



Timber Provision on Soft Soils in Forests Providing Protection Against Natural Hazards: A Productivity and Cost Analysis Using the Koller 507 in the Horizontal Yarding Direction in Switzerland

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Abstract

Forest soils can be sensitive to traffic for various reasons, such as a high water table and the absence of sturdy ground, both of which can lead to fragile ground conditions under wet weather conditions. Extracting timber from such stands is a challenge, and cable-based systems might be the best option. While damage to the remaining stand and to the soil during extraction is not always avoidable, the use of cable-based systems completely eliminates ground-based traffic in the case of fully suspended loads and at least reduces soil compaction, soil surface damage and erosion. From a technical viewpoint, cable-based systems can be applied in most forest types and at almost any time if they are equipped properly and with an appropriate configuration (e.g. with all-terrain cable yarders). However, only a few previous studies have been focused on the productivity and related costs that can be expected when cable-based systems are used in flat and environmentally sensitive areas. Therefore, we evaluated a forest operation using a Koller tower yarder with the aim to develop a productivity model that makes it possible to predict the productivity of comparable yarding operations beforehand and estimate related costs. In June 2021, we collected data from 473 cubic metres over bark (m^3ob) during 104.25 h of commercial operation. We analysed the resulting 276 work cycles using ordinary least squares regression models. We categorised the work steps into felling (28.3%), yarding (68.0%) and piling (3.7%). The average yarding cycle time was 10.77 ± 5.40 min and resulted in an average yarding productivity of $9.95 \text{ m}^3\text{ob PMH}_{15}^{-1}$. The variable *payload*, which was suboptimal in the analysed case, was the predictor with the greatest impact on productivity. Production costs were $86.65 \text{ CHF m}^3\text{ob}^{-1}$ at roadside, corresponding to $80.59 \text{ € m}^3\text{ob}^{-1}$.

Keywords Flat terrain · Forest operation · Lateral yarding · Soil-sensitive terrain · Working-time study · Yarder

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Introduction

The impact of vehicle traffic on forest soils has been the subject of research almost since self-propelled vehicles became common (Wästerlund 2020). It is generally agreed that forest soil compaction (Kremers and Boosten 2018; Hansson 2019) should be avoided to maintain forest growth and the capability to provide biodiversity and multiple ecosystem services in the long term (Gebauer et al. 2012; Schweier et al. 2019; Page-Dumroese et al. 2021). Closer attention to soil protection is required because an increasing number of forest stands in trafficable terrain grow on soils on which vehicles cannot establish sufficient traction. This makes these soils sensitive to traffic (Cambi et al. 2015; Lehtonen et al. 2019), and it increases the erosion potential of forest infrastructure (Haas et al. 2020; Rodrigues et al. 2020). Both issues are exacerbated by more intensive precipitation and shorter frost periods in winter, which are forecasted to increase in the future (Sinha and Cherkauer 2010; Ménégou et al. 2020; Kahraman et al. 2021).

There is therefore an urgent need to identify the machine-based forest operations with the smallest impact on soils in order to ensure sustainable forest management (Marchi et al. 2018; Schweier et al. 2019; Picchio et al. 2020). The aim of many studies has been to assess and reduce the impact of harvesting and extraction machines on forest soils (Sakai et al. 2008; Labelle and Jaeger 2011; Abdi et al. 2017; Giannetti et al. 2017; Cambi et al. 2018; Labelle et al. 2018; Grigorev et al. 2021), and effective technological solutions have been developed (Engler et al. 2021), such as the use of machines equipped with bogie tracks (Edlund et al. 2013; Cambi et al. 2016; Ala-Iiomäki et al. 2021).

On sensitive terrain, the use of cable-based systems might be an appropriate alternative to conventional extraction systems using ground-based machines (Erber and Spinelli 2020; Schweier and Ludowicy 2020) because they have a low impact on soils. Usually, cable-based systems are only applied in steep terrain because they are more expensive than conventional systems (Abbas et al. 2018). However, from a technical viewpoint, cable-based systems can be applied in most forest types and at almost any time if they are equipped properly and with an appropriate configuration (e.g. with all-terrain cable yarders). While damage to the remaining stand and to the soil during extraction is not always avoidable, the use of cable-based systems completely eliminates ground-based traffic in the case of fully suspended loads and at least reduces soil compaction, soil surface damage and erosion. Moreover, extraction in a cable-based system can result in lower environmental impacts (Spinelli et al. 2010; Enache et al. 2016; Bont et al. 2019). This argument represents a new perspective in the application of cable yarders in environmentally sensitive areas (Schweier and Ludowicy 2020; Schweier et al. 2020).

Only a few existing studies have been focused on the productivity and related costs of cable yarders in environmentally sensitive areas. Traditionally, most studies refer to common yarding operations on steep terrain in the uphill and sometimes the downhill direction (Erber et al. 2017). Therefore, the main goal of this study was to analyse a cable yarding operation that was conducted in an area with sensitive soil. Specifically, the objectives were:

- to analyse the productivity of the yarding process and to identify variables with a significant influence on productivity;
- to develop a productivity model that can be used to estimate the productivity of comparable yarding operations before their implementation;
- to investigate the installation times of cable yarders, which contribute significantly to the total costs of felling and extraction by cable yarders;
- to estimate the resulting production costs.

Materials and Methods

Study Site

The study was carried out in a state forest of the region Gottschalkenberg in the Swiss canton of Zug (47°08'45"N, 8°40'23"E; ca. 1000 m a.s.l.). In general, the terrain in the study area is flat with a few exceptions, namely occasional block overlays and two ravines containing a stream. The average inclination of the cable roads is 5–7.5%. The forest is accessible throughout the area of the forest operation. One dominant forest type in that area is fir–beech forest, with the predominant species beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), spruce (*Picea abies* (L.) H. Karst) and sycamore maple (*Acer pseudoplatanus* L.). Up to 85% of the ground is covered by a layer of moss. The herb layer is characterised by purple lettuce (*Prenanthes purpurea* L.), sweet woodruff (*Galium odoratum* (L.) Scop.) and wood cinquefoil (*Mercurialis perennis* L.), among other species. The edaphic conditions include a low to high degree of wetness, with some stagnation and a medium nutrient storage capacity.

The other dominant forest type in the study area is whip-moss spruce–fir forest. Predominant tree species are spruce, silver fir and beech, supplemented with rowan (*Sorbus aucuparia* L.) and oak species (*Quercus* sp.) in the shrub layer. The coverage of the moss layer is around 80% and that of the herb layer is about 50%. The latter is dominated by blueberry (*Vaccinium myrtillus* L.), wood sorrel (*Oxalis acetosella* L.) and hairy wood-rush (*Luzula pilosa* (L.) Willd.). Ferns (*Blechnum spicant* (L.) Roth and *Dryopteris* sp.) are common. The subsoil is acidic and the soil has partially moist expressions because permeability is inhibited. The nutrient storage capacity is good to very good (Frehner et al. 2005; Ziegler 2014).

The five-hectare forest area in which the forest operation was conducted in 2021 is protection service of 2nd priority category (Ziegler and Bernath 2016) due to its function in protection against flooding, landslides and erosion. The stands in the study area have been used for pasture for the last 200 years but have never been completely deforested. Before the forest operation the stocking volume was around 300 m³ ha⁻¹, and about 100 m³ ha⁻¹ was removed during the operation. The forest area is managed as continuous cover forestry with single to group plentering; thus, many different tree dimensions and heights occur. In 2021, the average diameter at breast height (DBH) was 24 cm and ranged from < 10 cm to > 60 cm. The stand consisted of 60% spruce that was reforested on a large scale, as well as 20% naturally established white fir and 20% broadleaves (10% beech, 8% sycamore maple,

2% ash). However, due to an infestation of the fungus *Hymenoscyphus fraxineus* (T. Kowalski) Baral, Queloz, Hosoya, comb. nov., most of the ash trees were dead. When possible, they were left in the stand to support biodiversity and were removed only when necessary due to safety reasons.

