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Evaluation of Different Modes for Yarding Windthrown Timber with a Double-Hitch Carriage

Raffaele Spinelli, Karl Stampfer, Natascia Magagnotti, Giulio Cosola, Fabio De Francesco, Gernot Erber, Matevž Mihelič

Abstract

Yarding whole trees is the most efficient way of extracting timber in steep terrain and allows reaping the combined benefits of mechanization and biomass recovery. In downhill yarding, however, whole-tree extraction is associated with a greater risk of loosening rocks or debris by the incoming loads as they bounce around along the extraction corridor. That may also cause damage to the cables and anchors by corresponding shock loads, ultimately endangering the yarder and its crew. To avoid these risks, »double-hitch carriages« can be employed. They combine a conventional motorized dropline carriage with a secondary carriage (»trailer«), equipped with a further, independent dropline winch. Thus, loads can be attached at two points and transported fully suspended above the ground in a horizontal position.

Operation of these carriages may not be limited to the »horizontal« mode: the main carriage could also be operated without trailer (»single« mode), or separate loads may be attached to the two droplines (»double« mode), but their impact on the efficiency and economy of yarding operations is yet unknown. Therefore, the present study investigated how these modes affect the productivity and cost of downhill whole tree yarding. To this end, a classic time and motion study was conducted during a salvage logging operation in Northern Italy under a strictly controlled experimental design.

Average productivity (18.2±7.2 to 24.5±15.4 m^3 PSH_0^{-1} merchantable volume per productive system hour excluding delays) and extraction cost (18 to 20 Euro m^{-3}) did not differ significantly between treatments, while load composition and time consumption by task did. More (2.2±0.5) pieces per load were yarded under the »double«, than under the »single« (1.4±0.5) and »horizontal« (1.1±0.3) treatments. Inhaul speed (3.1±0.6 m s^{-1}) was significantly higher under the »horizontal« treatment, which compensated for increased loading time derived from attaching the load at least at one point outside the corridor. Unloading took significantly longer under the »double« treatment, as loads had to be dropped successively due to the confined conditions on the landing. Though slowest (2.5±0.9 m s^{-1}) during inhaul, the »single« treatment exhibited none of the other treatments disadvantages and larger loads could be accumulated due to partial suspension. From an economic viewpoint, the »horizontal« mode may only be warranted over yarding distances substantially beyond average. On shorter ones, it must be justified by other reasons, such as minimizing product contamination, soil disturbance or excessive strain to the skyline when the terrain profile impedes sufficient ground clearance.

Keywords: harvesting, logging, steep terrain, carriage, horizontal yarding, safety, efficiency

1. Introduction

Cable logging is very popular in the European Alps, where rugged terrain often prevents efficient ground-based operations (Bont and Heinimann 2012, Enache et al. 2016). In such instance, cable logging avoids building a dense network of skidding trails, with all the associated cost and impact (Spinelli et al. 2010). The mechanization of cable logging operations often takes the form of a processor, stationed at the landing for the fast and safe production of merchantable logs (Spinelli et al. 2012). This is a very effective harvesting solution, which has rapidly gained favour among mountain loggers. The widespread popularity of processors and the establishment of a viable market for forest biomass have pushed many contractors to adopt whole-tree extraction, so as to reap the combined benefits of mechanization and biomass recovery (Valente et al. 2011). As a result, yarders are now moving much longer and bulkier loads than they did before, when the shortwood system was dominant. Such longer loads require higher ground clearance and have a greater tendency to swing during extraction, compared with traditional shortwood loads (Ghaffariyan et al. 2009, Tsioras et al. 2011). The issue is especially critical with downhill yarding, when the load can strike the ground or suddenly drop, generating a shock-load that may damage the cables and/or the anchors (Jorgensen et al. 1978). Tying the load at two points and holding it horizontally is a good way to increase ground clearance and limit swinging, and this technique is commonly practiced in civil engineering, where cableways are used to move building materials to locations that cannot be reached otherwise, as when building bridges, dams or pipelines.

In fact, the use of double-hitch carriages in forest operations was documented in the late 1960s (Giordano 1967, Drăgan et al. 1971), but these earlier »load beam« carriages were not suited for lateral yarding and could not be applied in selection cuts (FAO 1981). Recently, newer carriage models have appeared that have both full suspension and lateral yarding capabilities (Varch et al. 2021). That is achieved with the use of hydraulically powered motorized dropline winches, which were not available before. These new carriages consist of two components: a main body and a detachable secondary carriage (»trailer«), connected by an adjustable spacer bar. The main carriage body contains the diesel engine, the hydraulic pump and reservoir and a hydraulic winch, while the detachable secondary carriage contains another hydraulic winch powered by the same pump installed in the main body. Basically, the whole device is just a conventional motorized dropline carriage fitted with an optional add-on secondary carriage, which can be easily reconverted to the single-hitch mode by removing the latter, when horizontal full suspension is not necessary. The few studies available on the subject indicate that horizontal double-hitch suspension results in a significant reduction of both skyline cyclic loading (oscillation) and the occurrence of shock-loads (Spinelli et al. 2021a). In turn, the reduction of cyclic loading may allow for a faster inhaul speed (+15%), while the availability of two independent winches supports the accumulation of larger loads (+12%) (Spinelli et al. 2021b). Further, horizontal double-hitch yarding offers obvious advantages with regard to clearance and this type of carriages is particularly suitable for yarding in sensitive areas (Varch et al. 2021) or on flat terrain (Erber and Spinelli 2020).

