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ORIGINAL PAPER

Effect of labour costs on wood harvesting costs and timber provision

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Abstract

Efficient forest operations are essential for forest enterprises, who provide wood and numerous ecosystem services for the society. Important factors influencing the efficiency of forest operations, and thus the harvesting costs, are the level of mechanization, the harvesting method applied, the forest road network, and the training of the labourers. The cost of labour, i.e. salaries, is another important driver of harvesting costs. However, its effect on and relative importance for overall harvesting costs is poorly described in the scientific literature. Thus, this study aims to analyse the influence of labour costs in more detail, especially on the country-wide wood harvesting potentials. In addition, we aimed to cross-compare the effect of labour costs with the effect of switching to a more efficient harvesting method. For this purpose, we calculated timber harvesting costs with varying salaries for all sample plots of the Swiss National Forest Inventory (NFI) for both, the currently applied harvesting method recorded in the NFI, and the potential best suitable harvesting method. A 1% change in labour costs affects harvesting costs by 0.33–0.77%, depending on the harvesting method applied. The influence is larger for systems that involve a large share of motor-manual work and for cable-based methods. Changing labour costs by ± 30% affects the number of plots for which timber harvesting is economically feasible, by 5 to 15 percent points. The effect of switching from the current to the best suitable harvesting method is comparable to that of reducing labour costs by 15–30%. These results indicate that the efficiency of wood harvesting can be increased with further mechanization and does not require cutting salaries of forestry personnel. In that, our results may inform forestry planning and policy making at regional to national level.

Keywords Operations · National forest inventory · Wood potential · Productivity models · Ecosystem services · Salary

Introduction

In Europe, about 550 million solid cubic metres of roundwood are produced annually, generating revenues for more than 20 billion euro per year (Köhl and Linser 2020). The wood is harvested and extracted in various ways and with different levels of mechanization (Erler et al. 2023), i.e. motor-manually, semi-mechanized or fully-mechanized. Lundbäck et al. (2021) analysed worldwide trends in methods for harvesting and extracting industrial roundwood and found that a high gross domestic product per capita is associated with a high level of mechanization, while a large share of steep terrain and publicly owned forest land is associated with a low level of mechanization (Krč et al. 2015). Other factors, such as terrain roughness or soil strength, also limit the use of fully-mechanized systems (Cavalli and Amishev 2019). In countries with a large share of steep terrain, such as Austria and Switzerland, cable-based harvesting systems are mainly used (Bont and Heinimann 2012), which usually involve motor-manual work (86% of the managed forest area in the case of Switzerland; Brändli et al. 2020). However, it is well known that cable-based (Spinelli et al. 2017) and motor-manual felling is expensive (Nordfjell et al. 2004; Cavalli and Amishev 2019) due to high labour costs and low productivity compared with mechanized systems.

One of the most important steps concerning harvesting planning is the estimation of machine and labour costs (Nutto et al. 2016). Louis et al. (2022) pointed out that there is a need to understand how site conditions and stand, operational and silvicultural variables (such as clear-cut, close to nature, or thinning forestry practices) affect timber harvesting cost and productivity. Bont et al. (2018) and Fraefel et al. (2021) showed that forest accessibility also

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influences the harvesting method and hence the harvesting costs. A better understanding of both the individual and combined effects of these factors is pivotal in forest management planning. For this purpose, numerous productivity models have been developed to estimate harvesting costs (Lindroos and Cavalli 2016; Holm et al. 2020). These models require information on the characteristics of the cut, the machines used, and the machine and labour cost rates, among other input data. By carefully combining productivity models and spatial models, it is also possible to calculate the so-called best suitable harvesting methods (referred to as BEST). 'Best suitable' means a technically feasible harvesting method that is compliant with environmental (e.g. soil protection) and occupational health and safety demands but also involves the most economical timber harvesting method concerning tree felling, processing, and extraction and transportation (Bont et al. 2022).

The literature is thin regarding labour costs as an important driver of harvesting costs. Ackerman et al. (2014) described how salaries are calculated but did not analyse the effect of varying labour costs on the total harvesting cost. Since labour costs contribute significantly to the overall harvesting cost, they have an important impact on the wood and biomass potential that can be provided at a certain market price. Thus, they play an important role in the mobilization of biomass for material and energetic purposes, as well as for the bioeconomy.

To close this gap of knowledge, the objective of this study is to analyse the effect of labour costs in more detail, such as the influence of varying labour costs on total harvesting costs and thus on countrywide biomass or wood potentials. The outcomes should further serve as a basis to estimate the uncertainty regarding the future development of labour costs for assessing economic biomass or wood potentials.

