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Productivity and cost analysis of tower yarder systems using the Koller 507 and the Valentini 400 in southwest Germany

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ABSTRACT

Cable-based timber extraction offers some advantages with regard to impacts to forest stands and soils, and can be used under a wide range of conditions. It is important not only in steep terrain, but also increasingly in flat terrain when soils have low bearing capacity. In this study, utilization data from two commonly used tower yarding systems were analyzed: a tower yarder with a mounted processor (K507) and a medium-distance tower yarder (V400). Collected data included explanatory variables, such as the proportion of hardwood timber, length of skyline, direction of yarding and dimension of harvested timber. Data were analyzed with regard to the time required for machine installation including set-up and dismantling, machine productivity and resulting production costs. Possible combinations of machines and partial working steps were evaluated. Results indicated an increasing utilization of cable crane systems in horizontal yarding direction throughout the analyzed time period. Further, more time was required to process full trees when the K507 was used, although machine productivity increased. The proportion of processed timber that was hardwood significantly influenced installation times. Results demonstrated that, if the machines had above average productivity, total costs could be reduced in flat terrain by using a cable crane instead of conducting the extraction by skidders.

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Introduction

Timber harvesting and extraction methods are continuously adapted to match changes in conditions, such as silvicultural goals, nature conservation measures or developments in technology. With the advancing mechanization of timber harvesting, the use of cable-based yarding technologies has been introduced to mobilize biomass in stands that are not accessible with ground-based machinery. There are different ways to categorize cable cranes: according to the range of the system (short-, medium- or long-distance), the mobility of the cable cranes (mobile or stationary) or the type of system applied (high lead or skyline). While high lead systems are mainly used in North America, skyline systems are quite common in Europe and are probably the more popular system overall (Anon 2004). They include running skyline, live skyline and standing skyline systems and differ from high lead systems in their components and procedure for use (Heinimann et al. 2001; Dietz et al. 2011; Lindroos and Cavalli 2016).

An alternative to the use of cable cranes in inaccessible terrain is extraction with helicopters or zeppelins (Dykstra 1976), but these practices are very expensive and only used if no other method of extraction is possible. Winch-assisted extraction systems are an alternative to cable yarding extraction systems in terrain with slopes from 30% to about 50%. In some cases, winch-assisted tractors or skidders are used in inaccessible flat terrain. However, the extraction distance is limited to the length of the auxiliary cable (100 m). It should also be noted that the damage caused to the remaining stand increases as the extraction distance of the auxiliary cable becomes longer.

Cable crane systems are increasingly being used in all terrains as an alternative to conventional fully mechanized systems using harvesters and forwarders, because of their low impact on soils (Erber and Spinelli 2020). An increasing number of stands have soils on which vehicles cannot establish sufficient traction, making the soils sensitive to traffic. Compaction or displacement of these sensitive soils should be avoided. Earlier studies have shown that the use of skid trails by heavy forest machines can have a considerable influence on the soil biological properties of a stand (Labelle and Jaeger 2011; Abdi et al. 2017). Moreover, Eliasson (2005) found that repeated passes with a forwarder can cause increased soil compaction, even compared to the heaviest impact of the first pass of a harvester.

Extraction damage to the remaining stand is not always avoidable when using skidders or forwarders and even with cable crane systems, (Han and Kellog 2000) especially when the spacing between the skylines is large. Overall, cable crane

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operations lead to less damage to the stand and less impact on soil properties compared with other techniques (Marchi et al. 2014), such as ground-based cable extraction using winch-assisted tractors or skidders. While the use of ancillary equipment can reduce soil disturbance, the employment of a cable crane system completely eliminates ground-based traffic and reduces soil compaction, soil surface damage and erosion (Miller and Donald 1986; Laffan et al. 2001).

Due to environmental considerations, cable cranes are increasingly being used for timber extraction in flat terrain (Kirsten 2019), but this topic has rarely been the focus of existing literature. Most often, uphill or downhill yarding systems were investigated in scientific studies. If data on horizontal yarding were available, they often covered only a small proportion of the harvested volume analyzed (e.g. 2–4% horizontal yarding). Thus, to a large extent data were insufficient for further analyzes or general statements (Lindroos and Cavalli 2016; Erber et al. 2017).

Further, operating conditions are changing as a result of climate change and silvicultural strategies (e.g. an increase in the proportion of hardwoods). Cable crane systems can be applied in most stands, including hardwood stands. Usually, hardwoods are felled and extracted as full trees to avoid any processing work under the difficult and risky conditions of the felling site. Instead, processing is carried out motor-manually on the forest road, which offers more space and safety for the forest workers (Spinelli et al. 2017a).

The productivity of a cable crane application is strongly influenced by log volume, length of skyline, silvicultural prescription (harvesting intensity) and lateral extraction distance (Hoffmann et al. 2016). In addition, terrain slope, stand density and direction of the yarding (uphill/downhill) have an influence on the extracted volume per time (Eroglu et al. 2009; Ghaffariyan et al. 2010; Lindroos and Cavalli 2015; Spinelli et al. 2015; Erber et al. 2017; Cho et al. 2018).

The main goal of this study was to analyze and evaluate two cable-supported systems with regard to economic aspects. Specifically, the objectives were:

- to show possible trends in the application area of cable crane systems, taking into account the amount of harvested hardwood of the total harvested volume, the diameter distribution of harvested stems, the productivity of the machinery, and areas with multiple extraction directions;
- to investigate in detail installation times (including positioning of the excavator with a tail spar), as these significantly contribute to the total working time;
- to analyze productivity of different machines and determine respective processing costs;
- to analyze performance and processing costs when a mini forestry crawler is used for pre-winching trees to the cable corridors before yarding.

Materials and methods

Analyzed forest operations

In this study, two cable-based extraction methods using skyline systems were analyzed in the black forest area of southwest Germany:

a. The first cable yarding system analyzed included a tower yarder with a mounted processor (Koller Forsttechnik GmbH, Austria, Type K507) and was employed in the following operational set up: Motor-manual felling, extraction of full trees and processing by processor.

After operator instruction, planning and preparation of the cable corridors, the trees are felled and, if necessary, pre-winched with a radio-controlled mini forest crawler to the cable corridor before the tower yarder system is set up on the forest road (Table 1, 2). This method is suitable for heavy timber due to the large payload of the tower yarder (~3 t). Very heavy timber, i.e. with thick branches, is coarsely delimbed motor-manually at the felling site in the stand.

To set up the tower yarder, anchor trees, tail trees (tail spar) and intermediate supports are determined. If there are no suitable anchor trees, or for reasons of work safety, an excavator with tail spar function can be used, as long as the machine has appropriate access to the stand. Besides terrain slope and length of cable corridors, terrain shape also influences the number of intermediate supports required for the skyline. The K507 is mounted on a truck and works with a two- or three-cable system, depending on the yarding direction (horizontal, uphill or downhill). The two-cable system is used for uphill yarding (skyline and mainline), while at least three cables are required for downhill and horizontal yarding (skyline, mainline and haulback line). The maximum length of the cable corridor is 700 m.