In these early studies, the new motorized dropline carriages have been compared with conventional self-clamping models, which use the mainline to lift the loads and the haulback line for pulling slack out of the mainline when loading. This is a logical first step, where the innovative product is matched against the traditional one (control), but such comparison may only show the combined effects of yarding mode and carriage design. In order to focus on the specific effects

a) single-hitch (»single«)

b) double-hitch (»double«)

c) horizontal double-hitch (»horizontal«)

Fig. 1 Three yarding modes applicable with a double hitch carriage

of yarding mode, the same motorized dropline carriage should be tested with and without the add-on secondary carriage. In that case, the possibility of using the two winches to attach independent loads could also be explored, as normally done with the double-drum winches installed on skidders (Zečić et al. 2011). Therefore, there are three different yarding modes in which a double-hitch carriage can be operated, namely single-hitch (one dropline only), double-hitch (two droplines connecting separate loads) and horizontal double-hitch (two droplines connecting the same load with the purpose of holding it horizontal) (Fig. 1).

Accordingly, the goal of this study was to compare the productivity and cost achieved with the three yarding modes, applicable with the same motorized dropline carriage. The corresponding null hypothesis was that of no significant differences in load size, time consumption, productivity and cost between the three alternatives.

2. Materials and Methods

The study was conducted in a mixed fir-spruce-beech (*Abies alba* L., *Picea abies* Karst., *Fagus sylvatica* L.) stand in the Eastern Italian Alps, near Forni Avoltri (46°34′45.7″ N, 12°47′12.5″ E) in the Province of Udine. The stand grew over a steep detrital slope on a southwest face and in its lower part bordered with a service road, leading to a high mountain farm. The stand originated from natural regeneration and was over 100 years old. The forest management plan prescribed a shelterwood system based on regular selection cuts performed at 20 to 30-year intervals. Unfortunately, the stand was hardly hit by the catastrophic windthrow event of October 2018 that affected 42,000 ha and blew down over 8 million m^3 in one night (Motta et al. 2018). The storm wrecked the forest estate of 500 municipalities spread over three regions in northeastern Italy (Chirici et al. 2019). Salvage operations started almost immediately and within the first year from the event, between 70 and 80% of the volumes targeted for salvage had already been harvested (AA.VV. 2020). By the time of this study, only the least accessible sites had been left, which could not be reached with ground-based equipment and had to be salvaged with cable yarders.

In particular, the study site was located inside compartment n° 26 of the Forest Management Plan drafted by the Forni Avoltri Municipality (PEFC certified). The harvesting plan for compartment n° 26 had been approved by the Regional Forest Service Office on December 7, 2018, right after the storm and provided for the installation of six cable yarding corridors. The study itself was conducted on corridor n° 3 during June 2021.

The operation selected for the study used a Valentini V600/M3/1000 trailer-mounted tower yarder – a popular model among Alpine loggers in Austria, Germany and Italy with over 50 units sold. The machine had a maximum skyline capacity of 1000 m (22 mm cable) and was equipped with three hydraulically powered working drums, for the skyline, mainline and haulback line (22 mm, 11 mm and 11 mm, respectively). All cables were wire rope core, swaged, ordinary lay. The mainline and haulback drums were fitted with a hydraulic interlock. Additional drums were available for the strawline and the guylines. The machine was fitted with its own 175 kW diesel engine, and its telescopic tower was fully extended (12.5 m) during the study.

The carriage was a SEIK Skytiger ST 30 motorized (Kubota 33 kW) dropline model, coupled with the dedicated SEIK Skytiger NL 30 secondary carriage. Both the primary and the secondary carriage were fitted with a 3 t capacity winch, powered by the diesel engine of the primary carriage through a hydraulic transmission. Weight was 790 kg and 330 kg for the primary and the secondary carriage, respectively. The carriage had an emergency brake but no clamps, and during loading it was held in place by the mainline and the haulback line.

The tower was stationed by the service road at the lower end of the compartment and the yarder was set up in a standing skyline configuration designed for downhill yarding, with a haulback line to bring up the unloaded carriage and to control its descent once loaded, and a mainline for pulling the loaded carriage down (Studier and Binkley 1974). Total skyline length (tower tip to tailhold block) was 348 m. The horizontal and vertical distance to the tailhold was 301 m and 174 m, respectively. The line offered good clearance and did not require any intermediate supports. It was set at a 30° angle with the maximum slope, so that any debris eventually released by the moving loads would not come straight at the processor and the tower.

The harvesting system was manned by a crew of four: three at the loading site (two fellers, one choker setter) and one at the unloading site (machine operator). The operators at the loading site were tasked with preparing the loads and connecting them to the dropline(s) using radio-controlled chokers. Load preparation consisted in separating windthrown trees from their root plates and crosscutting the stems that were too heavy or too entangled for the dropline(s) to break out. The operator at the unloading site sat inside the cab of a 22 t Komatsu PC 210 excavator fitted with a

Konrad Woody 61H four-wheel-drive processor that cut the incoming trees and tree sections into commercial assortments. Use of radio-controlled chokers allowed this operator to release the loads without dismounting from his machine cab (Dyson 2016, Stampfer et al. 2010). Both the processor operator and the choker setter could operate the yarder drums and carriage using a remote control. The remote controls were mutually exclusive, so that operators could not interfere with the carriage movements when the carriage was outside their own defined work zones. All operators were experienced and possessed the proper formal qualifications according to the regional certification scheme.