Analysed Forest Operation

The commercial operation was planned by the local forester. It was a selective cutting that was conducted to maintain the protection service of the forest. Although this study was mainly focused on the yarding of the wood, the full forest–wood chain is as follows:

Felling At first, trees were felled motor-manually by a team of two to three forest workers (from the state forest's own labour force) between April and June 2021. In principle, the tree-length harvesting system was applied (Kellogg et al. 1993). However, there was a modification because forest workers cut most trees motor-manually into logs before extraction. This was done to avoid injuries to the forest floor during yarding, as the soil was very wet and sensitive to compaction, which was actually the reason for choosing a cable-based extraction system. The cable yarder was not yet installed during felling, but it was clear where the two cable roads would be located. Their lengths were 551 m and 637 m in slope distance, and the distance between the two cable roads was between 61 and 85 m (Fig. 1).

Yarding After the trees were felled, the extraction was conducted in June 2021 by a contractor using a cable-based system that included a tower yarder (Koller Forsttechnik GmbH, Austria, Type K507; Fig. 2) with a mounted processor (Konrad Forsttechnik GmbH, Austria, Type Woody 60; Fig. 3). The electrically powered Eckboost (Konrad Forsttechnik GmbH, Austria) was used as carriage.

Anchor trees, tail trees and intermediate supports (two per line) were identified beforehand by the yarding contractor and the local forester working together. The K507 was set up on the forest road and installed by a team of four to five people. After the tower yarder was set up, the full trees and logs were yarded to the forest road and picked up by the processor. This was done by a team of two people, but it

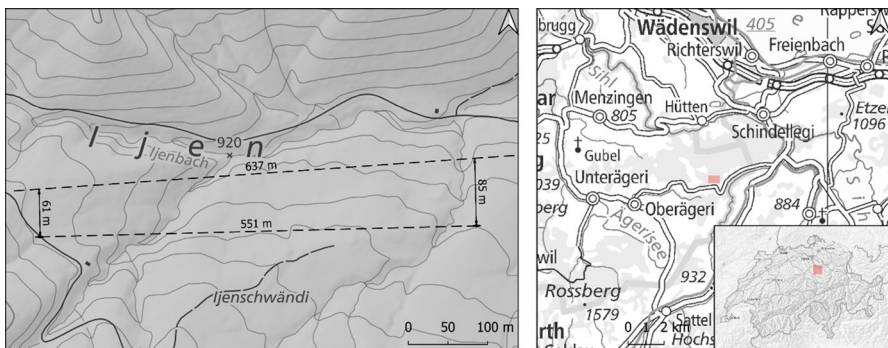


Fig. 1 Position, distance and length of the cable roads (left) and the location of the study site in Switzerland (right) (47°08'45"N, 8°40'23"E). Reproduced with permission from swisstopo (JA100118)



Fig. 2 The K507 is mounted on a truck and applied with a three-cable system due to the horizontal yarding direction. An Eckoboost (Koller Forsttechnik GmbH, Austria) was used as carriage, with a maximum load capacity of 4 t (Fig. 3)

was not the same team every day and not all workers had the same level of experience. The full trees and logs were immediately processed, i.e. delimited, measured, cut-to-length and then piled. This was done because there was not adequate storage capacity next to the yarder, as is typically the case.

Piling A small truck with a crane was used sporadically for sorting and piling of the different assortments along the forest road before on-road transport (Fig. 4).

Transport Five different assortments were produced. The share for material use (roundwood) was 74% and that for energy use was 18%. Another 8% remained in the forest after felling to serve as potential habitat trees, thereby fostering biodiversity. All assortments were transported by trucks to regional suppliers (not covered in this study).

Data Collection

The yarding operation was conducted within 10 working days between 19 May and 02 June 2021. The average daily working time was 9.5 h. The driving time from site to company and vice versa (ca. 20 min each) was considered in the total working time (TWT), but not in the productive time.

The overall operation was accompanied by a team of two researchers conducting a time and motion study, both equipped with a chronometer. One observed the processor and carriage at the forest road, while the other observed the forest worker(s) who attached the logs at the choker in the forest stand. One yarding cycle was defined as the period from the moment when the carriage started moving from the tower yarder processor until the point when it started moving for the next time. Processing



(a)



(b)

Fig. 3 Operation of the Koller Eckoboost carriage



Fig. 4 Piling of assortments by truck

work cycles were split into processing and delay times. In total, data from 473 cubic metres over bark (m^3ob) were collected during 104.25 h and 276 work cycles, with 211 m^3ob harvested in the first and 262 m^3ob in the second cable road. The harvested volumes were reported for each work cycle by the machine operator of the tower yarder processor, who saw the respective columns in the display of the board computer and reported them via radio.

Determination of Productivity

The time required for installation was recorded, i.e. the time spent setting up and dismantling the cable yarder in both cable roads. Furthermore, the following operation times were recorded for each cycle:

Yarding

- Productive yarding time (*yard_prod_t*): one cycle starts when the carriage starts moving away from the tower yarder processor, (=outhauling) and it ends when the carriage returns back to the tower yarder processor and stops moving (=inhauling); including delays of up to 15 min.

- Yarding waiting time (*yard_wait_t*): begins when the carriage stops at the tower yarder processor and ends when the carriage starts moving away from the tower yarder processor (= unhooking).
- Total yarding time (*yard_tot_t*): is the sum of productive the yarding time and the yarding waiting time.
- Lateral yarding (*latyard_t*): begins when the carriage stops and ends when trees and logs are in the skyline corridor and the carriage starts moving towards the tower yarder processor (= hooking).

Processing

- Productive processing time (*proc_prod_t*): processing time, without delays.
- Total processing time 15 (*proc_prod_15_t*): processing time, including delays of up to 15 min.

Machine productivity was defined as the volume (m³ob) extracted per productive machine hour (PMH₁₅), including delays of up to 15 min. To determine the PMH₁₅, all recorded cycles ($N=276$) were analysed. Those that were associated with indirect machine hours (IMH; e.g. service time, such as repair and maintenance, or refuel time, including delays of up to 15 min), unproductive machine hours (UMH; e.g. delay time due to breaks or personnel needs; Rickards et al. 1995) or incomplete cycles ($N=34$) were not considered for the analysis of the PMH₁₅, resulting in a total of $N=240$. Table 1 shows the productivity response variables that were derived for model building. Analyses were conducted to determine if the explanatory variables (predictors) shown in Table 2 had a significant impact on the yarding or processing productivity.

All of the variables listed in Tables 1 and 2 were measured during the operation. The terrain difficulty during lateral yarding (low, medium or high) was evaluated by visual estimation based on the authors' personal experience. The level of experience of the workforces was assigned according to their level of education:

- E: still in education, lowest experience
- W1: trained workforce 1, medium experience
- W2: trained workforce 2, medium experience
- W3: trained workforce 3, medium experience
- H: head of the enterprise most experienced workforce.