Using an additional machine for pre-winching the trees or assortments to the cable corridors, i.e. a mini forestry crawler, offers the advantage that the distance between cable corridors can be extended. As one consequence, fewer installations of the cable crane are necessary. However, as lateral pulling over long distances reduces productivity and may cause severe damage to the remaining stand, a maximum distance of approx. 60 m between the cable corridors is recommended.

Table 1. Technical data for the tower yarders investigated.

Machine	Tower yarder with mounted processor	Medium-distance tower yarder
Machine brand	Koller	Valentini
Machine type	K507	V400
Payload	3000 kg	2000 kg
Carriage model	MSK-4	Bergwald
Processor	Woody 60	-
Height of tower	11.4 m	10.0 m
Length of skyline	700 m	400 m
Tree size	large	small and medium
Yarding direction	all	uphill

Table 2. Technical data for the mini forestry crawler investigated.

Machine	Mini crawler[1]
Machine brand	Wicki
Machine type	50.6 B
Machine weight	2,600 kg
Winch tractive force	6,000 kg
Length of cable	150 m

[1]Always a combined operation with the K507.

In general, road spacing depends strongly on the existing cable corridors and the shape of the terrain.

When trees are not pre-winched, the distance between the cable corridors is approx. 30 m. After the tower yarder has been set up, full trees or logs are extracted to the forest road and picked up by the processor. Self-opening electronic chockers help to increase efficiency for the processing process. The trees are immediately de-branched, measured, bucked, sorted and, if necessary, piled. Typically, the assortments are moved by a skidder to the landing if there is not enough space next to the yarder or if hauling is delayed. While processor and skidder are operating, further logs can be added to the cable.

The skidder is equipped with a grapple for easier sorting, skidding and piling of the logs at the landing along the forest road before on-road transport. If necessary, the logs are manually processed and measured at the landing. This is usually the case for hardwood logs, as they cannot always be processed by the processor head. Stems or logs close to the road (up to 50 m) are extracted using a ground-based cable with winch-equipped skidders, then processed and piled. In both cases, between five and eight machine operators are needed.

b. The second cable yarding system analyzed included a medium-distance tower yarder (Valentini S.R.L., Italy, Type V400).

After operator instruction, planning, preparation of the cable corridors and installation of the tower yarder on the forest road, the trees are felled motor-manually, if necessary with support of the mainline, and then extracted. The number of extracted full trees per load depends on the stem volume. Once extracted, the trees are processed at the roadside. For this harvesting and extraction method, felling and extraction depend on each other in terms of time.

This extraction method using the V400 is only suitable for trees of small and medium dimensions because the payload of the tower yarder is limited to a maximum of 2 t (Table 1). The V400 is mounted to a tractor (and also hauled by it). To set up the cable crane, trees are selected as anchors, tails and intermediate supports. If there are no suitable anchor trees, or for reasons of work safety, an excavator with tail spar function can be used, assuming that appropriate access to the stand is available.

Usually, the V400 is used as a gravity system only, i.e. for uphill yarding (terrain slope >15%), and therefore works with a two-cable system. Although it is technically possible to use this machine for horizontal yarding as well, it would require either a mechanical carriage, and a mechanism to lock the carriage to the skyline; or a three-cable system and the presence of a carriage with a motor for spooling out the mainline. The maximum length of the skyline is 400 m, which is much shorter than that of the K507 (700 m). The distances between cable corridors are approx. 30 m.

After timber has been extracted, full trees are processed at the roadside, either immediately or in an independent and decoupled work step with a time shift. The degree of mechanization of the processing depends on the proportion of hardwood timber, the diameter distribution and the total volume. The trees can be processed motor-manually or mechanically, e.g. with the aid of a pull-through delimber or a separate processor. A pull-through delimber can be useful if the amount of wood produced is small (~200 m^3 per operation). If there is a large volume of softwood, full trees are mainly processed with an additional processor. Motor-manual processing is mainly applied in hardwood dominated stands.

A skidder with a crane operating on the forest road skids and piles the provided assortments at the landings along the forest road (skidding, piling). If necessary, logs are also manually measured. This is particularly the case in the absence of a processor or when hardwoods have large dimensions and cannot be processed by the processor. Stems or logs close to the road (up to 50 m) are extracted using a ground-based cable with winch-equipped skidders, then processed and piled. Three machine operators are needed for this system.

Data collection and system boundaries

Over a period of six years (2013–2018), data from forest operations in southwestern Germany with the two tower yarders K507 and V400 were systematically collected by a state forest machinery company, which belongs to the state forest service "Forst Baden-Württemberg" (ForstBW) (c.f. Kirsten 2019).

In total, data from 122,130 cubic meters under bark (m^3_{ub}) of timber and 9,903 productive machine hours (PMH_{15}, including delays of up to 15 minutes) of the tower yarders were collected during 138 operations. This corresponds to an average harvesting volume of 885 m^3_{ub} per operation. The collected data also included the use of additional machines, such as the mini forestry crawler and the excavator with tail spar function.

The mini forestry crawler was used for the first time in 2014 and has been in regular use since 2015. In the four years from 2015 to 2018, it was used for extracting 11,107 m^3_{ub} in total, corresponding to 996 PMH_{15}. The crawler was used in 17 operations to support the extraction by yarder.

The excavator with tail spar function was partly used in a total of 23 operations (19,717 m^3_{ub}) and processed on average 3,943 m^3_{ub}/y. In most cases (N = 20; 17,228 m^3_{ub},) it was used in combination with the K507.

In order to ensure that all procedures used were as consistent as possible, data from various operations were excluded from the analysis:

- operations with downhill extraction (N = 1; 771 m^3_{ub}),
- training cuts without a skidder (N = 1; 193 m^3_{ub}),
- operations with an abnormal sequence of work elements (V400 in combination with mini forestry crawler: N = 2; 2,578 m^3_{ub}),
- salvage operations of damaged wood (insect infected wood or wind throw: N = 21; 16,858 m^3_{ub}).

Thus, analysis was completed for a total of 113 operations with a processing volume of 101,812 m^3_{ub} and a duration of 8,118 PMH_{15} (referring specifically to running of the tower yarders) in 2013–2018.