The study is conducted in Switzerland, as Switzerland represents a broad range of topographic and biogeographical conditions resulting in broad set of different harvesting methods applied. Further, assessing the economic biomass and wood potential is currently an actual issue, as the government aims to increase the use of domestic biomass and wood (Pauli-Krafft et al. 2021). Thus, we addressed the following research questions:

a. How do labour costs affect the overall harvesting cost of the applied harvesting method?
b. Does harvesting cost differ among Swiss (production?) regions, as a result of differences in labour costs?
c. How do differences in labour costs affect the overall provision of timber and the share of area for which harvesting is economically feasible?
d. Is the effect of labour costs greater than the effect of switching from the currently applied harvesting method to the best suitable harvesting method (BEST)?

Important steps in this endeavour were to model timber harvesting methods on the approximately 6500 sample plots of the Swiss National Forest Inventory and to calculate timber harvesting costs using productivity models. Both the currently applied method and the BEST method were considered, with concurrently varying labour costs ranging from −30% to +30% compared with actual labour costs.

Methods

Case study area

We used the whole of Switzerland as the case study area. Switzerland is divided into five production regions, namely: Jura, Swiss Plateau, Pre-Alps, Alps, and Southern Alps. These regions differ considerably with respect to production and growth conditions (Brändli et al. 2020). Differences in timber harvesting conditions and resulting costs across the regions can therefore be expected, especially as the country features both mountainous and flatter terrain and a broad range of road accessibility situations, making Switzerland an attractive case study area. The currently applied harvesting method is recorded in each sample plot of the Swiss National Forest Inventory (NFI) (Düggelin et al. 2020), and the resulting harvesting costs are estimated based on the integrated timber harvesting productivity model HeProMo (Fischer and Stadelmann 2019; Holm et al. 2020). The Swiss NFI consists of a systematic 1.41 km × 1.41 km sampling grid, resulting in about 6500 sample plots in the forest (Brändli and Hägeli 2019). The underlying productivity model HeProMo has been reported to predict the total harvesting cost in each plot and map relevant predictors accurately (Schweier et al. 2022).

Currently applied and best suitable harvesting method

Harvesting cost is calculated based on the timber harvesting methods applied. Here, we distinguish between two approaches, referred to as calculation method REF and BEST.

[I] Currently applied harvesting method (REF)

The currently applied harvesting methods, based on an interview survey with the local forest services conducted as part of the fourth Swiss NFI, were considered as the reference (Brändli et al. 2020). However, related labour costs reported by forest enterprises and contractors were not used because it was unknown if and to what extent they run their business economically. Instead, the salaries used in the official Swiss estimation of future forest biomass and timber harvesting potential were taken as the reference (Stadelmann 2020).

[II] Best suitable harvesting method (BEST)

'Best suitable' means a technically feasible harvesting method that is compliant with environmental (e.g. soil protection) and occupational health and safety demands but also involves the most economical timber harvesting method concerning tree felling, processing, and off- and on-road transportation (Bont et al. 2022). This method includes a spatial decision support system to allocate the estimated BEST methods to plots, while concurrently considering hauling route limitations, extraction route properties, and stand characteristics.

In our study, the distribution of the REF harvesting methods remained unchanged for all labour-cost scenarios (Fig. 7, Appendix). In contrast, the distribution did not remain constant when BEST methods were applied with different labour-cost scenarios (Fig. 8, Appendix), as in this case the chosen harvesting method was also the result of economic optimization (Bont et al. 2022).

Applied labour-cost scenarios

We used the currently applied harvesting method as the reference. Next, we calculated the resulting harvesting costs when increasing or decreasing the labour costs by 15% and 30% (REF_0, REF_{+15}, REF_{+30}, REF_{-15}, REF_{-30},), and we estimated the related impacts according to our research questions. We conducted the same calculations for the BEST method ($BEST_0$, $BEST_{+15}$, $BEST_{+30}$, $BEST_{-15}$, $BEST_{-30}$). Considering that the average yearly increase of Swiss labour costs in forestry has been 1.4% since 1990 (Niederer and Bill 2015), an increase and decrease by 15% and 30% seemed to be reasonable scenarios. In all cases, we changed only the labour cost and did not vary the machine costs or utilization rates. Table 1 shows the resulting labour costs per scenario. A change in labour cost is only caused by a change in salary and not in the number of personnel, which also appears in the equation in Sect. "Productivity models and differentiation between machine and labour costs".