The study method aimed at determining, on a cycle basis: extraction distance, load size and time consumption. Distance between the tower and the loading point (carriage stop on the skyline) was measured with a Bushnell Yardage Pro 500 laser range finder. Since it was not always possible (or safe) to get a viable distance reading, distance was also measured at 30 m intervals along the line before commencing work, and distance markers were painted on nearby trees or other terrain features. Lateral yarding distance was not measured, since the extraction corridors were quite close to each other and the trees had been blown perpendicular to the slope, so that almost all trees would intercept the projection of the skyline at some point. Therefore, the yarder picked up its loads directly under the line or just a few meters to the sides and it was decided to include the eventual minor variations in lateral distance as part of the random variability.

Load size was obtained by scaling every single log produced from each turn, using a calliper and a measuring tape. Diameter was taken at mid-length. The species of each log was identified and recorded. The mass of the residues (branches, tops and off-cuts) was estimated by visually attributing two branch loading indexes to each tree or tree section as follows: a score between 0 and 4 was attributed based on the total length of the stem covered with branches (0 – no branches; 1 – branches observed on one quarter of the total length; 2 – branches observed on half of the total length, etc.) and an additional score between 0 and 4 was attributed based on the proportion of the total circumference covered with branches, according to the same principle. The factorial combinations of the two weights yielded the following possible scores: 0, 1, 2, 3, 4, 6, 8, 9, 12, 16. The results of all observations were analyzed, and the mode was extracted. The baseline biomass expansion factor (BEF) was attributed as reported in bibliography for windthrown spruce in the Eastern Italian Alps, equal to 0.14 m^3 (solid equivalent) of biomass per m^3 of commercial timber volume (Spinelli et al. 2006). This baseline value was then corrected by the ratio between the actual combination score for each tree or tree section and the score mode.

Time was recorded with the time-and-motion technique, separated by the following tasks: unloaded carriage trip (outhaul); lowering the dropline; connecting the chokers to the load; breaking out the load and dragging it under the skyline; lifting the load under the carriage; travel loaded (inhaul); unloading; downtime – split into mechanical, operational and personnel delays (Magagnotti et al. 2013). Eventually, the separate work steps constituting the loading task were merged into a single element, since separation did not add much informative value to the study. Time data was physically collected using a ruggedized notebook with the dedicated time study software UMT Laubrass.

For machine cost estimation, the method developed by European COST Action FP0902 (Ackerman et al. 2014) was used. Required input data, such as machine purchase price, service life estimates or the costs of fuel, insurance, repair and service were obtained directly from the machine owner (Table 1). For labour cost, a

Table 1 Cost estimates for tower yarder, both carriage options and a crew of four. Costing assumptions were provided by machine owner

Operation	Unit	Single carriage	Double carriage
Investment	€	640,000	660,000
Resale	€	192,000	198,000
Service life	Years	8	8
Utilization	h $year^{-1}$	1000	1000
Interest rate	%	4	4
Depreciation	€ $year^{-1}$	56,000	57,750
Interests	€ $year^{-1}$	17,760	18,315
Insurance	€ $year^{-1}$	2500	2500
Diesel	€ $year^{-1}$	27,600	27,600
Lube	€ $year^{-1}$	4140	4140
Repairs	€ $year^{-1}$	28,000	28,875
Total	€ h^{-1}	136	139
Crew	n°	4	4
Labour	€ h^{-1}	80	80
Overheads	€ h^{-1}	54	55
Total rate	€ h^{-1}	270	274

Note: The cost includes the yarder, the carriage, and the processor with the whole crew (4 operators) and accounts for all work needed to convert windthrown trees laying in the forest as they were blown down, into cut-to-length assortments stacked at the roadside landing, to the exclusion of yarder set up and dismantle. Costing assumptions were provided by the machine owner. The »double carriage« option is also valid for the »horizontal« treatment rate of 20 € per person per scheduled hour, inclusive of indirect salary costs, was adopted. To account for overhead costs, the calculated cost of all operations was increased by 25% (Hartsough 2003). Further detail on cost calculations is shown in Table 1. Actual machine rates may differ from our calculated rates, based on local market conditions (Spinelli et al. 2015).

The experimental design consisted of randomly alternating the three treatments on the same line as the work advanced. To that purpose, 5 tokens per treatment were placed in a bag and randomly extracted by the researcher at the beginning of each cycle to select the treatment to apply in that given cycle: if the token read »single«, only the dropline on the main carriage was used; if it read »double« both droplines were used for connecting separate loads; if it read »horizontal« both droplines were connected to the same load to lift it horizontally and fully suspended. Once the bag was empty, the tokens were replaced, and the extraction process started anew. This was done for three days, starting near the roadside right after the line had been installed, and ending when all the line was cleared, and the tail spar had been reached. Overall, the study included 101 valid cycles (a few more were excluded due to missing data elements).

Data were analyzed statistically using the Minitab 17 software. Descriptive statistics were obtained, separately for each work activity and carriage treatment. The individual turn was assumed as the observational unit. The significance of the differences between mean values for different treatments was tested using a general linear model (GLM), which is both accurate and robust against violations of the main statistical assumptions. Furthermore, regression analysis was used to test the effect of extraction distance, tree volume and treatment type on time consumption. For the development of a model for estimating yarding time consumption, an approach employed before by Nurminen et al. (2006) in modelling time consumption of fully mechanized harvesting systems was chosen: firstly, separate models were developed for outhaul, loading, inhaul and unloading; then, those models were combined to estimate complete cycle time (excluding delays). These models were enhanced by a model for estimating load size and then combined into an overall productivity model. For all analyses, the significance level was set at $\alpha<0.05$. Eventually, the results of the GLM and regression analyses were blended into a simple calculator, used to search for a possible break-even distance between alternative work technique options.