Variables examined

a. **Developments in timber harvesting and extraction with tower yarders**

To reach the study's main goal, the quantities of extracted wood and productive machine hours during the investigation period were analyzed, taking into account the tower yarder used, the yarding direction and the use of other machines. In general, the volume of salvage harvesting of damaged timber volume of salvage harvesting of was excluded. However, when analyzing the total volume of timber extracted per year, this volume was considered in order to show the actual use intensity of the cable crane systems. To investigate potential changes in the usage of tower yarders, the proportion of operations in flat terrain was calculated as a time series. To determine possible changes over time with regard to the proportion of hardwood, diameter distributions and productivity, the mean performances and the extracted wood volumes per assortment were analyzed by multiple mean value comparison and examined with linear regression.

b. Installation times

To make reliable estimates regarding the working times needed to install the tower yarders, the variable factors with a significant influence on working time were first selected. Analyzes were then completed using average installation times per cable corridor as input data to determine how the installation times in particular were influenced by these factors. Possible influencing factors of the total installation time per stand included the presence of hardwood, the length of the skylines and the use of the excavator with a tail spar. Further, the use of the mini forestry crawler might require fewer corridors. The installation times of both cable crane systems were analyzed accordingly.

Due to the elimination (a priori) of outliers, another 1.1% (N = 1) of the data were excluded. Only uphill extractions were included, to ensure comparability between the K507 and the V400. Subsequently, the number of intermediate supports was also analyzed using the same procedure. The number of supports was defined as the average number per cable corridor.

In a separate analysis, the installation times were analyzed exclusively for operations using the K507, taking into account the various yarding directions. The correction (a priori) of outliers resulted in an exclusion of 1.7% (N = 1) of the data, so that 57 operations were ultimately investigated.

c. Machine productivity

The machine productivity of the tower yarders or the mini forestry crawler (MFC) were defined as the volume (m^3_{ub}) extracted per productive machine hour (PMH_{15}). In order to analyze the dependency of the performance on possible influencing factors, the variable factors significantly influencing machine performance were first identified. Possible influencing factors investigated in this study included the presence of hardwood, the extracted volume per meter length of cable corridor, and the mean diameter breast height (DBH) of extracted trees (Table 3).

Machine performance in extraction was examined both as a comparison between the two tower yarder systems and separately for the K507, taking into account further potential influencing factors that only varied in K507 cuts. The machine performance of the mini forestry crawler was analyzed, taking into account terrain slope of operating areas and extraction distance for pre-concentration.

Due to outlier correction, 1.1% of the data were excluded from the statistical analysis of machine productivity in both systems, which corresponds to one cut (N = 1).

A separate investigation of the productivity of the K507 ($Prod_{K507}$) resulted in an outlier correction of 3.3% of the data (N = 2) and logarithm transformation of the dependent variable.

d. Procedural costs

For a separate analysis of the cost dependence of the system applied, variable factors with a significant influence on total costs (without piling) were explored with linear regression. Possible influencing factors were, e.g. the presence of hardwoods, the use of an excavator with a tail spar, the machine output and the number of installations. Machine costs were reported by the company (Table 4).

In order to investigate the total costs for the V400 system (felling, extraction and processing), the costs of the mechanized processing using a separate excavator processor (Komatsu, Tokio, Japan) were added based on values from the literature (KWF 2008). This was necessary because the analyzed original data did not include processing costs.

Table 3. Data collected during the investigated operations using the tower yarders K507 and V400 over a period of six years (2013–2018), reported per yarding direction.

	K507							
	horizontal yarding (N = 19)							
	vol [m^3]	DBH [cm]	N(cable corridor(s))	Lcr [m]	n(IS)	Hardwood [%]	VM [m^3/m]	Ets [%]
Min	452.3	24.0	2.0	122.0	0.0	0.0	0.1	0.0
Max	1984.5	45.0	16.0	400.0	1.5	99.0	1.2	100.0
Mean	955 ± 435	35.5 ± 5.5	6.0 ± 3.7	269.3 ± 94.2	0.6 ± 0.5	38.5 ± 44.8	0.6 ± 0.3	38.8 ± 37.6
	uphill yarding (N = 41)							
	vol [m^3]	**DBH [cm]**	**N(cable corridor(s))**	**Lcr [m]**	**n(IS)**	**Hardwood [%]**	**VM [m^3/m]**	**Ets [%]**
Min	96.0	25.0	1.0	118.0	0.0	0.0	0.2	0.0
Max	3163.9	55.0	23.0	450.0	2.7	82.0	2.6	98.9
Mean	1032 ± 680	39.0 ± 6.0	8.8 ± 5.9	252.6 ± 85.6	0.5 ± 0.5	18.8 ± 22.0	0.5 ± 0.4	10.6 ± 23.6
	V400							
	uphill yarding (N = 53)							
	vol [m^3]	**DBH [cm]**	**N(cable corridor(s))**	**Lcr [m]**	**n(IS)**	**Hardwood [%]**	**VM [m^3/m]**	**Ets [%]**
Min	116.0	17.0	2.0	120.0	0.0	0.0	0.1	0.0
Max	4344.6	45.0	81.0	320.0	1.0	95.0	0.6	100.0
Mean	779 ± 687	29.3 ± 5.6	14.9 ± 13.4	202.6 ± 45.3	0.16 ± 0.3	18.5 ± 26.8	0.2 ± 0.1	5.6 ± 22.8

Mean = arithmetic mean with standard deviation; vol = average total timber volume harvested per felling; DBH = diameter at breast height; N = number of; Lcr = length of cable corridor; IS = intermediate supports; VM = timber volume per meter of the cable corridor; Ets = proportion of timber volume harvested with support from an excavator with tail spar.

Table 4. Machine cost calculation. Costs are reported in € per hour and refer only to machines governed by ForstBW in the year 2019, excluding VAT and wages for machine operators.

Machine	Costs (€/h)
K507	140
V400 (tractor as power unit included)	60
Excavator	35
Tail spar	25
Tractor with winch (4 wheel)	35
Skidder with grapple (4 wheel)	42
mini forestry crawler	35

Processing costs considered three average DBH classes (24 cm, 26 cm and 28 cm). The investigated cuts with the respective average DBH values were allocated to the cost rates as shown in Table 5. The theoretical costs for processing were then included in the total costs according to the volume of wood processed, which was derived from the data on the volume of piled wood after processing. In cases where only the provision of wood was documented, processing of 100% of the provided wood volume was assumed.

In the analysis of the processing costs with the V400, outlier selection resulted in the exclusion of one cut (N = 1; 2.17% of the data). In addition, the total costs were evaluated separately without processing to check the influence of hypothetically included values, whereby the exclusion of one cut (N = 1; 1.89% of the data) resulted from outlier selection.

In principle, any additional work, such as brushwood removal, road maintenance and subsequent stand cultivation, were not included in the investigated costs. The transport of timber from forest road to mill was not included, as the timber is sold directly from the forest road.