Table 1 Labour cost per scenario. (1 EUR = 0.98 CHF, 1 USD = 0.92 CHF, Date: 15 December 2022)

Scenario	Abbreviation REF / BEST	Change (%)	Factor	Labour cost (CHF h^{-1})
Very low	− 30	− 30%	0.7	49
Low	− 15	− 15%	0.85	59.5
Currently applied	0	0%	1	70
High	+ 15	+ 15%	1.15	80.5
Very high	+ 30	+ 30%	1.3	91

Harvesting methods and costs

The Swiss NFI differentiates between 17 currently applied harvesting methods (Table 2; Brändli et al. 2020). Nine of these can be considered BEST methods. The respective machine costs were considered fixed (Table 3). Machine cost rates were taken from the calculation tool HeProMo (Holm et al. 2020) and are used in the Swiss NFI (Brändli et al. 2020). These machine costs represent a machine utilization of 850–1300 h per year, depending on the machine type.

To derive the timber volume and other properties of each cut, we assumed that all trees were harvested per plot. This assumption does not necessarily reflect reality, but it was made to ensure comparability among sample plots where no information on cutting thresholds is available and with other NFI studies that had to use the same assumption, such as Fischer et al. (2020).

Transportation costs were not included; thus, the system boundary of the cost calculation was from forest stand to roadside (extraction) and included processing (felling, bucking and delimbing). We refer to these costs as C_{OP} (cost of off-road transportation and processing) [CHF m^{-3}].

Productivity models and differentiation between machine and labour costs

The calculations of the machine costs and the labour costs are based on the productivity model HeProMo (Holm et al. 2020). HeProMo is a collection of different cost and productivity models, for operations and equipment such as motor-manual felling, motor-manual felling and processing, skidder, forwarder, harvester, tower yarder, long-distance yarder, tower-yarder processor, and helicopter. A detailed description of the modules can be found in Holm et al. (2020). We refer to one single productivity model in this collection as a module. The productivity modules deliver the productive machine hours per m^3 (PMH_{15}) as raw outputs, which are then converted to costs. The total costs in each module are computed according to Eq. 01, which is composed of labour and machine costs. The time system is based on Björheden et al. (1995).

$$C_{Tot} = C_{L,i} + C_{M,i} \tag{1}$$

where

C_{Tot}: Total cost of one module [CHF m^{-3}].

$C_{L,i}$:Total labour cost of one module [CHF m^{-3}].

$C_{M,i}$:Total machine cost of one module [CHF m^{-3}].

The labour cost is computed according to Eqs. 2, 3 and 4.

$$C_L = WPPH * c_l \tag{2}$$

$$WPPH = PMH_{15} * F_{ind} * F_{travel} * F_{break} * N \tag{3}$$

Table 2 Overview of currently applied harvesting methods (REF) and best suitable harvesting methods BEST) in Switzerland, according to the Swiss National Forest Inventory (NFI)

Code NFI	Description of harvesting method	Abbreviation	REF	BEST
1	Motor-manual felling and processing, skidding with skidder (assortments)	MM_SK	**X**	**X**
2	Motor-manual felling and processing, pre-skidding with skidder, forwarding (assortments)	MM_SK_FW	**X**	
	Motor-manual felling and processing, forwarding (assortments)	MM_FW		**X**
3	Motor-manual felling, skidding with skidder (full tree), processing at forest road	PM_SK	**X**	
4	Fully mechanized felling and processing with harvester, forwarding (assortments)	FM_FW (merged with #5)	**X**	**X**
5	Fully mechanized felling and processing with tracked/crawler harvester, forwarding (assortments)	FM_FW (merged with #4)	**X**	**X**
6	Walking harvester and tower yarder	FM_TY	**X**	
7	Motor-manual felling and processing, cable-based harvesting (tower yarder, assortment yarding	MM_TY	**X**	**X**
8	Motor-manual felling and processing, yarding with long-distance yarder (assortments)	MM_LY	**X**	**X**
9	Motor-manual felling, yarding with tower yarder, processing (full tree)	PM_TY	**X**	
10	Motor-manual felling, yarding with long-distance yarder, processing (full tree)	PM_LY	**X**	
11	Motor-manual felling, yarding and processing with tower yarder with mounted processor	PM_TYP	**X**	**X**
12	Motor-manual felling and processing, logging with helicopter (assortments)	MM_H	**X**	
13	Motor-manual felling and processing, logging with helicopter (assortments)	MM_H	**X**	
14	Motor-manual felling, logging with helicopter, processing (full tree)	PM_H	**X**	**X**
15	Motor-manual felling, logging with helicopter, processing (full tree)	PM_H	**X**	**X**
16	Motor-manual felling (pre-skidding), mobile chipper on forwarder	MM_FWCH	**X**	
17	Motor-manual felling and processing, hand-skidding	MM_MS	**X**	
18	Other	Other	**X**	