Table 1 Productivity response variables (in m³_{ob} PMH₁₅⁻¹)

Response variable	Label	Formula
Productive yarding productivity	<i>yard_prod_prod</i>	Payload * $\text{yard_prod_t}^{-1} * h$
Total yarding productivity (incl. delays)	<i>yard_tot_prod</i>	Payload * $\text{yard_tot_t}^{-1} * h$
Lateral yarding productivity	<i>latyard_prod</i>	Payload * $\text{latyard_t}^{-1} * h$
Productive processing productivity	<i>proc_prod_prod</i>	Payload * $\text{proc_prod_15_t}^{-1} * h$

Yard_prod_t^{-1} = productive yarding time; yard_tot_t^{-1} = total yarding time; latyard_t^{-1} = lateral yarding; $\text{proc_prod_15_t}^{-1}$ = total processing time 15; h = hour

Table 2 Analysed explanatory variables (predictors)

Predictor	Label	Unit	Description
Yarding distance [m]	<i>yard_dist</i>	m	Distance between yarder processor and carriage
Lateral yarding distance	<i>laryard_dist</i>	m	Distance between carriage in the middle of the skyline corridor and logs/trees
Lateral yarding difficulty	<i>laryard_diff</i>	1–low 2–medium 3–high	Lateral yarding difficulty due to terrain (considering microtopography, regeneration/ground cover, stand density, block overlays and slope gradient)
Payloads per cycle	<i>load_pieces_no</i>	no	Number of logs/trees per cycle
Payload	<i>payload</i>	m ³ _{ob}	Volume per cycle
Average piece volume	<i>avg_piece_volume</i>	m ³ _{ob}	Volume per log/tree
Person yarding	<i>resp_person_yard_proc</i>	person	Operator of the tower yarder processor
Person lateral yarding	<i>resp_person_laryard</i>	person	Forest worker operating in the field and responsible for carriage loading

Statistical Analysis

Regression Models

Ordinary Least Squares (OLS) regression models were used to predict productivity. The OLS regression model formulation is defined in Eq. 1:

$$Y(x) = \beta_0 + \beta_1 Z_1 + \beta_2 Z_2 + \dots + \beta_p Z_p + \varepsilon(Z) \quad (1)$$

with error term $\varepsilon(Z)$ independent and identically distributed, $E(\varepsilon(Z)) = 0$, and $\text{Var}(\varepsilon(Z)) = \sigma^2$, where $Y(x)$ is the response variable, $\beta_0 \dots \beta_p$ are the regression coefficients, $Z_1 \dots Z_p$ denote the predictor variables, and p is the number of predictor variables. All models are displayed using the following formatting: $Y \sim Z_1 + Z_2 + \dots + Z_p$ (see Table 4 in the results section).

Model Selection

The initial model tested was the complete model, containing all predictors but without interaction terms (step 1). To find a satisfactory relationship between the goodness of fit and the simplicity of the model (to avoid overfitting), a further model formulation was evaluated by performing variable selection based on the Akaike Information Criterion (AIC, Akaike 2011; step 2). Next, a model diagnosis was done (step 3). This was an essential step to perform before any findings from the summary output, confidence intervals or predictions could be interpreted. Model diagnosis included checking the error assumptions using residual analysis and was done by visually analysing the following plots: normal plot, tukey-anscombe-plot, scale-location plot, leverage plot, and a plot of each potential predictor versus the residuals (see Appendix).

If the error assumptions were not fulfilled, two options were pursued. Option 1 (step 4) was to add meaningful interaction terms. In the case of the yarding operation, for example, a potentially meaningful interaction term was between *yard_dist* and *payload*. Option 2 (step 5) was to check whether a predictor or the response variable required a so-called ‘first-aid’ transformation (log, square root or arcsine). In this case, the model fitting started anew, i.e. steps 1 to 3 were performed again. The formulations for the best-performing model are given in Table 4 in the results section.

Model Assessment

Root mean square error (RMSE) from leave-one-out cross-validation (LOOCV) was used to denote model accuracy (Eq. 2):

$$RMSE = \sqrt{\frac{\sum_{x \in s} (\hat{Y}(x) - Y(x))^2}{n}} \quad (2)$$

where $Y(x)$ is the observed productivity for one cycle $x \in (s)$ [$\text{m}^3 \text{PMH15}^{-1}$], $\hat{Y}(x)$ is the predicted productivity for one cycle $x \in (s)$ [$\text{m}^3 \text{PMH15}^{-1}$], and s is the modelling dataset composed of n cycles. Table 4 lists the multiple linear regression models tested. The statistical software R (version 3.5) was used for model analyses (R Core Team 2018).

The results are presented in terms of the relative RMSE, defined as the RMSE relative to the mean y_{mean} of the observed values (Eq. 3):

$$RMSE[\%] = \frac{RMSE}{y_{\text{mean}}} * 100, \text{ with } y_{\text{mean}} = \frac{1}{n} \sum_{x \in s} Y(x) \quad (3)$$

Adjusted R-squared (R_{adj}) values are also reported, indicating the share of the total variation that is accounted for by the regression, along with the AIC values (AIC 2011), which gauge the goodness-of-fit to the data while also considering the complexity of the model. To check for multicollinearity, the variance inflation factor (VIF) was calculated. A VIF value of one indicates the absence of multicollinearity, while any variable with a high VIF value > 5 indicates a multicollinearity problem and should be removed (James et al. 2017).

If a response variable is transformed during model building, biased estimates of the mean value can be reached after the back transformation (“back transformation bias”), which must be corrected. Flewelling and Pienaar (1981) described a correction factor for logarithm transformations, which was applied in this study.

Production Costs

Costs were calculated using real costs reported by the forester and the entrepreneur and are presented with the time requirements (Table 3 in the results section).

Results

Distribution of Total Working Time

The TWT for the overall forest operation was 498 h (Table 3), split into felling (28.3%), yarding (68.0%) and piling (3.7%).

Felling A sum of 140.5 h was needed for three forest workers to conduct the felling process. The machines and equipment used in this process are listed in Table 3.

Yarding The operation managers from the state forest and the yarding contractor invested a sum of 4.5 h into the planning before the operation (planning on a computer, physical meeting on site; Table 3). Subsequently, a team of four forest workers needed 34 h for the installation and dismantling of the yarder (= 136 h summed working time): 19.5 h for the 650-m-long cable road 1 (13.0 h for installation

Table 3 Time consumption and resulting costs

Process	Staff/machine involved	Staff/machine involved	Unit	Total h	Cost rate	Total cost		
Felling	Staff	Head of the enterprise	Hour	2.00	81.00	162.00		
		Very skilled workforce	Hour	34.00	66.00	2244.00		
		Worker in education	Hour	30.00	35.00	1050.00		
		Worker in education	Hour	42.50	28.00	1190.00		
		Trained workforce 1	Hour	23.50	59.00	1386.50		
		Trained workforce 2	Hour	8.50	59.00	501.50		
		Total staff	Hour	140.50		6534.00		
	Machines	Car (Nissan)	km	168.00	1.00	168.00		
		Chainsaws	Hour	83.00	14.00	1162.00		
		Forestry tractor	Hour	4.00	80.00	320.00		
		Felling lifter	Lump	n.a	300.00	300.00		
		Total machines				1950.00		
		Installing	Staff	Planning	Hour	2.50	55.00	137.50
				Head of the Enterprise	Hour	30.00	55.00	1650.00
Very skilled workforce	Hour			6.00	66.00	396.00		
Worker in education	Hour			27.00	28.00	756.00		
Trained workforce 1	Hour			10.00	59.00	590.00		
Trained workforce 2	Hour			30.25	55.00	1663.75		
Trained workforce 3	Hour			30.25	55.00	1663.75		
Total staff	Hour			136.00		6857.00		
Machines	Forestry tractor		Hour	1.00	75.00	75.00		
	Car (Nissan)		km	288.00	1.00	288.00		
	Koller yarder		Hour	11.00	230.00	2530.00		
	Total machines					2893.00		
	Yarding		Staff	Trained workforce 1	Hour	67.50	55.00	3712.50
Trained workforce 2		Hour		39.75	55.00	2186.25		
Trained workforce 3		Hour		19.00	55.00	1045.00		
Head of the enterprise		Hour		11.25	55.00	618.75		
Worker in education		Hour		4.00	28.00	112.00		
Total staff		Hour		141.50		7674.50		
Machines		Koller yarder	Hour	52.00	230.00	11,960.00		
		Car (Mitsubishi)	km	300.00	1.00	300.00		
		Total machines				12,260.00		
		Sorting and piling	Staff	Head of the enterprise	Hour	18.50	81.00	1498.50
Total staff	Hour			18.50		1498.50		
Machines	Truck with crane		Hour	16.50	80.00	1320.00		
	Total machines		Hour	16.50		1320.00		
Total	Staff					22,564.00		
	machines					18,423.00		
Sum						40,987.00		
CHF/m ³						86.65		

CHF = Swiss franc, 1 CHF corresponds to 0.93 EUR or 1.11 USD (03 August 2021)

and 6.5 h for dismantling) and 14.75 h for the 560-m-long cable road 2 (8.0 h for installation and 6.75 h for dismantling; Table 3). The installation and dismantling accounted for 27.3% of the TWT or 40.2% of the time dedicated to yarding.

