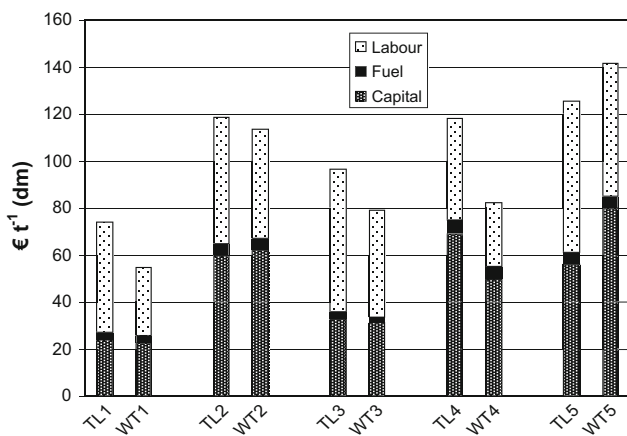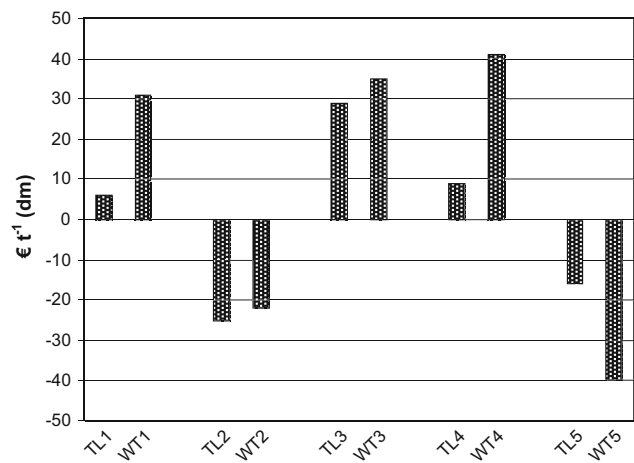
Fig. 7 Harvesting profit by site and harvesting method. *Note* the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.)

attaches a price tag to increased biomass retention, which is essential to making informed management decisions. To our knowledge, no paper has yet produced such information for mountain operations, where profit margins are especially thin.

The residue loads reported in this study are compatible with those reported in previous studies, which vary from 4 (Hytönen and Moilanen 2014) to 140 (Cormier et al. 2012) t ha^{-1} dry matter. The data in this study are most often within the 20–50 t ha^{-1} dry matter range, where the majority of the bibliography data tend to group as well (Thiffault et al. 2014). The very high residue loads recorded at Site 1 match those recorded for similar fast-growing conifer plantations established with spruce or pine, which amounted to 170 t ha^{-1} (Cuchet et al. 2004) and 238 t ha^{-1} (Smethhurst and Nambiar 1990), respectively. Assuming a moisture content of 50 %, these figures would convert to 85 t ha^{-1} dry matter for spruce and 119 t ha^{-1} dry matter for pine, which are very near to the 90 t ha^{-1} dry matter recorded at Site 1 for spruce.

Unfortunately, the boundary between paired corridors was difficult to identify with certainty at the end of the harvest, as already happened in previous similar studies (Kizha and Han 2015). For this reason, it was decided not to include the exact surface covered by each treatment in the data collection, because small errors might have been magnified during data processing, leading to uncertain results. As a consequence, differences in biomass retention could not be matched exactly with differences in removals, although the study findings are quite consistent, as they indicate increased retention where removals were lighter.

In that regard, the only apparent inconsistency is conifer product breakdown. One would expect the adoption of WT

Fig. 6 Total harvesting cost per unit product by site, harvesting method and production factor. *Note* the X axis reports harvesting type and site number (i.e. TL1 = tree length, site 1; WT1 = whole tree, site 1; TL2 = tree length, site 2 etc.)

harvesting to shift the product mix towards an increased proportion of chips, as additional branch material is recovered from the site (Spinelli et al. 2014). In fact, the contrary occurred: relative timber yield increased when WT harvesting was applied. That was observed systematically on both conifer sites, which makes coincidence unlikely. The logical explanation is the better value recovery normally achieved with improved work conditions (Murphy et al. 2014). Under the TL harvesting treatment, trees were topped at the stump site, under unfavourable conditions that could motivate quick and imprecise work. In contrast, WT harvesting moved these activities to the landing, where improved job quality would derive from better work conditions and closer supervision (Chung et al. 2014). Of course, salvaging timber material from the chip wood pile may cause a reduction of chip quality and price, which may reflect on total revenue (Spinelli and Magagnotti 2010). However, price effects were not investigated in the study. At any rate, it is unlikely that eventual reductions in chip price may completely offset the value gains obtained from recovering additional timber products, for as low as their grade might be.