3. Results

During the observation period, 101 complete cycles were recorded. The study lasted for a total of 14.4 productive system hours (PSH), or 16.0 scheduled hours. Delays accounted for 10% of scheduled time, thus adding 11% to productive time. During the test, the

Table 2 Main study results by treatment

Treatment		Single, n°=35		Double, n°=33		Horizontal, n°=33	
Parameter	Unit	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Distance	m	207^a	72	210^a	71	195^a	72
Pieces	n	1.4^a	0.5	2.2^b	0.5	1.1^a	0.3
Load	m^3 merch	3.023^a	1.682	2.797^a	1.107	2.668^a	1.119
Load	m^3 total	3.353^a	1.866	3.062^a	1.219	2.978^a	1.296
Piece volume	m^3 merch	2.641^a	1.858	1.356^b	0.615	2.525^a	1.210
Biomass share	%	9.8^a	6	8.6^a	5.8	9.9^a	5.4
Net cycle	s	478^a	161	526^{ab}	136	536^b	108
Loading	s cycle^{-1}	260^a	118	294^{ab}	133	347^b	99
Unloading	s cycle^{-1}	57^a	23	83^b	35	68^{ab}	15
Outhaul speed	m s^{-1}	3.6^a	0.8	3.3^a	0.8	3.8^a	1.4
Inhaul speed	m s^{-1}	2.5^a	0.9	2.7^{ab}	0.8	3.1^b	0.6
Productivity	m^3 merch PSH$_0^{-1}$	24.5^a	15.4	19.6^a	7.8	18.2^a	7.2

Note: n° – number of observations; different superscript letters on mean values on the same line indicate a statistically significant difference between means

m^3 merch – m^3 solid volume over bark for the merchantable log portion, only

m^3 total – m^3 solid volume over bark for the merchantable log portion and the biomass portion as well (solid volume equivalent)

PSH$_0$ – Productive System Hour, excluding delays yarder extracted 286 m^3 of timber (commercial volume over bark) and 30 m^3 of biomass material (solid volume equivalent). The number of observations and the average extraction distance (the site factor with the strongest potential effect on net cycle time) were almost the same for the three treatments on test, due to the great care devoted to regularly and randomly alternating the three treatments for the whole duration of the study (Table 2).

Extraction distance ranged between 70 and 350 m, with a grand mean around 200 m, while cycle time ranged between 240 and 900 s (4 to 15 minutes), with a grand mean at 512 s (slightly more than 8 minutes). The mean cycle time for the »horizontal« treatment was 12% longer than for the »single« treatment, and the difference was statistically significant. Such difference was mostly related to the longer loading time experienced under the »horizontal« treatment, which exceeded the loading time under the »single« treatment by 1/3, as an average. In contrast, mean unloading time was 26 s (45%) longer under the »double« treatment than under the »single« treatment and this difference was also significant (Table 2, Fig. 2).

Load size commonly varied (interquartile range) from 1.2 to 4.5 m^3 merchantable volume over bark, or from 1.3 to 4.9 m^3 total volume over bark, including biomass. Mean values were 2.7, 2.8 and 3.1 m^3 merchantable volume over bark, respectively, for the horizontal, double and single treatments. Mean load volume did not differ significantly between treatments, but the number of pieces did. Overall, the yarder moved between 1 and 3 pieces per cycle, whether whole trees, tree lengths, tree sections or tops. Given that piece number is a discrete variable rather than a continuous one, the comparison between treatments was conducted using a Chi-Square test, which confirmed a statistically significant difference in the distribution of the observations among the three treatments ($\chi^2 = 11.6$; $p = 0.003$). Two- and three-piece loads accounted for the largest proportion of work cycles under the »double« treatment, while one-piece loads were dominant under the »single« and the »horizontal« treatment (Fig. 3), and this difference was significant. Given that total load volume was the same for all treatments, it seems that the workers used the availability of a second dropline to deal with smaller elements, in order to accumulate a large enough load even when piece size was inadequate, thus offsetting the small piece constraint through mass handling. Correspondingly, average piece volume was significantly lower under the »double treatment«, while it did not differ between »single« and »horizontal« treatments (Table 2).