For the yarding (without installation and dismantling), a team of three forest workers needed 67.5 h (= 202.5 h summed working time). Thereof, 74.3% was spent on yarding and processing, 11.9% on personal delays, 11.1% on daily routing to/ from the site, and 2.8% on handling machine disturbances. Thus, the productive working time of the yarding was 74.3% (Table 3). The time required for lateral yarding was 3.23 min on average.

Piling The local forester handled the sorting and piling, and prepared assortments for being picked up at the forest road. This task took 18.5 h (3.7% of TWT).

Total Productivity

In total, data from 240 yarding cycles were analysed. The average yarding productivity was $9.95 \text{ m}^3\text{ob PMH}_{15}^{-1}$. Three regression models were fitted to analyse the influence of each model predictor on the productivity of a complete cycle (*yard_tot_prod*): model #1 without person/operator as a predictor (Fig. 5) and two models with a person/operator predictor—model #2 including the machine operator (*resp_person_yard_proc*; Fig. 6) and model #3 including the lateral yarding person/team (*resp_person_latyard*; Fig. 7). A model including both machine operator and yarding team as predictor variables was not fitted because these predictors were highly correlated. All models for *yard_tot_prod* were generated with a log-transformed response

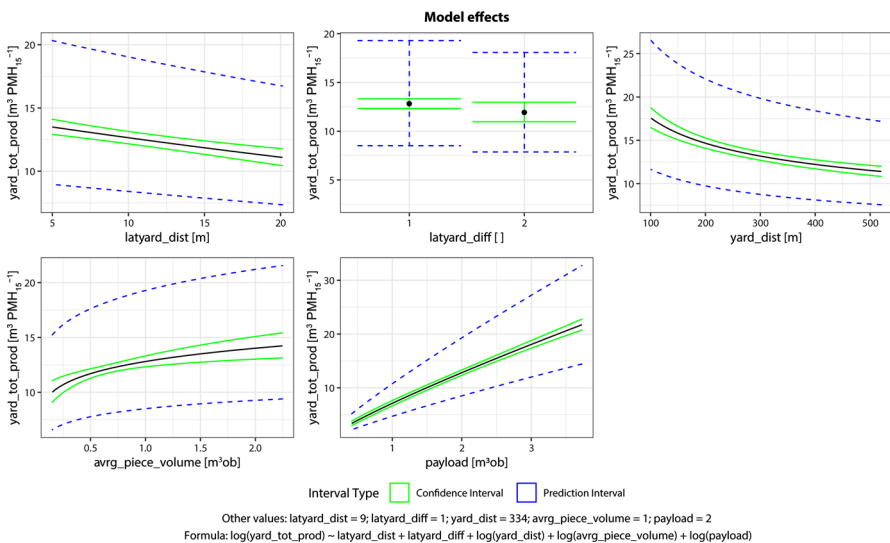


Fig. 5 Model effect plot for model #1, with the productivity of a complete cycle (*yard_tot_prod*) as the response variable and without person/operator as a predictor variable

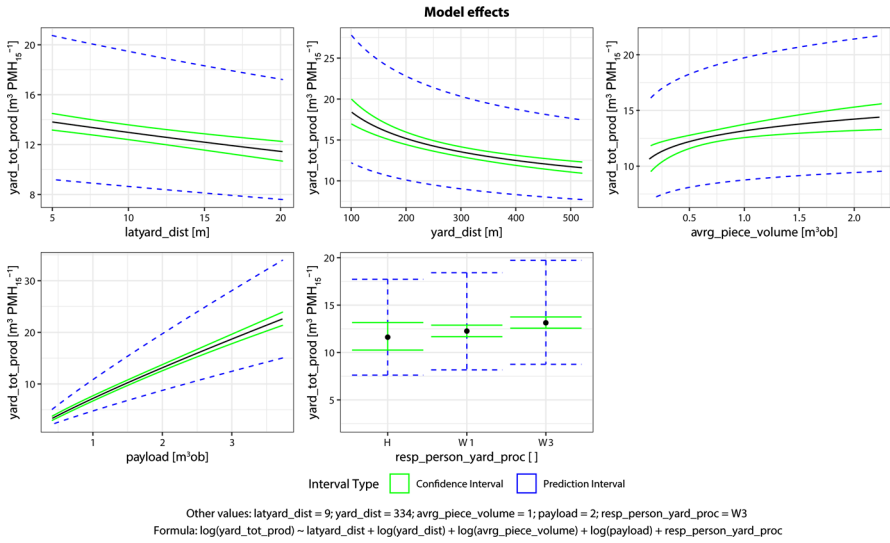


Fig. 6 Model effect plot for model #2, with the productivity of a complete cycle (yard_tot_prod) as the response variable and including the machine operator as a predictor variable

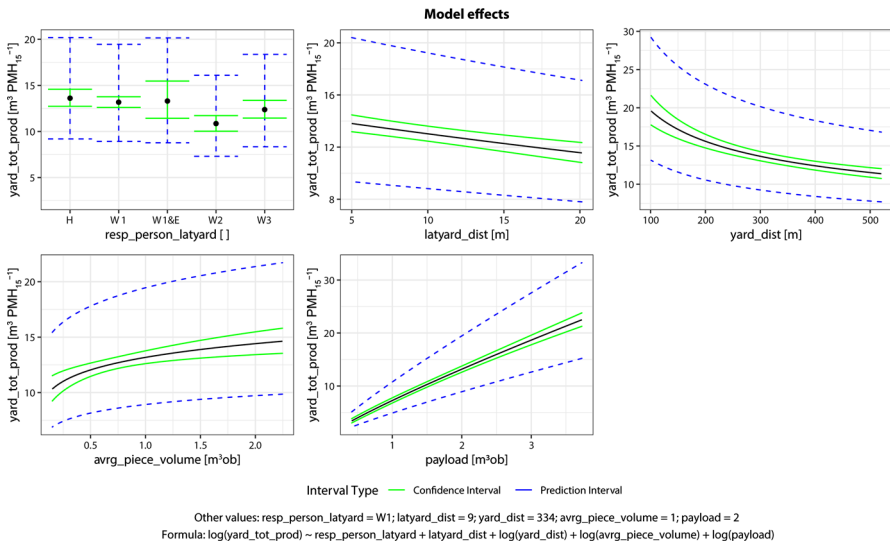


Fig. 7 Model effect plot for model #3, with the productivity of a complete cycle (yard_tot_prod) as the response variable and including the lateral yarding person/team as a predictor variable

variable and mainly also with log-transformed predictors (models #1–3 in Table 4). The models with untransformed response and predictor variables showed significant problems in the model diagnostics (residual plots). This also applies to models for all other response variables. In model #1, the predictors