Statistical analysis

Linear regression

Statistical analyzes were performed in R version 3.5.2 (R Core Team 2018). Linear regression was used to examine the influence of given variables (regressors) on a dependent variable. Prior to linear regression, statistical outliers of the dependent variable were adjusted according to the following criterion: $x \geq 2.5 \times SD$ (with x = outlier, SD = standard deviation). Regressors were selected stepwise by backward selection based on the Akaike Information Criterion (AIC). The influence of the regressors on the dependent variable, as well as potential interactions between the regressors, were examined for significance by variance analysis (ANOVA). The overall significance of the model was assessed using the F-test (p-statistic of the F-value < 0.05). Model quality was evaluated by the empirical and adjusted coefficient of determination (R2, Adj.R2).

Table 5. Hypothetical processor costs assigned to the average DBH of investigated operations using the V400 tower yarder.

DBH class	1	2	3
Hypothetical DBH* (cm)	24	26	28
Hypothetical cost* (€/m^3)	7.13	6.24	5.54
Average DBH of felling (cm)	17–25	>25–27	>27–40

*Source: KWF 2008

The linear dependence, the normal distribution of residuals and the homoscedasticity were visually checked by diagnostic plots. If necessary, right-skewed data were logarithm transformed (installation time, productivity of extraction) and weak right-skewed data were square-root transformed (number of supports). The normal distribution of the residuals was additionally tested by a Shapiro-Wilk test.

Cook's distance (Cook's D) was used to test whether the removal of outliers had a significant influence on the model selection. The outliers examined fulfilled at least the following prerequisite: $D_i > 4 \times D_m$ (with D_i = Cook's D, D_m = mean value of Cook's D). A decisive influence of an outlier was determined exclusively in the linear regression to describe the number of intermediate supports. In this case the outlier ($D_i > 20 \times D_m$) was not considered.

The presence of multicollinearity was investigated using the variance inflation factor (VIF) and variables were excluded where appropriate. Finally, all independent variables used met the VIF < 5 condition.

Multiple mean value comparison

In order to examine several mean values for significant differences, a single factor analysis of variance (ANOVA) was performed, followed by Tukey's honestly significant difference (HSD) post-hoc test.

Results

General observations

Throughout the sample period from 2013 to 2018, the largest annual volume of timber extracted by tower yarders was 20,701 m^3_{ub} in 2015 (including 8,412 m^3_{ub} salvaged logs). On average, the volume of annually processed timber without salvage logs was constant (9,352 m^3_{ub}). On an annual base, about 31% more timber was extracted using the K507 (11,481 m^3_{ub}) compared with the V400 (7,870 m^3_{ub}), and the K507 was utilized 11% more compared with the V400 (810 vs. 723 PMH_{15}). However, the observed difference in the mean utilization rate was not as large as the difference between the amounts of yearly extracted wood.

The use of tower yarders in flat terrain significantly increased from approximately 21 % in 2013 (2,377 m^3_{ub}) to 67 % in 2018 (3,735 m^3_{ub}) (Figure 1). The highest utilization in flat terrain was 5,100 m^3_{ub} in 2017 (Figure 1). When interpreting these results it should be noted that the proportion of salvage logging, which was not included in the analysis, was rather large in the last year 2018 (6,243 m^3_{ub} salvaged timber from a total extraction volume of 11,798 m^3_{ub}).

The volume of hardwood extracted by yarder was 25% of the total annual volume for both cable yarding systems, corresponding to 14,343 m^3_{ub} for K507 and 10,755 m^3_{ub} for V400 (excluding salvaged timber). There was no significant increase or decrease in hardwood extraction from 2014 to 2018 (the proportion in 2013 was unknown).

Further, the number of assortments did not change throughout the years. In all cases, the most frequent assortment was stem wood (normal, long stem wood), with an average of 35–38% per operation, while firewood was the rarest assortment (0.1–0.3% per operation) (data not shown). A continuous change over time

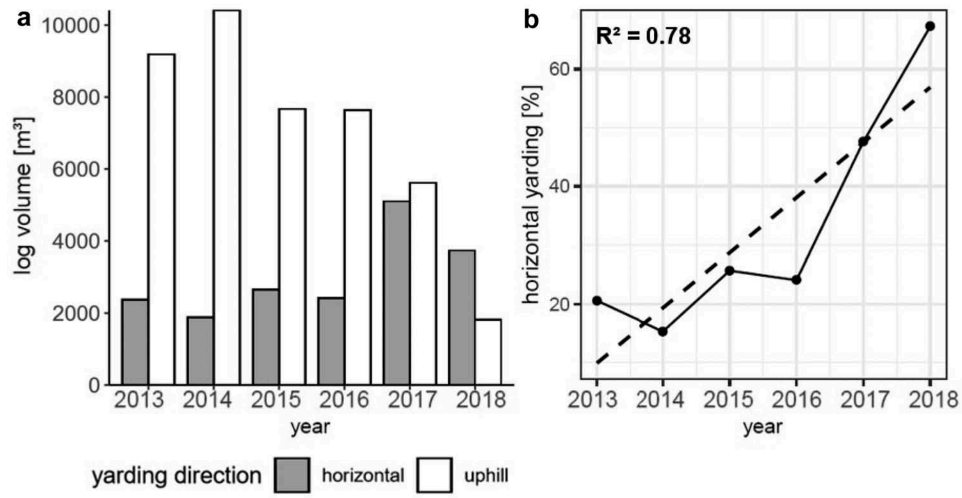

Figure 1. (a) Total timber volume (in m^3_{ub}) extracted with the tower yarder K507 over a period of six years (salvage timber excluded), separated by yarding direction (horizontal =shaded, uphill = not shaded). (b) The percentage of horizontal yarded timber in relation to the total timber volume, displayed per year (solid line). The (dashed) regression line indicates the correlation between the years and horizontal yarding ($p < 0.05$). N = 60.

was noted for stem wood for pallet ($p < 0.0001$; F-test) and standard lengths ($p < 0.01$; F-test). The produced volume of these assortments increased significantly across the years, but it did not differ between the investigated tower yarders. However, the system applied, i.e. K507 or V400, did have an influence on the assortments with respect to variation in harvested volumes, and volumes were significantly larger for operations using the K507 compared with those using the V400 ($p < 0.01$; t-test). Since no significant change in the number of assortments was found, these data indicated that the volumes of assortments extracted by the K507 varied more strongly, i.e. the distribution among the assortments was not as homogeneous as in case of the V400.

Since 2015, the mini forestry crawler has been used to pre-winch an amount of 2,702 ± 510 m^3_{ub}/y (245 ± 48 PMH_{15}), which corresponds to 23% of the total volume extracted by the K507. There was no tendency of increase or decrease in the use of the mini forestry crawler.

Table 6. AIC-based stepwise multiple regression model and test statistics for the installation times of cable corridors installed for the K507 and V400 systems.