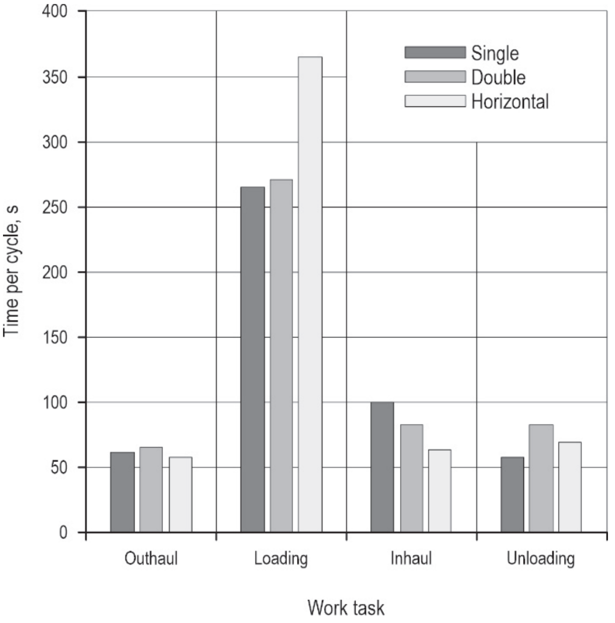

Fig. 2 Comparison of duration of main work tasks by treatment

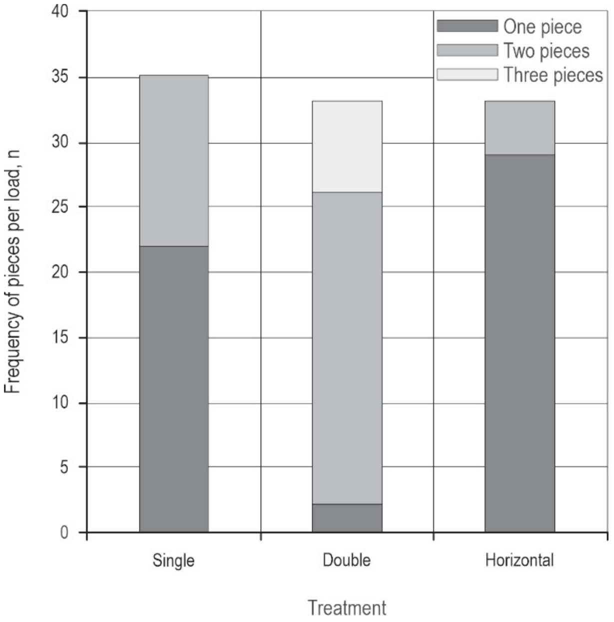

Fig. 3 Frequency distribution of number of pieces per load by treatment

Regression analysis also found significant relationships between outhaul, loading, inhaul and unloading time and independent variables such as yarding distance, piece volume and treatment type, as well as between load volume, piece volume and treatment type. Considering the specific constraints of windthrown salvage operations, where the chaotic arrangement of the loads and the dense presence of all kinds of obstacles prevent a more regular workflow, all models represented quite well the actual point clouds and could thus be combined into a corresponding productivity model (Table 3, Fig. 4).

Over 65% of the variability in outhaul time could be explained by yarding distance. Logically, treatment type had no effect on outhaul time, since any functional differences between the treatments are effective during loading, inhaul and unloading, but not when the empty carriage is moving out from the tower and towards the loading position (which is the definition of outhaul).

In contrast, the work task »inhaul« consists of pulling the carriage back to the tower with a full load, connected in different ways depending on treatment type. Accordingly, one may expect that the duration of the inhaul trip is related to the distance travelled, a load size parameter and the way in which the load is connected to the carriage itself. Regression analysis combined all these relationships in a multi-factor model that quantified them and confirmed their statistical significance. Coefficients went in the expected direction, whereby time increased with distance and piece volume, and decreased for the »horizontal« treatment with increasing yarding distance, which entails considerable time savings, particularly over extended yarding distances. However, the regression model also showed a significant »offset«, which indicated that time consumption is initially higher under this treatment. Taken together, yarding distance, piece volume and treatment type (horizontal full suspension) explained over 70% of the total variability (Table 3, Fig. 4).

Background noise was particularly strong in case of loading. Therefore, the explanatory power of the regression models was considerably low and differences in time consumption could solely be related to treatment type (Table 3, Fig. 4). The picture was clearer in the case of unloading: unloading time consumption increased with piece volume and under the treatment type »double«. The interaction between the treatment type »double« and piece volume indicated that treatment effect is emphasized with larger volumes.

The higher speed achieved under the full suspension treatment was indeed one of the hypotheses of this study, based on design specifications and manufacturer claims, and the study did verify such hypothesis. A faster inhaul under the horizontal full suspension treatment might offset the longer loading time and make this option preferable when corridor length is overstretched. However, that was not the case of the study corridor that spanned over little more than 300 m;

Table 3 Regression models for estimation of inhaul and outhaul time per cycle

Outhaul				
Time Outhaul, min $PSH_0 = a + b * Dist$				
$R^2_{adj} = 0.658, n = 99$				
	Coeff	*SE*	*T*	*P*
a	5.664×10^{-2}	7.494×10^{-2}	0.756	0.452
b	4.741×10^{-3}	3.468×10^{-4}	13.673	<0.001
Loading				
Time Loading, min $PSH_0 = a + b * Mode\_Hor$				
$R^2_{adj} = 0.068, n = 99$				
	Coeff	*SE*	*T*	*P*
a	4.330	0.333	12.987	<0.001
b	1.458	0.482	3.022	0.003
Inhaul				
Time Inhaul, min PSH_0 $a + b * Dist + c * Horizontal + d * Horizontal * Dist + e * Dist * Piece\_Vol$				
$R^2_{adj} = 0.713, n = 99$				
	Coeff	*SE*	*T*	*P*
a	–0.271	0.370	–0.733	0.466
b	7.331×10^{-3}	1.885×10^{-3}	3.890	<0.001
c	1.030	0.342	3.012	0.003
d	-5.688×10^{-3}	1.522×10^{-3}	–3.737	<0.001
e	1.130×10^{-3}	5.109×10^{-4}	2.211	0.030
Unloading				
Time Unloading, min PSH_0 $a + b * Piece\_Vol + c * Double + d * Piece\_Vol * Double$				
$R^2_{adj} = 0.279, n = 99$				
	Coeff	*SE*	*T*	*P*
a	0.627	0.126	4.978	<0.001
b	0.123	3.916×10^{-2}	3.147	0.002
c	1.367	0.226	6.054	<0.001
d	–0.569	0.136	–4.178	<0.001
Load volume				
Load volume, m^3 merchantable $a + b * Piece\_Vol + c * Piece\_Vol * Double$				
$R^2_{adj} = 0.840, n = 99$				
	Coeff	*SE*	*T*	*P*
a	0.670	0.112	6.223	<0.001
b	0.872	3.998×10^{-2}	21.818	<0.001
c	0.652	8.280×10^{-2}	7.873	<0.001
Productivity				
Productivity, m^3 PSH_0^{-1} ((Time Outhaul + *Time Loading* + *Time Inhaul* + *Time Unloading*) / 60) / *Load volume*				