Table 4 Model overview

#	Response variable	Formula	adjusted R-squared	RMSE absolute	RMSE [%]	Proposed for predictive use
1	yard_tot_prod	$\log(\text{yard_tot_prod}) \sim \text{latyard_dist} + \text{latyard_diff} + \log(\text{yard_dist}) + \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.93	2.60	22.96	X
2	yard_tot_prod	$\log(\text{yard_tot_prod}) \sim \text{latyard_dist} + \log(\text{yard_dist}) + \log(\text{avg_piece_volume}) + \log(\text{payload}) + \text{resp_person_yard_proc}$	0.93	2.46	21.79	
3	yard_tot_prod	$\log(\text{yard_tot_prod}) \sim \text{resp_person_latyard} + \text{latyard_dist} + \log(\text{yard_dist}) + \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.94	2.35	20.78	
4	yard_prod_prod	$\log(\text{yard_prod_prod}) \sim \text{latyard_dist} + \text{latyard_diff} + \log(\text{yard_dist}) + \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.95	2.83	19.09	X
5	yard_prod_prod	$\log(\text{yard_prod_prod}) \sim \text{resp_person_latyard} + \text{latyard_dist} + \text{latyard_diff} + \log(\text{yard_dist}) + \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.95	2.89	19.51	
6	proc_prod_prod	$\log(\text{proc_prod_prod}) \sim \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.79	6.26	52.82	X
7	proc_prod_prod	$\log(\text{proc_prod_prod}) \sim \log(\text{avg_piece_volume}) + \log(\text{payload}) + \text{resp_person_yard_proc}$	0.82	5.74	48.48	
8	latyard_prod	$\log(\text{latyard_prod}) \sim \text{latyard_dist} + \text{latyard_diff} + \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.72	36.69	78.35	X
9	latyard_prod	$\log(\text{latyard_prod}) \sim \text{resp_person_latyard} + \text{latyard_dist} + \text{latyard_diff} + \log(\text{avg_piece_volume}) + \log(\text{payload})$	0.74	37.40	79.86	

latyard_dist + *yard_dist* + *avrg_piece_volume* + *payload* were identified as highly significant (Fig. 5). The RMSE for this model was 22.96%. Both model #2 and model #3 showed a slightly improved RMSE compared with model #1, with model #3 having the lowest and therefore best RMSE of 20.78%. In all three models, the payload played a major role in determining the productivity of a complete cycle.

The lateral yarding distance (*latyard_dist*), the yarding distance (*yard_dist*), and the average piece volume (*avrg_piece_volume*) also had significant effects on total productivity. In particular, the average piece volume had a strong influence on the total productivity for pieces with a volume $< 1 \text{ m}^3$. In model #2, a slightly but significantly higher productivity resulted when machine operator W3 was involved (Fig. 6). In model #3, a slightly but statistically significant (p -value: $1.26\text{e-}05$) lower productivity resulted when person W2 was responsible for lateral yarding (Fig. 7).

Yarding Productivity

To further analyse the productive yarding time (*yard_prod_t*), and thus the productive system hours without delays (PSH_0), we excluded waiting times of the carriage at the tower yarder processor. The average yarding cycle time was 10.77 ± 5.40 min including and 8.17 ± 3.18 min excluding unproductive times.

Two models resulted, one without labour influence (#4) and one including the person responsible for carriage loading (*resp_pers_latyard*; #5). Both models included *latyard_dist* + *latyard_diff* + *yard_dist* + *avrg_piece_volume* + *payload* as significant predictors.

The payload was on average 1.72 m^3 ob per cycle. This was, however, distributed across one to seven pieces, three on average. The lateral yarding distance was on average 8.04 m and conditions were evaluated as “not difficult” overall, with few difficulties occurring 89% of the time and medium difficulties 11% of the time. The lateral yarding distance (*latyard_dist*) and the lateral yarding difficulty (*latyard_diff*) both had a significant influence on productivity.

Model #5 further indicated that the involvement of workers ‘H’ and ‘W3’ had a slight but significant positive influence on productivity (Fig. 8). The model RMSE was lower for the simpler model #4 that included fewer variables. Model effects were similar to those for the predictor *yard_tot_prod*. A model effect plot is presented only for model #5 (Fig. 8), as results were quite similar for the two models.

Processing Productivity

One processing cycle was defined as the period from the moment when the boom with grapple started to move (to take logs from the carriage) until the next carriage arrived at the tower yarder processor and the boom with grapple started to move again. The average processing cycle time was 11.0 ± 6.5 min. Within each cycle the following two work steps were carried out: processing (93.2%) and waiting for next carriage including delays (6.8%).

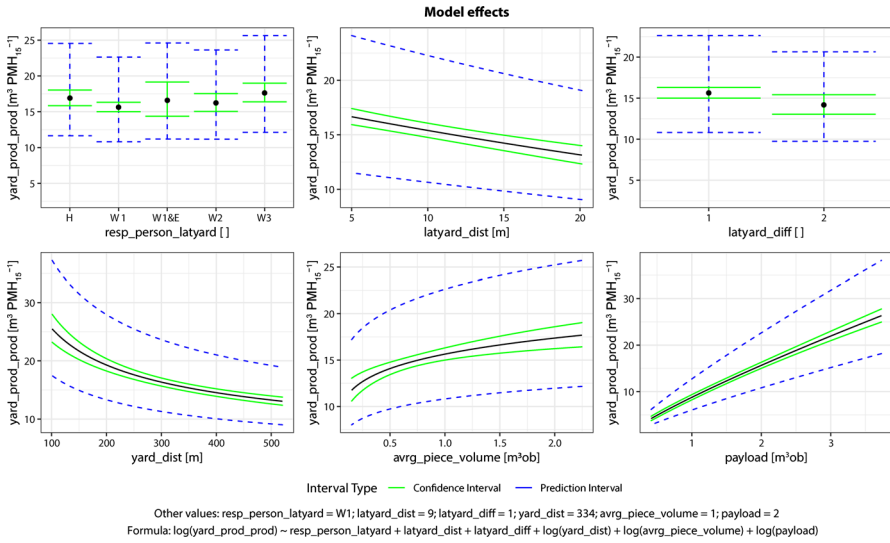


Fig. 8 Model effect plot for model #5, with the yarding productivity (yard_prod_prod) as the response variable and including the person responsible for carriage loading as a predictor variable

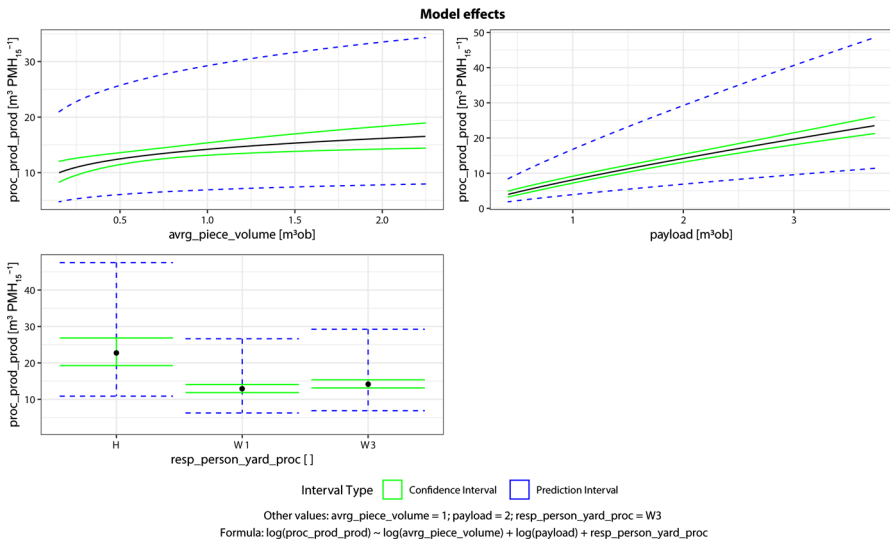


Fig. 9 Model effect plot for model #7, with the productive processing productivity (proc_prod_prod) as the response variable and including payload, average piece volume, and machine operator as predictor variables

To model the processor productivity, we fitted two models: model #6 included ‘avg_piece_volume’ + ‘payload’ as predictors, whereas model #7 additionally included the machine operator as a predictor variable (resp_person_yard_proc). The

effect plot of model #7 indicates that the payload, the average piece volume, and the operator had a large influence on processing productivity (Fig. 9).

Machine operator H, who was the most experienced operator, performed significantly better than the other operators W1 and E. Compared with the models describing the yarding productivity, the models for processing were less accurate, with an RMSE of 48.5% (#7) or 52.8% (#6).