Formula*		R2	Adj. R2	SE	*p*-value	N
$log\ IT = \beta_o + \beta_1 \times Lcr + \beta_2 \times V400 + \beta_3 \times v_m$		0.67	0.65	0.28	<0.0001	90
Coefficient	***t*-statistic**					
β0 1.11	6.33			0.17	<0.0001	
β1 0.003	6.10			0.0005	<0.0001	
β2 −0.28	−3.24			0.09	<0.01	
β3 0.94	5.47			0.16	<0.0001	

*IT = average installation time per cable corridor [in h]; β= Coefficient; Lcr = length of cable corridor [in m]; V400 = V400 yarding system [Factor]; Vm = volume per meter of the cable corridor [m^3/m]; SE = standard error.

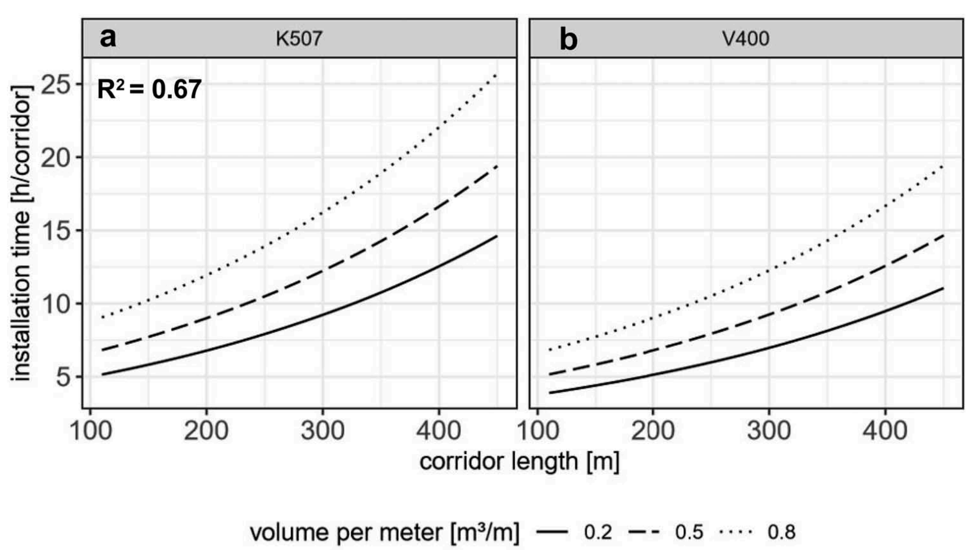

Figure 2. Installation time per cable corridor with tower yarders K507 (a) and V400 (b) depending on the length of the cable corridors and the log volume per meter (volume per meter). The analysis considered uphill yarding only. R^2 refers to (a and b).

Installation times

Results confirmed that the installation of the tower yarders is time consuming. On average, these tasks took 8 ± 4 h per cable corridor. A significant relationship was observed between the logarithm of installation time, the length of the corridor, the amount of volume and the type of tower yarder investigated (Table 6, Figure 2). The time required was 0.28 h per cable corridor lower with the V400 compared with the K507 (Table 6, Figure 2), irrespective of other influencing factors.

Operations using the K507 were further analyzed to determine whether the yarding direction had a significant impact on the installation time per cable corridor, but no significant impact was found. However, more intermediate supports were required in the horizontal yarding direction and there was a positive correlation between the installation time per cable corridor and the number of intermediate supports (p-value <.0001, Pearson's r = 0.72).

Also, the time required for installation per cable corridor increased with increasing percentage of hardwoods (Figure 3 (a)). This was true for cable corridors longer than 100 m. Further, the time required for installation increased with increasing length of the cable corridor (Figure 3(b)), indicating that the installation of intermediate supports was possibly more time consuming in hardwood dominated stands.

The presence of timber with smaller dimensions had a negative effect on the yarding volume per linear meter of the cable. We expected that setting up and dismantling of the intermediate supports required more time in stands with predominantly small diameter wood because twice as many trees were needed as intermediate supports to ensure stability. No significant relationship was found, however, which might be due to the fact that an average DBH gives no information about the homogeneity of the stands.

Machine productivity

The average yarding productivity was 8.9 ± 2.1 m^3_{ub}/PMH_{15} for the V400 and 13.3 ± 2.6 m^3_{ub}/PMH_{15} for the K507 (Table 7). The linear regression showed that DBH and the system applied had a significant influence on the yarding productivity (p = <0.0001). It increased with increasing DBH and tended to be lower when the V400 was applied. No other significant relationships were found.

More detailed analysis of the K507 demonstrated that its productivity was significantly higher when it was used in combination with the mini forestry crawler. Further, its productivity increased with increasing DBH and decreased with increasing pre-winching distance (Figure 4).

Production costs

Total production costs were calculated for both systems, but excluding the working step piling because data were not available in all cases. Resulting costs were on average 32.5 ± 5.90 €/m^3_{ub} for the K507 and 30.10 ± 8.50 €/m^3_{ub} for the V400 (Table 8).

When the K507 was applied, production costs decreased with increasing yarding productivity and increasing percentage of stem wood (Table 9, Figure 5). In contrast, production costs tended to increase as smaller trees or assortments were yarded with the tower yarder (and otherwise with a skidder) and as more timber was pre-winched (Table 9). Use of the mini forestry crawler brought additional costs. The value of costs depended on the amount of timber that was pre-winched (x%*0.06€/ m^3_{ub}). When the mini forestry crawler was used to pre-winch 50% of the total harvesting volume, the resulting additional costs were 3 €/m^3_{ub}.

When productivity was higher than 20.92 m^3_{ub}/PMH_{15}, the overall costs were reduced when the K507 was used for extraction instead of a skidder, corresponding to an extraction distance from the skid road of around 50 m. Whenever productivity was below this value, extraction with the skidder was cheaper and thus should be considered the preferred method to minimize production costs.