Notes: All times in seconds, s; Dist – extraction distance in m; Piece_Vol – average piece volume in m^3 of merchantable log volume over bark; Horizontal – Indicator variable for double-hitch horizontal suspension treatment: 1 if treatment is horizontal full suspension (»horizontal«), 0 if otherwise (»single« or »double«); Double – Indicator variable for double-hitch horizontal suspension treatment: 1 if treatment is double-hitch, separate loads treatment (»double«), 0 if otherwise (»single« or »horizontal«)

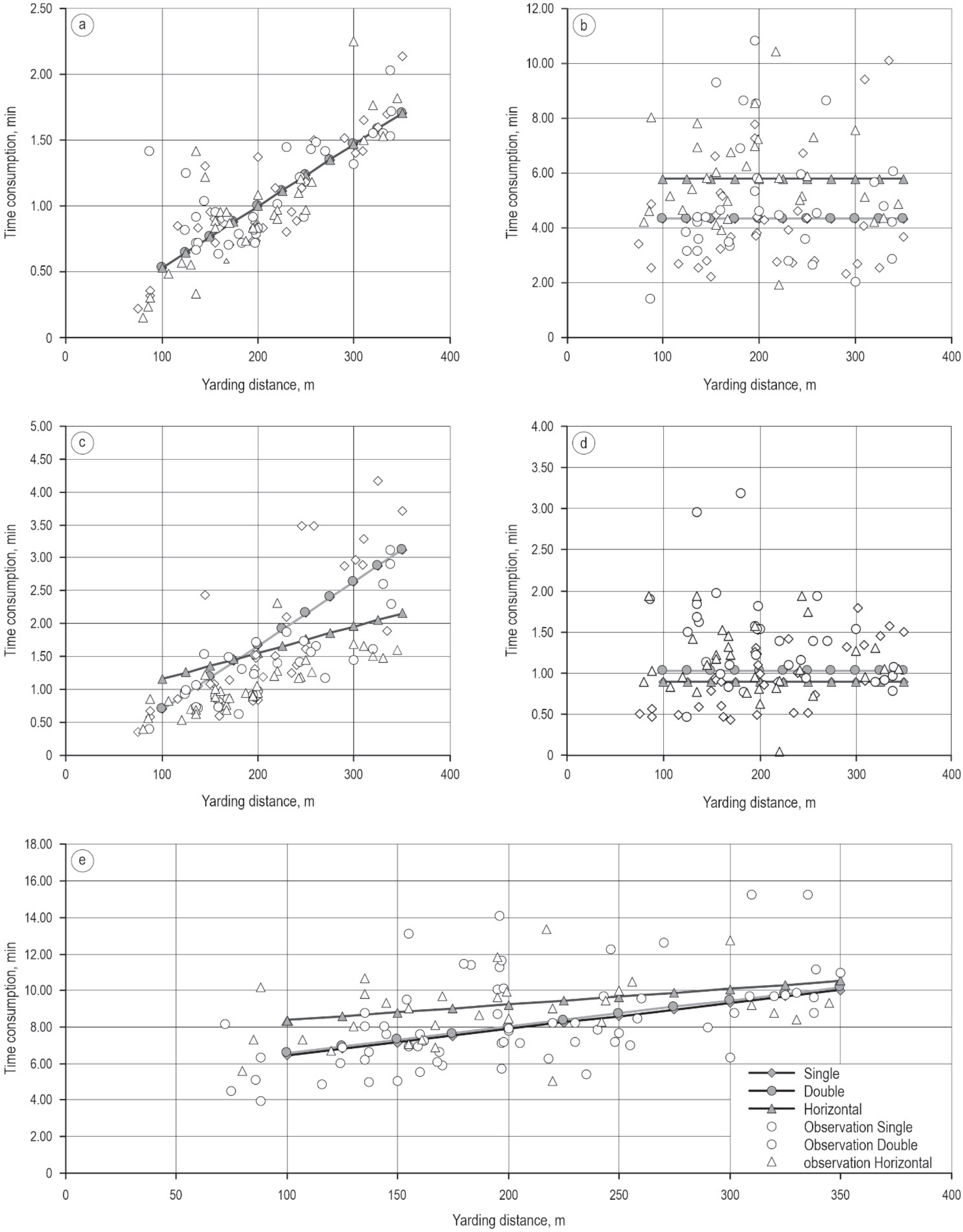

Fig. 4 Outhaul (top left), loading (top right), inhaul (mid left), unloading (mid right) and total (bottom) time per cycle for an average piece volume of 2.17 m^3 and as a function of yarding distance: scattergram and regression graphs