Lateral Yarding Productivity

Two models were fitted to analyse the lateral yarding productivity. Model #8 included the predictors ‘*latyard_dist*’ + ‘*latyard_diff*’ + ‘*avrg_piece_volume*’ + ‘*payload*’. Model #9 further included a variable for the person responsible for carriage loading (*resp_pers_latyard*). All predictors in model #8 had a significant influence on lateral yarding productivity. In model #9, workforce personnel W3 performed significantly better than the others. However, the model performance was rather low for both models, with RMSE values of 78.4% (#8) and 79.7% (#9). The model effect plot for model #9 is displayed in Fig. 10.

Models for Predictive Use

Table 4 lists all the models that were evaluated in our study. For each response variable, we selected the model that we recommend for predictive use (final column in Tables 4, 5). These selected models do not include a variable for the responsible workforce, as this information is difficult to gather in practice. Nevertheless,

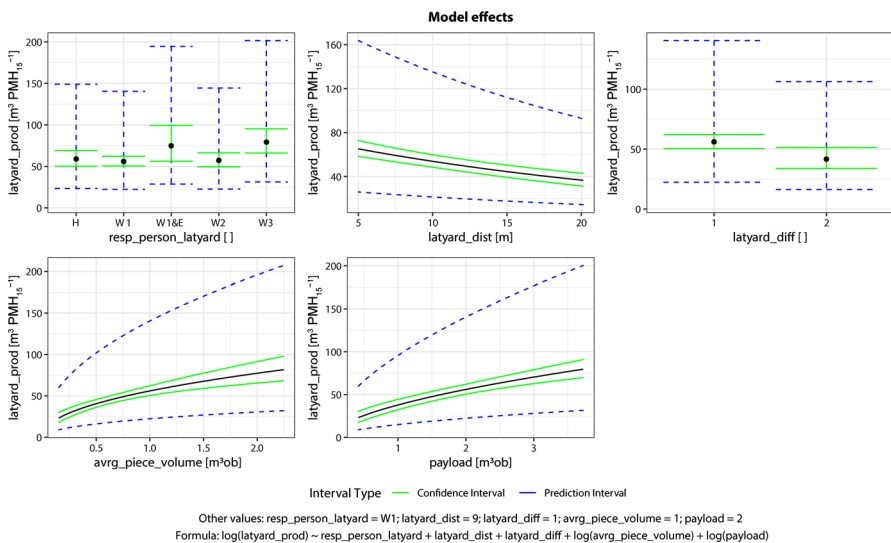


Fig. 10 Model effect plot for model #9, with lateral yarding productivity (*latyard_prod*) as the response variable and including the person responsible for carriage loading as a predictor variable

Table 5 Overview of model formulae recommended for predictive use, including the model coefficients

#	Model formula with coefficients	Remarks
1	yard_tot_prod = $\exp(\beta_0 - 0.013 \text{ latyard_dist} - 0.263 * \log(\text{yard_dist}) + 0.130 * \log(\text{avg_piece_volume}) + 0.847 * \log(\text{payload}))$	$\beta_0 = 3.588$ for latyard_diff = 1; $\beta_0 = 3.516$ for latyard_diff = 2
4	yard_prod = $\exp(\beta_0 - 0.016 \text{ latyard_dist} - 0.406 * \log(\text{yard_dist}) + 0.124 * \log(\text{avg_piece_volume}) + 0.863 * \log(\text{payload}))$	$\beta_0 = 4.657$ for latyard_diff = 1; $\beta_0 = 4.562$ for latyard_diff = 2
6	proc_prod = $\exp(2.064 + 0.237 * \log(\text{avg_piece_volume}) + 0.780 * \log(\text{payload}))$	
8	latyard_prod = $\exp(\beta_0 + 0.036 * \text{latyard_dist} + 0.398 * \log(\text{avg_piece_volume}) + 0.636 * \log(\text{payload}))$	$\beta_0 = 3.861$ for latyard_diff = 1; $\beta_0 = 3.537$ for latyard_diff = 2

models #4 and #8 are the best-fitting models (lowest RMSE) for their corresponding response variable.

Production Costs

Total production costs were 40,987 CHF (corresponding to 38,587 €) at roadside: 55.1% attributed to labour and 44.9% to machines (Table 3). Overall, 72.4% of the costs were attributed to yarding (23.8% installation and dismantling and 48.6% yarding), 20.7% to felling and 6.9% to sorting and piling.

On a relative basis, costs were 86.65 CHF m³ob⁻¹ at roadside (corresponding to 80.59 € m³ob⁻¹). The most expensive step was the yarding (62.76 CHF m³ob⁻¹, with 42.14 CHF m³ob⁻¹ for yarding and 20.61 CHF m³ob⁻¹ for installation), followed by felling (17.94 CHF m³ob⁻¹) and piling 5.96 CHF m³ob⁻¹). Another 5.00 CHF m³ob⁻¹ was incurred for booking and marketing, but this step was not analysed further.

Discussion

Installation Times

The installation and dismantling of the yarder in the 515-m-long and the 590-m-long cable roads was time consuming (136 labour-hours) and accounted for almost one-third of the TWT, even though the operation manager was very experienced. Schweier and Ludowicy (2020) reported a slightly lower time requirement: 133 labour-hours for the installation of 10 cable roads in the horizontal yarding direction. However, the cable road lengths in their study were 270 m on average, thus much shorter than in this study. The time requirement observed here was lower compared with values reported for steep terrain; for instance, Stampfer et al. (2006) reported 25.7 labour-hours as the average time for installation and dismantling in 155 operations in Austria with an average diagonal corridor length of 309 m. In another study, Schweier et al. (2020) reported a time requirement of 8 ± 4 h per cable road as the average value of 57 operations, but the average lengths of the cable roads were shorter: 253 m in the uphill yarding direction and 269 m in the horizontal yarding direction. The authors did not detect a significant difference between yarding directions (Schweier et al. 2020).

Productivity

Three productivity models (#1–#3) were developed that enabled estimation of the overall productivity of comparable yarding operations beforehand. They contained the predictor variables *lateral yarding distance*, *yarding difficulty*, *yarding distance*, *average piece volume* and *payload*, as well as an additional variable for the *personnel* working at the processor (#2) or in the stand (#3). For these models the accuracy was quite high, with a leave-one-out cross-validated RMSE between 21 and 23%

and an adjusted R-squared value between 0.93 and 0.94, which are good values compared with those of other models listed by Lindroos and Cavalli (2016).

The average yarding productivity in our study was $9.95 \text{ m}^3 \text{ob PMH}_{15}^{-1}$, which is lower than results reported in the literature. A reason might be the low payload, as shown by the quantile values of 1.0 (25% quantile)/1.6 (median)/2.4 (75%)/5.3 (100%) and the mean of 1.8 m^3 . In the operation studied here, full trees were cut into one to seven pieces before they were extracted to the landing, in order to reduce damage to the remaining stand and the soil. This was a time-consuming step, not only in felling but also in yarding and processing, and it could be—together with the low average DBH of the removed logs—the main reason for the relatively low productivity. However, it needs to be counterbalanced that the driver for this decision was to avoid damages to the remaining stand and to the soil.

The variable *payload* was the predictor with the greatest impact on productivity. That is why the load formation should be as compact as possible to reach the maximum allowable payload. However, for payload to accurately approximate load volume, many wood pieces would be needed, and for reasons related to protection of the remaining stand these pieces cannot be combined into a larger load. Thus, the actual load weight is often far below the technically feasible payload. Moreover, the tower yarder with a mounted processor is designed for full trees, but in the operation studied here full trees were not moved.

The *lateral yarding distance*, the *yarding distance* and the *average piece volume* also had significant effects on productivity. Average piece volume had a strong influence on the total productivity for pieces below 1 m^3 . The significance of our identified predictors has been confirmed in other studies. For example, Varch et al. (2020) modelled productivity as a function of average tree volume, yarding distance and lateral yarding distance and reported that lateral yarding was the most time-consuming work phase. The same authors confirmed that yarding productivity decreased considerably with increasing yarding distance.