When calculating the production costs of the V400, the processing step was considered, as described in the methods. Again, costs significantly decreased with increasing

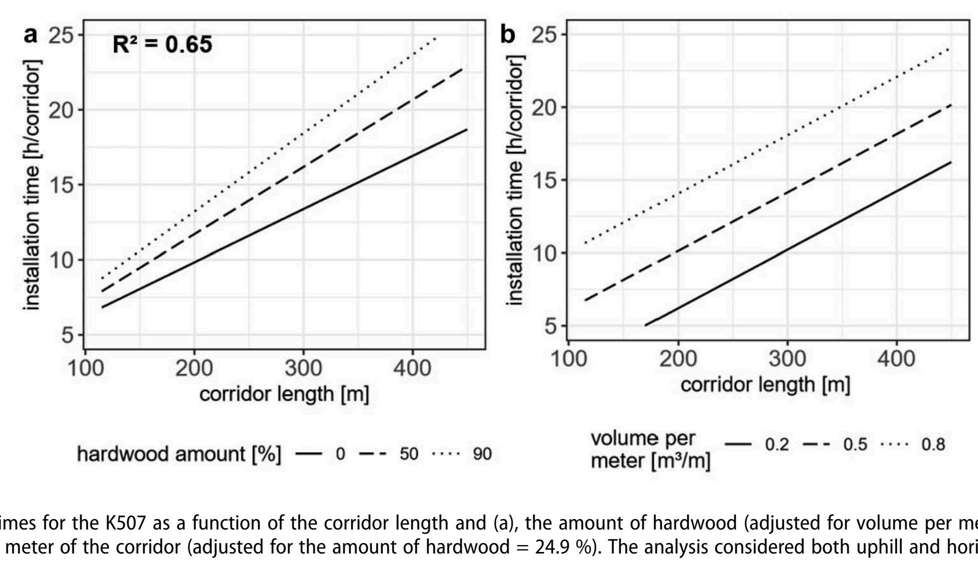

Figure 3. Installation times for the K507 as a function of the corridor length and (a), the amount of hardwood (adjusted for volume per meter = 0.55 m^3/m) or (b) the timber volume per meter of the corridor (adjusted for the amount of hardwood = 24.9 %). The analysis considered both uphill and horizontal yarding. R^2 refers to (a and b).

Table 7. Determined hours of operation and productivity, per machine.

Item/ Machine	K507	V400	MFC[1]
Productive machine hours (PMH_{15})	5,216	4,687	981
Productivity (m^3_{ub}/PMH_{15}) process	yarding	yarding	pre-winching
Mean ± standard deviation	13.3 ± 2.6	8.9 ± 2.1	12.0 ± 3.6
Min	9.0	5.8	8.2
Max	21.7	14.0	18.7

[1]MFC = mini forestry crawler, used in combination with the K507.

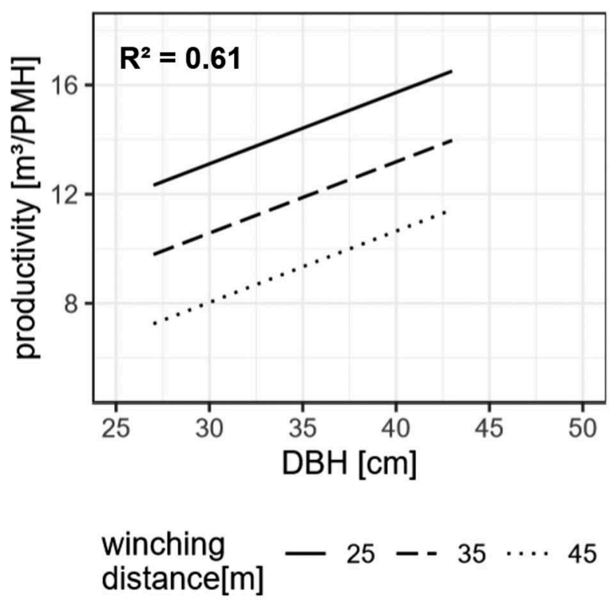

Figure 4. Productivity of the mini forestry crawler (MFC) as a function of timber diameter at breast height (DBH) and winching distance.

Table 8. Determined costs of operation, per machine.

Item/ Machine	K507	V400	MFC[1]
Cost (€/m^3_{ub})/ process	yarding	yarding	pre-winching
Mean ± standard deviation	32.50 ± 2.60	30.10 ± 8.50[2]	10.40 ± 3.40
Min	19.40	12.30	4.60
Max	44.70	57.10	15.60

[1]MFC = mini forestry crawler, used in combination with the K507; [2] = excluding processing and piling.

Table 9. AIC-based stepwise multiple regression model and test statistics for harvesting costs using the K507, without piling.

Formula*		R2	Adj. R2	SE	*p*-value	N
$C_{K507} = K_0 + K_1 \times Y + K_2 \times WI + K_3 \times SW + K_4 \times Prod_{K507} \times Y$		0.75	0.73	2.79	<0.0001	60
Coefficient	***t*-statistic**					
K_0 22.41	7.81			2.87	<0.0001	
K_1 0.41	9.67			0.04	<0.0001	
K_2 0.06	4.35			0.01	<0.0001	
K_3 −0.06	−2.28			0.02	<0.05	
K_4 −0.02	−10.26			.002	<0.0001	

*C_{K507} = harvesting costs using the K507, without piling [€/m^3]; WI = Percentage of proportionally winched timber [%]; Y = percentage of proportionally yarded timber using the K507 [%]; $Prod_{K507}$ = productivity of the K507; SW = percentage of harvested stem wood [%]; SE = standard error.

yarding productivity of the V400 and increased as more timber was only partially yarded (Table 10). When yarding productivity was higher than 13.74 m^3_{ub}/PMH_{15}, it was cheaper to use the V400 instead of the skidder, corresponding to an extraction distance from the skid road of around 50 m. However, as the average productivity of the V400 was only 8.9 ± 2.1 m^3_{ub}/PMH_{15} (Table 7), extraction should be carried out by skidder in the majority of cases. Linear regression without considering hypothetical processing costs led to the same results (data not shown).

Discussion

General observations

Among mechanized extraction methods, cable cranes are considered expensive. In the literature, productivity and costs of various operations have been analyzed. Tunay et al. (2003) investigated the use of a Koller K300 in Turkey and reported an average productivity of 6.4 m^3/h. Erber et al. (2017) evaluated applications of a Koller K507 with a total extracted volume of >71,000 m^3 over several years and reported an average productivity of 10.1 m^3 PMH_{15}^{-1}. Ghaffariyan et al. (2009) analyzed the use of Syncrofalke and Wanderfalke (with the processors Wolf 50 B and Woody 50) in Austria and determined average productivities of 7.0 m^3/PMH and 10.7 m^3/PMH, respectively. The resulting costs included felling, extraction, processing, piling and skidding to the landing, and they ranged on average from 22.70 €/m^3 to 25.30 €/m^3 (Ghaffariyan et al. 2009). In the Italian Alps, costs for extracting and processing with a long-distance cable crane were reported to be 9–40 €/m^3 (Spinelli et al. 2017b). These previous studies demonstrated that productivity and costs differed a lot depending on the variables considered, such as the machines used and whether partial or total costs were considered.