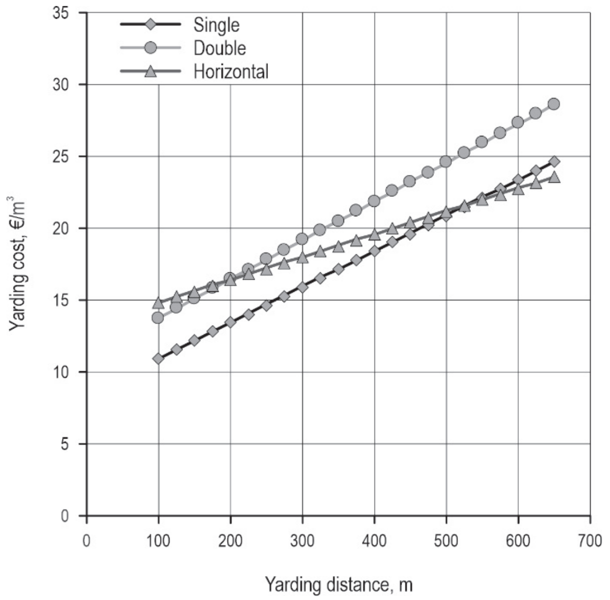

Fig. 5 Estimated harvesting cost as a function of yarding distance and treatment

for such a corridor, harvesting cost averaged 19 € per m^3 merchantable volume over bark (excluding set up and dismantle time), with no significant differences between treatments.

For determining the potential break-even point between treatments, productivity estimates were calculated based on observed mean piece volumes and for a yarding distance up to about two times the study corridor distance. A delay share of 10% was taken into account by inflating cost rates correspondingly, and yarding costs were derived through division of cost rates by estimated productivity. The exercise showed that yarding in the single-hitch mode incurred the lowest cost for all distances up to 550 m: above this limit, the higher inhaul speed achieved through the horizontal full-suspension work technique entailed a significant productivity advantage. By contrast, the »double« treatment advantage compared to the »horizontal« treatment was restricted to yarding distances below 200 m (Fig. 5).

4. Discussion

Modern double-hitch carriages adopt a flexible modular design, which combines a standard motorized carriage with a dedicated secondary carriage (so-called »trailer«). Each of the two carriages is equipped with its own dropline winch, but both winches are powered by the engine installed on the standard main carriage. That allows to operate the standard carriage with or without the secondary carriage, as needed. Therefore, the double-hitch carriage may be operated under three different modes, and namely: single-hitch, double-hitch and horizontal double-hitch. The present study investigated how operation under those different modes may affect productivity and confirmed differences in the time consumption for loading, inhaul and unloading observed during a previous study on double-hitch carriages (Spinelli et al. 2021b). Nevertheless, average productivity and cost did not differ significantly between the treatments on test. In general, the recorded productivity and cost were within the ranges observed for salvage logging operations in previous studies with similar or the same type of yarder or carriage (e.g. Spinelli et al. 2017, Spinelli et al. 2021a,b).

As expected, outhaul time consumption and speed did not differ between treatments. However, it may be argued that the »single« treatment did not exactly reflect the case in which the main carriage is used alone, because it was performed with the secondary carriage still attached, which added approximately 300 kg to the single carriage weight. Nevertheless, it was considered that the bias introduced by this additional weight would only affect time consumption in the outhaul phase and that this effect would likely be negligible, considering the abundant power of the haulback line winch. Similarly, the additional tare weight was small compared with the large payload capacity of the carriage (3 t). On the other hand, such small licence in experiment design enabled complete randomization, which would far outweigh the possible carriage weight bias.

The shorter loading time under the single-hitch treatment was expected, since attaching one line must take less time than attaching two lines. However, one may wonder why this difference was significant only for the horizontal double-hitch treatment and not for the standard double-hitch treatment. The fact is that under the horizontal double-hitch treatment, a load had to be fixed at a point close and a point far from the yarding corridor, which involved traversing areas of entangled trees to reach that point. In contrast, both lines could be attached to loads at points just below the skyline in the »double« treatment, and that could be done equally fast as when attaching a single line given that three operators were available at the loading point.

The higher inhaul speed and shorter inhaul time achieved under the full suspension treatment was indeed one of the hypotheses of this study, based on a) design specifications, b) manufacturer claims and c) the results of an earlier study (Spinelli et al. 2021b). The current study did verify such hypothesis. Therefore, higher inhaul speed can be rightly considered one of the primary advantages of horizontal full suspension, particularly in downhill yarding: with a standard, single-hitch carriage and partial suspension of the load, inhaul speed would have to be reduced to avoid uncontrollable swinging of the load and loosening rocks or debris through contact of the load with the ground. That would endanger the yarding crew and equipment, which is the primary reason why inhaul speed in downhill yarding is lower than in uphill yarding (Ghaffariyan et al. 2009, Tsioras et al. 2011).

While the observed relationship between inhaul time consumption and yarding distance is perfectly plausible, the observed treatment effect may require deeper consideration. The combination of additional time consumption as an effect of the »horizontal« treatment may not be plausible at first glance and under the premises of a higher observed inhaul speed; however, in combination with the interaction between increasing distance under the same treatment, it may be interpreted as a representation of the requirement for stabilization of the load at the beginning of the inhaul and before gaining momentum, which is later offset by the higher inhaul speed. The observed interaction between distance and piece volume, in turn, is an obvious one. The larger the average piece volume (and thus the load), the more difficult its stabilization during travel; therefore, inhaul speed decreases, an effect that is more pronounced over longer yarding distances.