In addition to the models mentioned above, we developed productivity models for the individual processes. The model for the yarding process alone (without delay at the tower yarder) was very similar to the overall model, with the same significant variables, an RMSE of 19%, and an adjusted R-squared value of 0.95 (models #4 and #5). The processing productivity depended on the significant predictors average piece volume, payload and machine operator (model #7) and was less accurate (RMSE = 48%, adjusted R-squared value = 0.82). For machine operator, the level of experience played a major role: when the experienced operator H took over machine control, the productivity almost doubled compared with that with operators W1 and W3. However, in the overall productivity model (#2), which also included machine operator as a predictor, this effect was not observed. This indicates that the productivity of the processing does not play a decisive role in the productivity of the overall system. The importance of matching the various system components to each other was also reported by Kizha et al. (2020).

An additional aspect, which we did not analyse but recommend testing in comparable future studies was whether using double-hitch carriages, as proposed by Spinelli et al. (2021), would improve productivity in terms of time consumption but also in terms of soil protection. Within the scope of this study we could not analyse

whether the type of carriage had an influence on yarding productivity and costs (Spinelli et al. 2017; Varch et al. 2020). This might be interesting to investigate because the electrically powered Eckoboost carriage was developed quite recently. It uses a high-power capacitor as energy storage and is charged when pulling.

When interpreting our results, it must be kept in mind that this was a case study only and not a series of investigations. Nevertheless, it provided interesting insights into yarding on flat terrain. Specifically, the sustainable maintenance of this forest area might be of increasing relevance to ensure the continued provision of its protection function. Further, forest areas like the one studied here play an important role in the provision of renewable resources that are needed for material and energy purposes to substitute fossil products and contribute to a modern bioeconomy.

Production Costs

Production costs, including all work tasks related to felling and extracting timber to the forest roadside, were 86.65 CHF m³ob⁻¹. This value is quite high from an international perspective, but it represents the average harvesting cost in Switzerland when a cable-based system is applied. In a comparison study in France, Erber and Spinelli (2020) reported costs of 12 € m⁻³ for ground-based operations and 48 € m⁻³ for cable-based operations. A similar approach was undertaken by Schweier and Ludowicy (2020), who reported 28.3 € m⁻³ for a ground-based operation and 27.8 € m⁻³ for a cable-based one in southwest Germany. In this case, cable-based operations were cost-competitive when planned well.

It is indisputable that labour costs are much higher in Switzerland compared to other European countries. Thus, the wood price does not cover the production costs. In the specific case studied here, the local forester received subsidies from the state to ensure the maintenance of the forest. Moreover, the subsidies made it possible to keep some harvested trees in the forest stand to serve as potential habitat trees, thereby fostering biodiversity.

Conclusions

In this case study, we analysed the productivity and costs of a cable-yarding operation that was conducted in relatively flat terrain in a forest with a protection function against flooding, landslides and erosion.

The installation and dismantling of the yarder in the two cable roads accounted for almost one-third of the total working time, which confirms that careful planning beforehand is essential for an efficient operation. Still, time requirements were lower compared with the installation and dismantling times previously reported for cable roads in steep terrain. Productivity models (#1–#3) were developed to estimate the overall productivity of comparable yarding operations beforehand. We found that the predictor *payload* had the greatest impact on productivity, stressing the importance of achieving the maximum allowable payload. Cost analysis showed that production costs were 86.65 CHF m³ob⁻¹,

which is in line with other Swiss yarding operations. However, this value is higher than the production costs of ground-based systems and therefore cannot be considered competitive. On the other hand, the ground was wet and conditions did not allow traffic, not even with a tethered winch. Thus, using the yarder was reasonable.

Appendix

Model Diagnostics Plots

See Fig. 11.

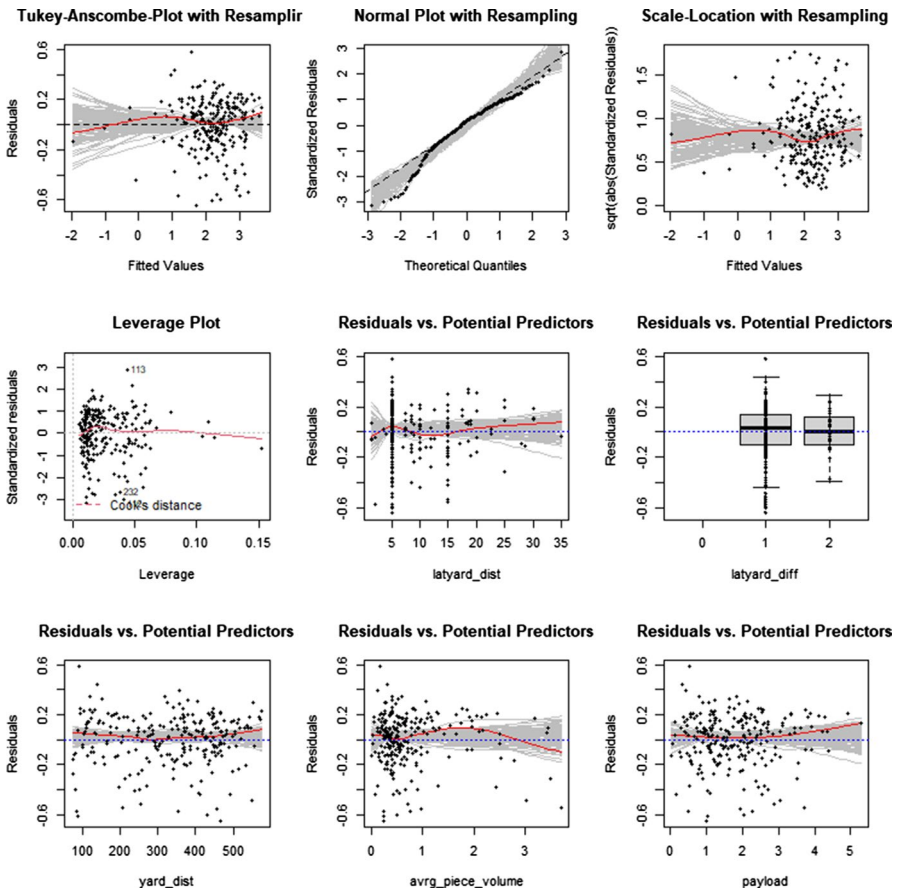


Fig. 11 Model diagnostic plot (residual analysis plot) for model #1

Model Summary Outputs

 Model # 1

Call:

```
lm(formula = log(yard_tot_prod) ~ latyard_dist + latyard_diff +
    log(yard_dist) + log(avrg_piece_volume) + log(payload), data =
    sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.64694	-0.10356	0.03568	0.14029	0.58385

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	3.588000	0.153348	23.398	< 2e-16 ***
latyard_dist	-0.012980	0.002261	-5.742	2.90e-08 ***
latyard_diff2	-0.071634	0.042820	-1.673	0.0957 .
log(yard_dist)	-0.263257	0.027549	-9.556	< 2e-16 ***
log(avrg_piece_volume)	0.130154	0.031542	4.126	5.12e-05 ***
log(payload)	0.847692	0.033751	25.116	< 2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2067 on 234 degrees of freedom

Multiple R-squared: 0.9325, Adjusted R-squared: 0.931

F-statistic: 646.4 on 5 and 234 DF, p-value: < 2.2e-16

 Model # 2

Call:

```
lm(formula = log(yard_tot_prod) ~ latyard_dist + log(yard_dist) +
    log(avrg_piece_volume) + log(payload) + resp_person_yard_proc,
    data = sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.67518	-0.09224	0.03469	0.13617	0.53438