Heinimann et al. (2001) pursued a different idea and showed that the cost efficiency of motor-manual felling in combination with ground-based cable extraction and mechanized processing by an attached processor does not differ significantly from that of mechanized felling, processing by harvester and subsequent cable yarding extraction. The authors pointed out that the greatest cost savings were accomplished by mechanization of the stem processing. If a cable-supported harvesting operation was nevertheless necessary, applying a harvester would not automatically be

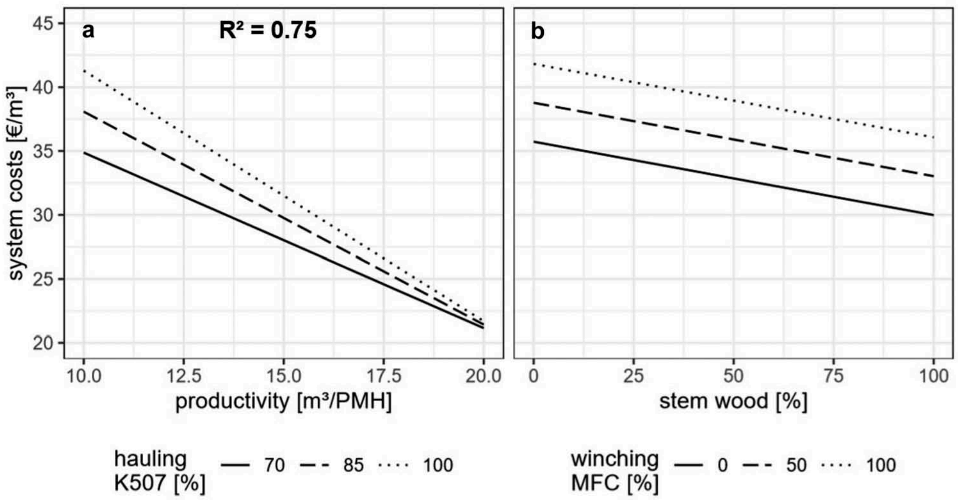

Figure 5. Total system costs with the K507 as a function of (a) the productivity during extraction and the log proportion extracted with the cable yarder (adjusted for: winching = ~16%, stem wood = ~66%) and (b) the proportion of winched timber with the MFC and the percentage of roundwood related to total log volume (adjusted for hauling K507 = ~91%, productivity = 13.5 m^3/PMH). The analysis did not include costs of piling with the skidder. R^2 refers to (a and b).

Table 10. AIC-based stepwise multiple regression model and test statistics for harvesting costs using the V400, without piling.

Formula*			R2	Adj. R2	SE	*p*-value	*N*
$C_{V400} = KV_0 + KV_1 \times Y + KV_2 \times HA \times Prod_{V400}$			0.71	0.70	4.10	<.0001	45
	Coefficient	***t*-statistic**					
KV_0	21.73	5.65			3.85	<.0001	
KV_1	0.45	8.76			0.05	<.0001	
KV_2	−0.03	−9.28			.003	<.0001	

*C_{V400} = harvesting costs using the V400, without piling [€/m^3_{ub}]; Y = percentage of proportionally yarded timber using the V400 [%]; $Prod_{V400}$ = productivity of the V400; SE = standard error.

more cost-efficient (Heinimann et al. 2001). Overall, it was shown that the costs depend on the stem volume, the extraction distance and also additional variables such as the silvicultural prescription. This finding could probably be attributed to the fact that costs are largely determined by productivity (Keegan et al. 2002; Hartley and Han 2007; Ghaffariyan et al. 2009; Spinelli et al. 2017b).

Notably, the major advantage of cable-based extraction systems is their independency from many system-influencing factors. Planning and implementation can be done almost anytime and on any terrain. In steep terrain there is no cost-efficient alternative to the cable-based extraction. Additionally, soils in flat terrain might be too sensitive or have other limitations (e.g. boulder overlay) that make ground-based extraction methods unfavorable.

The amount of extracted timber did not differ throughout the sampling period, possibly indicating that cable yarding was of constant importance. The analysis showed that the V400 was used less frequently than the K507, probably because it is not suitable for stands with timber of large dimensions, for long-distance yarding or for horizontal yarding.

In the case of the K507, the percentage of horizontal yarding increased from about 20% in 2013 to more than 50% in 2018. However, it is important to mention that the percentage of salvage logging was large in 2018 but these operations were excluded from the study. Hence, the overall volume considered in 2018 was only around 5,555 m^3_{ub}, which was lower than the yearly average (11,481 m^3_{ub}/y).

In the analyzed period, no increase or decrease in the use of the mini forestry crawler was observed. Nevertheless, the crawler was consistently used for pre-winching around 20% of the total volume. Data showed that the productivity of the K507 was significantly higher when trees were pre-winched by the mini forestry crawler. However, its use is limited by a maximum slope of around 55%, as well as by difficult micro topography and timber of larger dimensions (around 2 m^3/tree) (Kirsten 2019).

When considering tree types, we did not observe any significant differences between the amount of extracted hardwoods and softwoods. Keeping in mind that increasing the proportion of hardwoods is one of the management strategies in response to climate change, cable yarding might be an attractive option for the extraction of hardwoods in future. This will hold true at least until mechanized systems are fully developed for hardwood dominated stands.

Installation times

Installation times are strongly influenced by the length of cable corridors (Stampfer et al. 2006; Borz et al. 2011). Borz et al. (2011) reported 2.1–3 h as the average time required to dismantle a MOUNTY 4100 on short cable corridors (150–300 m) when no intermediate supports are required. In our case, the total time for setting up, installing intermediate supports and dismantling was around 8 ± 4 h per cable corridor. However, results were dependent on the type of yarder: the time required was significantly shorter for the mid-sized tower yarder V400 compared to the K507, which is in line with findings reported by Stampfer et al. (2006). This result seems reasonable because the cable corridors were shorter when the V400 was used and usually required fewer intermediate supports. Other aspects also affect the time required, such as the height of intermediate supports or the yarding direction (Stampfer et al. 2006; Erber et al. 2017). For instance, Stampfer et al. (2006) reported that a downhill cable corridor required more time compared with an uphill cable corridor.

Based on our data, there was no evidence for a significant impact of the yarding direction (uphill vs. horizontal) on the installation times. Horizontal yarding was expected to cause longer installation times because a third cable is required. As our data only included information about the total installation time per operation and the total number of cable corridors, no further analysis could be undertaken to identify possible significant relationships. For the same reason, we could not verify the hypothesis that the use of a mini forestry crawler for pre-winching reduces the overall number of cable corridors required. Future studies should report the installation times per cable corridor.

Stampfer et al. (2006) reported an increase in required installation time with increasing length of the cable corridors and number and height of intermediate supports. Our results confirmed that the time required correlated with the number of intermediate supports, which in turn depended on the length of the cable corridors and the yarding direction (more for horizontal yarding). Nevertheless, our model described only 41% of the variance of the dependent variable, which indicated the presence of further influential factors that we did not analyze (e.g. height of intermediate supports).

Surprisingly, the percentage of hardwoods turned out to have a significant impact on the installation times. With higher percentages of hardwoods, longer installation times were reported for cable corridors longer than approximately 100 m. This might be explained by the requirement of more intermediate supports on longer cable corridors. Corresponding installation times were probably affected by hardwood stems, which usually provide more hazards for climbing.