Although it may be expected that the significantly longer unloading time observed under the »double-hitch« treatment is associated with the larger number of pieces collected under this treatment, that was not the case. The actual reason for the longer unloading time was the need for performing two separate unloading manoeuvres for the two carriage elements, since the two fairleads on the main carriage and the add-on secondary carriage are placed about 4 m apart. Therefore, the operator at the unloading must drive the main carriage over the drop point, release the first load component, then move the carriage ahead to position the secondary carriage over the drop point and release the rest of the load. As suggested by the observed interaction, the effect is more pronounced if larger pieces are involved. To unload in one go, a larger landing site would be required; however, the confined work conditions presented by the forest roads in alpine areas often preclude such an approach (Stampfer et al. 2002). A further option, particularly suitable when working with an integrated yarder type, would be to release the first load over the drop point, while grabbing the second with the processor head at the same time.

Considering the specific case of windthrown salvage under the observed conditions, all the tested work techniques have their pros and cons that operators must consider when they select their own option. The single carriage is fastest and most productive, which is a strong reason to adopt it. In that regard, it may be worth recalling that the same work technique could be applied with a conventional self-clamping carriage, where lift is provided by the mainline and not by a separate small motor installed on the carriage itself (Spinelli et al. 2017). For that reason, the self-clamping solution offers a significantly larger break-out force than a motorized dropline carriage, which can be used with profit for overcoming the high resistance opposed by tangled trees, provided the skyline and anchors are strong enough (Nicoll et al. 2016, Smith and Mc Mahon 1995). The latter can be a limiting factor in salvage operations, where the root system of outwardly undamaged trees may also have been injured by the storm (O'Sullivan and Ritchie 1993). In that regard, the clearance advantage of horizontal yarding (Spinelli et al. 2021a) may also render setting up an intermediate support unnecessary: that is a time consuming and costly task (Stampfer et al. 2006), and an impossible one to accomplish where trees have been windthrown on large areas.

Similar to several other recent studies on the effect of yarding mode (Spinelli et al. 2017a, b) and on double-hitch carriages (Spinelli et al. 2021a, b), it was possible to employ a strictly controlled experimental design, which is rather the exception than the rule in cable yarding research (Lindroos and Cavalli 2016) and a clear advantage of the present study. However, even a textbook randomization study like the current one could not prevent some bias from sneaking in: the results show that the workers tended to pick from the windthrown tangle specific elements for different treatments. That was especially the case of the double treatment, which lent itself quite well to cleaning up smaller trees and broken tops. Therefore, this treatment was used more frequently than the others for collecting multiple scattered elements, which is demonstrated by the significantly higher average number of pieces per cycle. While the tendency to attach smaller pieces under one treatment may represent a conceptual violation of the strict randomization design, it also illustrates one of the main assets of the double carriage, which may be especially suited to thinning operations, where loads are similarly scattered and where the possibility to extract loads from two separate locations at a time may significantly enhance productivity (Visser and Stampfer 1998).

Regarding harvesting cost estimation, it must be stressed that the estimates only illustrate how harvesting costs change with increasing yarding distance, if all other parameters remain at the same treatment-specific average. Furthermore, extrapolation beyond the actual yarding corridor length is an interim solution at best, until yarding with a double-hitch carriage will be studied over longer distances. Nevertheless, it suggests that the hypothesis of double-hitch carriage advantage is in fact a possible one, even though only on yarding distances beyond average.

5. Conclusions

In the present study, the single treatment proved to be the simplest and cheapest. It also had the potential for accumulating the largest loads, since it can be used for partial suspension, whereby a large proportion of the payload is leaning on the ground and does not contribute to skyline loading. These advantages are hard to beat, and the higher inhaul speed allowed by horizontal full suspension was not enough to offset the longer loading time. This may only be possible over yarding distances beyond average, as indicated by extrapolation. Therefore, the use of this technique must be justified by other reasons, such as minimizing product contamination, soil disturbance or excessive strain to the skyline when the terrain profile does not offer sufficient ground clearance. In the latter case, horizontal full suspension may save the cost of installing one or more intermediate supports, but this eventual benefit should be evaluated case-by-case.

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Authors' addresses:

Raffaele Spinelli, PhD
e-mail: raffaele.spinelli@ibe.cnr.it
Natascia Magagnotti, PhD
e-mail: natascia.magagnotti@ibe.cnr.it
Fabio De Francesco, MSc
e-mail: fabio.defrancesco@ibe.cnr.it
CNR-IBE – Consiglio Nazionale delle Ricerche
Istituto per la BioEconomia
Via Madonna del Piano 10
50019, Sesto Fiorentino (FI)
ITALY

Prof. Karl Stampfer, PhD
e-mail: karl.stampfer@boku.ac.at
Gernot Erber, PhD *
e-mail: gernot.erber@boku.ac.at
University of Natural Resources and
Life Sciences, Vienna
Department of Forest and Soil Sciences
Institute of Forest Engineering
Peter Jordan Strasse 82
1190, Vienna
AUSTRIA

Giulio Cosola, Msc
e-mail: giulio.cosola@gmail.com
CoNAIBo – Coordinamento Nazionale
delle Imprese Boschive
Piazzale Merizzi 17
23100 Sondrio (SO)
ITALY

Matevž Mihelič, PhD
e-mail: matevz.mihelic@bf.uni-lj.si
University of Ljubljana
Biotechnical Faculty
Večna pot 83
1000, Ljubljana
SLOVENIA

* Corresponding author