It is no surprise that the less mechanized TL harvesting resulted in a higher labour input per unit product. Here, all indicators were consistent: higher time consumption for stump-site work that becomes more complex; lower load size, as a result of trimming out part of the tree before extraction; possibly lower extraction productivity,

which is consistent with the lower load size (although this result is not conclusive); significant increase in total time consumption per unit product, deriving from all the above. Previous studies have indicated that opting out of WT harvesting has the very same consequences, which corroborates our results (Adebayo et al. 2007; Bisson et al. 2013). Decreased work efficiency leads to a harvesting cost increase, which the study quantified at 13 % or 12 € t^{-1} dry matter. Unfortunately, this difference did not pass the assumed significance level, and therefore such information must be considered suggestive, rather than conclusive. However, all indicators point in the same direction and a previous study offers strong corroboration by indicating a very similar harvesting cost increase (12 %) when shifting from WT to TL harvesting in ground-based operations (Putnam 1983). As a matter of fact, the eventual cost increase is relatively small and it may have struggled to emerge over the background noise generated by a study that was conducted under a wide variety of conditions. The relatively small cost gap between the two methods hints at similar variations in capital and labour costs, where the lower labour cost incurred by WT harvesting is almost completely offset by increased capital cost. In that regard, readers must be aware that the TL harvesting as applied in this study was already mechanized through the introduction of a grapple saw, and therefore the study was not comparing a fully mechanized system with a fully motor-manual one. In

Table 3 Comparison between TL and WT harvesting: summary data ($n = 10$)

		Mean			Median			WSR
		TL	WT	Δ (%)	TL	WT	Δ (%)	*p* value
Removal	t (dm) corridor^{-1}	96.5	118.5	−19	91.4	121.7	−25	***0.04***
Corridor length	m	261	280	−7	275	250	10	**>0.99**
Stump-site work	Worker hours t^{-1} (dm)	0.999	0.613	63	0.896	0.552	62	***0.04***
Extraction work	Worker hours t^{-1} (dm)	1.517	1.194	27	1.536	1.331	15	0.08
Landing work	Worker hours t^{-1} (dm)	0.464	0.468	−1	0.456	0.421	8	0.89
Total work	Worker hours t^{-1} (dm)	2.980	2.274	31	2.971	2.534	17	***0.04***
Petrol mix	L t^{-1} (dm)	0.373	0.244	53	0.362	0.244	48	***0.04***
Diesel	L t^{-1} (dm)	3.040	2.753	10	3.485	3.429	2	0.14
Yarder load	t (dm) turn^{-1}	0.380	0.549	−31	0.380	0.596	−36	***0.04***
Energy cost	MJ t^{-1} (dm)	209.2	183.6	14	231.3	222.5	4	***0.04***
Energy balance	Output Input^{-1}	105.4	131.0	−20	82.1	85.4	−4	***0.04***
Harvesting cost	€ t^{-1} (dm)	106.5	94.2	13	118.0	82.3	43	0.14
Product value	€ t^{-1} (dm)	107.4	107.8	0	110.0	110.5	0	0.50
Profit	€ t^{-1} (dm)	0.9	13.6	−93	6.5	30.8	−79	0.35

Wilcoxon signed rank test for the null hypothesis of no difference between TL and WT (null hypothesis is rejected if $p < 0.05$)

dm Dry matter, *TL* tree-length harvesting, *WT* whole-tree harvesting, *Δ* increment of TL over WT, *WSR p* *p* value obtained from the nonparametric

Bolditalic indicates statistically significant values i.e. $p < 0.05$

contrast, the goal was to check the performance of two state-of-the-art systems, each designed to achieve a different goal, i.e. increasing biomass retention or minimizing harvesting cost.

Similar considerations can be made for the revenues and the profits recorded in the study. These were quite variable and two operations actually incurred losses. Except for Site 5, WT harvesting performed better than TL harvesting, but it offered incremental benefits only, and could not change the main trend. It seems that the main drivers of operation profitability are others. This study suggests that removal is a stronger driver than harvesting method, which would be consistent with a harvesting technique (cable yarding) that is especially sensitive to removal intensity.

Conclusions

Under the conditions of cable operations, opting for TL harvesting over WT harvesting allows a large and significant increase in biomass retention, which may prove attractive where intensified biomass removal may jeopardize soil fertility and biodiversity. If properly applied, TL harvesting is likely to result in a moderate increase in total harvesting cost. However, the profit margins of cable operations are quite small and reducing them may drive management outside the limits of financial viability. Furthermore, TL harvesting requires 30 % more labour input than WT. That will make it especially attractive where employment opportunities are scarce, even if the sad reality of industrialized countries is that forest labour is scarce and local entrepreneurs generally need to increase the productivity of the little labour they have, not to reduce it (Allred 2009; Goldstein et al. 2005). Finally, it is worth noticing that the increased labour use in TL harvesting occurs mainly at the stump site, where accident risk is highest (Potočnik et al. 2009). For all these reasons, managers should take their decision very carefully. Ultimately, this study is about a management choice and its consequences: it offers managers solid elements to base their decisions, but these decisions will have to be made case by case depending on the specific conditions encountered at the time.

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