Machine productivity

For the V400, the average productivity reached in single tree harvesting was 8.9 ± 2.1 m^3/PMH_{15}, which is a bit lower but still in line with findings from other studies analyzing similar machines. For example, Stampfer et al. (2010) analyzed the Wanderfalke and reported productivities of 12.1–12.5 m^3/PMH in strip cuts. In our study, productivity was significantly higher when the K507 was used (13.3 ± 2.6 m^3/PMH_{15}) than when the V400 was employed. Ghaffariyan et al. (2009) also reported that yarder type impacts productivity. Spinelli et al. (2017b) identified an effect on cost-efficiency in the range of 30% caused by the specific carriage type used for hauling. The carriages applied in the investigated systems differed in our study as well, which might explain some observed differences in productivity.

As expected, productivity was strongly impacted by tree DBH. This so-called law of piece-size was reported earlier in many studies (e.g. Ghaffariyan et al. 2009; Stampfer et al. 2010; Huber and Stampfer 2015; Lindroos and Cavalli 2016; Hoffmann et al. 2016; Erber et al. 2017).

Erber et al. (2017) analyzed the productivity of the K507 based on the log volume per time. They included stem size, yarding direction (uphill, downhill), extraction distance and silvicultural treatment as significant independent variables to determine the corresponding productivity model. Interestingly, they reported lower productivities upon downhill yarding. Applying our model led to comparable results when only uphill yarding was considered: 12.42–12.68 m^3/PMH_{15} (this study) vs. 10.66–17.68 m^3per productive system hour including delays up to 15 minutes (Erber et al. 2017). It should be mentioned that the calculation was based, on the one hand, on the silvicultural treatment responsible for the lowest productivity and, on the other hand, on the treatment responsible for the highest productivity, both applied in single tree harvesting operations. This approach enabled the calculation of a range representative of all silvicultural treatments, as the treatments of individual stands were unknown in our study. In addition, stem size and DBH were selected to obtain comparable stem properties. The length of the cable corridor was set at 260 m in Erber et al. (2017), and this value was the average length of the cable corridors in our study.

Our productivity models described only 21–48% of the variance of the dependent variable, leading to the conclusion that other factors influenced productivity as well. Extraction distance and silvicultural treatment might have been important in our investigation, given that their effect has been well described in the literature (Ghaffariyan et al. 2009; Hoffmann et al. 2016; Erber et al. 2017).

The data used in this study were not measured per cable corridor or per working cycle. Thus, it is likely that not all relationships were identified. For example, horizontal yarding was not identified as having a significant impact on productivity, whereas other studies reported such an effect. For instance, downhill yarding had a lower productivity compared with uphill yarding when the tower yarders K507 (Erber et al. 2017), Urus MIII (Eroglu et al. 2009) and Syncrofalke (Ghaffariyan et al. 2009) were used. Since the haulback line is required in both downhill and horizontal yarding, similar effects can be expected.

There are further factors determining the productivity of extraction, such as professional training (Haynes and Visser 2001) and order of the trees after felling (Hoffmann et al. 2016). Since a slash in the stand leads to working delays, the resulting log presentation has a low quality and productivity is reduced. Interestingly, in our analysis the use of a mini forestry crawler enhanced the productivity of the cable yarder. Since this machine moves the logs to the cable corridor, the observed relationship might rely on an improvement in the arrangement of the trees after cutting, as well as a reduction in lateral yarding distance, which had a negative effect on productivity (Ghaffariyan et al. 2009).

Production costs

Overall, the production costs of the two systems analyzed in this study had a comparable range, between 32.5 ± 5.9 €/m^3 (K507) and 36.2 ± 7.5 €/m^3 (V400) (both including processing at roadside). However, the K507 system was used to process timber of significantly larger dimensions, which was more cost-efficient.

Spinelli et al. (2010) reported system costs for the provision of smaller sized timber of 24–32 €/m^3 in Italy. In general, the comparison of costs between different countries and among different environmental conditions is difficult. Additionally, costs of cable yarding as such vary greatly because various aspects have a strong impact on productivity.

Silvicultural treatments, for instance group selection, affect the costs by influencing the working time per cycle (Hartley and Han 2007) and installation times in relation to the total harvested timber volume. Hence, clear-cuts provide the best cost-efficiency (Hartley and Han 2007).

Our analysis showed an interaction between yarding productivity and the percentage of timber that was extracted by yarder, and both influenced costs. This relationship was observed for the K507 and also for the V400. In cases of high productivity, costs were reduced when log extraction nearby the road was carried out with a tower yarder and not with the skidder. The threshold was higher than the average productivity. Based on the data we recommend using the skidder for extraction up to a distance of 50 m whenever possible. This supports findings by Enache et al. (2016) who analyzed more than 600 operations in the European mountains and reported that a skidder was the most common extraction method. Nevertheless, the skidder cannot be used in all cases (e.g. in steep terrain).

Our results indicated that the combination of the investigated system with a mini forestry crawler led to an increase in costs. Even though pre-concentration of logs at the cable corridor increased the productivity of the tower yarder, the related cost-reducing coefficient originating from this productivity impact was less than the cost-increasing effect. However, aspects of increased safety and reduced physical demand of personnel when using a MFC were not considered. A previous study considered the use of a mini forestry crawler in combination with a harvester-forwarder system (Berendt et al. 2018). The authors reported an increase in the total production costs with increasing distance between the skid trails (Berendt et al. 2018). However, the choice of this system results in an improvement of soil protection because the trafficked area in a forest stand is reduced.

Regarding the K507 system, the proportion of stem wood was additionally identified as having a significant influence on the production costs, with costs decreasing with a greater proportion of stem wood. Since this variable was not found to affect the productivity of the cable yarder, these data suggest that the cost-reducing effect relies on additional operational steps. For instance, the processing may be more efficient because a few thick branches and the crown are processed motor-manually in the stand. Hence, mechanical processing is redundant.

Results related to the V400 did not suggest further impacts on production costs. The costs for processing were added based on hypothetical data, thus considering three DBH classes. These hypothetical costs were considered to be 5.54–7.13 €/m^3. The company that provided the analyzed dataset suggested 6–8 €/m^3. Further factors influencing the productivity of the processing were not considered. Hence, the calculated regression model may not respect the effects of all conditions.

Conclusions

We recommend using a skidder for extraction up to a distance of 50 m. In cases of high productivity, costs were reduced when extraction was carried out using a yarder and not a skidder. The major advantage of cable-based extraction systems seems to be their independency from many system-influencing factors. Planning and implementation can be done almost anytime and on any terrain. This, together with soil protection considerations, might be one reason why horizontal yarding has increased considerably in recent years.

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