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	3.627272	0.195887	18.517	< 2e-16 ***
latyard_dist	-0.012484	0.002309	-5.406	1.59e-07 ***
log(yard_dist)	-0.280760	0.033697	-8.332	6.87e-15 ***
log(avrg_piece_volume)	0.112225	0.031714	3.539	0.000485 ***
log(payload)	0.869133	0.034074	25.507	< 2e-16 ***
resp_person_yard_procH	-0.054229	0.066191	-0.819	0.413464
resp_person_yard_procW3	0.069205	0.029210	2.369	0.018641 *

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.2048 on 233 degrees of freedom

Multiple R-squared: 0.934, Adjusted R-squared: 0.9323

F-statistic: 549.9 on 6 and 233 DF, p-value: < 2.2e-16

 Model # 3

Call:

```
lm(formula = log(yard_tot_prod) ~ resp_person_latyard + latyard_dist +
  log(yard_dist) + log(avrg_piece_volume) + log(payload), data =
  sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.72581	-0.08372	0.03442	0.13391	0.47457

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	3.993969	0.217449	18.367	< 2e-16 ***
resp_person_latyardW1&E	0.009098	0.077408	0.118	0.907
resp_person_latyardW2	-0.194687	0.043624	-4.463	1.26e-05 ***
resp_person_latyardH	0.033414	0.036626	0.912	0.363
resp_person_latyardW3	-0.062802	0.041704	-1.506	0.133
latyard_dist	-0.011777	0.002198	-5.358	2.04e-07 ***
log(yard_dist)	-0.331120	0.038198	-8.669	7.80e-16 ***
log(avrg_piece_volume)	0.129382	0.031537	4.103	5.67e-05 ***
log(payload)	0.858745	0.033366	25.737	< 2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1965 on 231 degrees of freedom

Multiple R-squared: 0.9398, Adjusted R-squared: 0.9377

F-statistic: 450.8 on 8 and 231 DF, p-value: < 2.2e-16

 Model # 4

Call:

```
lm(formula = log(yard_prod_prod) ~ latyard_dist + latyard_diff +
  log(yard_dist) + log(avrg_piece_volume) + log(payload), data =
  sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.69632	-0.08742	0.02063	0.11456	0.48329

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	4.656564	0.140163	33.222	< 2e-16 ***
latyard_dist	-0.014559	0.002066	-7.046	2.05e-11 ***
latyard_diff2	-0.094651	0.039139	-2.418	0.0164 *
log(yard_dist)	-0.405901	0.025180	-16.120	< 2e-16 ***
log(avrg_piece_volume)	0.124308	0.028830	4.312	2.39e-05 ***
log(payload)	0.863493	0.030849	27.991	< 2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.189 on 234 degrees of freedom

Multiple R-squared: 0.9475, Adjusted R-squared: 0.9463

F-statistic: 844.1 on 5 and 234 DF, p-value: < 2.2e-16

 Model # 5

Call:

```
lm(formula = log(yard_prod_prod) ~ resp_person_latyard + latyard_dist +
    latyard_diff + log(yard_dist) + log(avrg_piece_volume) +
    log(payload), data = sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-0.64939	-0.09425	0.02685	0.11857	0.45963

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	4.667279	0.207097	22.537	< 2e-16	***
resp_person_latyardW1&E	0.058299	0.073587	0.792	0.4290	
resp_person_latyardW2	0.037330	0.041879	0.891	0.3737	
resp_person_latyardH	0.077089	0.034782	2.216	0.0276	*
resp_person_latyardW3	0.119421	0.039520	3.022	0.0028	**
latyard_dist	-0.015692	0.002094	-7.495	1.42e-12	***
latyard_diff2	-0.098185	0.039691	-2.474	0.0141	*
log(yard_dist)	-0.408248	0.036342	-11.234	< 2e-16	***
log(avrg_piece_volume)	0.151404	0.029898	5.064	8.42e-07	***
log(payload)	0.835353	0.031640	26.402	< 2e-16	***

 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.1862 on 230 degrees of freedom
 Multiple R-squared: 0.9499, Adjusted R-squared: 0.9479
 F-statistic: 484.4 on 9 and 230 DF, p-value: < 2.2e-16

 Model # 6

Call:

```
lm(formula = log(proc_prod_prod) ~ log(avrg_piece_volume) + log(payload),
    data = sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-1.55028	-0.20051	-0.03731	0.20322	2.19222

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	2.06444	0.06254	33.010	< 2e-16	***
log(avrg_piece_volume)	0.23697	0.05697	4.159	4.47e-05	***
log(payload)	0.77977	0.06305	12.368	< 2e-16	***

 Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.391 on 237 degrees of freedom
 Multiple R-squared: 0.7959, Adjusted R-squared: 0.7942
 F-statistic: 462.1 on 2 and 237 DF, p-value: < 2.2e-16

 Model # 7

Call:

```
lm(formula = log(proc_prod_prod) ~ log(avrg_piece_volume) + log(payload) +
    resp_person_yard_proc, data = sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-1.48719	-0.17902	-0.01555	0.19719	1.72691

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	1.93198	0.06921	27.916	< 2e-16 ***
log(avrg_piece_volume)	0.18692	0.05414	3.452	0.000659 ***
log(payload)	0.80868	0.05990	13.500	< 2e-16 ***
resp_person_yard_proch	0.56553	0.09223	6.132	3.64e-09 ***
resp_person_yard_prochW3	0.09422	0.05000	1.884	0.060759 .

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.3646 on 235 degrees of freedom
 Multiple R-squared: 0.8241, Adjusted R-squared: 0.8211
 F-statistic: 275.2 on 4 and 235 DF, p-value: < 2.2e-16

 Model # 8

Call:

```
lm(formula = log(latyard_prod) ~ latyard_dist + latyard_diff +
    log(avrg_piece_volume) + log(payload), data = sk_dat_clean)
```

Residuals:

Min	1Q	Median	3Q	Max
-1.54465	-0.28985	-0.02192	0.25913	1.81954

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	3.861197	0.091299	42.292	< 2e-16 ***
latyard_dist	-0.036379	0.005149	-7.065	1.81e-11 ***
latyard_diff2	-0.323710	0.096923	-3.340	0.000975 ***
log(avrg_piece_volume)	0.397760	0.069988	5.683	3.90e-08 ***
log(payload)	0.636385	0.076800	8.286	8.96e-15 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4753 on 235 degrees of freedom
 Multiple R-squared: 0.7289, Adjusted R-squared: 0.7243
 F-statistic: 158 on 4 and 235 DF, p-value: < 2.2e-16

```

-----
Model # 9

Call:
lm(formula = log(latyard_prod) ~ resp_person_latyard + latyard_dist +
    latyard_diff + log(avrg_piece_volume) + log(payload), data = sk_dat_clean)

Residuals:
    Min       1Q   Median       3Q      Max
-1.54004 -0.28771 -0.02995  0.29405  1.60591

Coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)      3.869388   0.091816  42.143 < 2e-16 ***
resp_person_latyardW1&E 0.288328   0.147763   1.951 0.052231 .
resp_person_latyardW2   0.021915   0.085084   0.258 0.796970
resp_person_latyardH    0.050369   0.086505   0.582 0.560951
resp_person_latyardW3   0.348579   0.098063   3.555 0.000459 ***
latyard_dist        -0.038120   0.005119  -7.446 1.89e-12 ***
latyard_diff2        -0.296892   0.098498  -3.014 0.002864 **
log(avrg_piece_volume)  0.465850   0.072192   6.453 6.37e-10 ***
log(payload)         0.564608   0.078063   7.233 6.90e-12 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.4639 on 231 degrees of freedom
Multiple R-squared:  0.7462,    Adjusted R-squared:  0.7374
F-statistic: 84.88 on 8 and 231 DF, p-value: < 2.2e-16

```

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Declarations

Conflict of interest The authors declare that there is no conflict of interest.

Human and Animal Rights The research did not involve human participants or animals.

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