The abbreviations of the harvesting methods are defined as follows: [1] felling and processing mode (MM, PM, FM) and [2] extraction means (SK, FW, FWCH, MS, TY, TYP, LY, H), where *MM* Motor-manual felling and processing, *PM* Motor-manual felling in the stand and fully-mechanized processing at the landing (partially-mechanized), *FM* Fully-mechanized felling and processing, *SK* Skidder, *FW* Forwarder, *FWCH* Forwarder chipper, *MS* Manual skidding, *TY* Tower yarder, *TYP* Tower-yarder processor, *LY* Long-distance yarder, and *H* Helicopter

Table 3 Cost assumptions and values for operation costs (1 EUR = 1.09 CHF, 1 USD = 0.90 CHF, Date: 16 June 2021). (*1) cost for chainsaw, (*2) Includes the helicopter staff, (*3) forestry workforce only

Model name (module)		Machine cost (without operator) (c_M)	Crew size (N)	Loader cost
		CHF h^{-1}	[]	CHF h^{-1}
Motor-manual felling		18 (*1)	1	
Skidder	… with crane	140	1	
	… with winch	120	1	
	… with wood clamp	140	1	
Forwarder		100	1	
Harvester		250	1	
Tower yarder		130	3	90
Long-distance yarder		90	3	90
Tower-yarder processor		230	3.5	
Helicopter		3600 (*2)	2 (*3)	80

$$F_{travel} * F_{break} = WT_D * \left(WT_D - T_{tb}\right) \tag{4}$$

where

$WPPH$: Workplace personnel hours for one module; the total time all personnel need to complete a task ("work time volume") [h m^{-3}].

c_l:Labour cost [CHF h^{-1}] (see Table 3).

N:Number of persons involved in the execution of the work in a module [] (see Table 1).

PMH_{15}: Productive machine hours: the amount of time that a certain machine was running, including interruptions up to 15 min (e.g. short maintenance times) [h m^{-3}].

F_{ind}: Factor for indirect working hours, default = 1.1 [].

F_{travel}:Factor for travel times > 15 min [].

F_{break}:Factor for breaks > 15 min [].

WT_D:Daily working time [min], default = 540 min.

T_{tb}:Paid travel and break times [min], default = 60 min.

The machine cost is computed according to Eqs. 5 and 6.

$$C_M = WPMH * c_m \tag{5}$$

$$WPMH = PMH_{15} * F_{ind} \tag{6}$$

where

c_m = Machine cost [CHF h^{-1}] (see Table 3).

$WPMH$:Workplace machine hours for one module [h m^{-3}].

The single module discussed above represents only one component of a harvesting method. To map the whole chain of a harvesting method, the single modules were combined. For example, the harvesting method FM_FW is composed of the modules 'Harvester' and 'Forwarder'. A table showing the composition of the harvesting methods from its single modules can be found in the Appendix (Appendix, Table 11). The total cost for one harvesting method (C_{OP}) is the sum of the modules (C_{Tot}) that belong to the corresponding harvesting method.

Statistical analysis

We used mixed models (random intercept models) to investigate which effect was stronger: labour cost variation or method switch (from REF to BEST). With this approach we could consider plot-specific effects, which were introduced as an additional source of variance and modelled as a random effect. The random intercept model is formulated in Eq. 7:

$$Y_j(x) = \beta_0 + \beta_1 Z_{1,j} + \beta_2 Z_{2,j} + \ldots + \beta_p Z_{p,j} + \varepsilon_j(Z) + u_j \tag{7}$$

with error term $\varepsilon_j(Z) \sim N\left(0, \sigma_\varepsilon^2\right) i.i.d.$ and $u_j \sim N\left(0, \sigma_u^2\right) i.i.d.$ (j: random effect of the intercept of the j-th plot number *clnr*), where $Y_j(x)$ is the response, $\beta_0 \ldots \beta_p$ are the regression coefficients, $Z_{1,j} \ldots Z_{p,j}$ denote the predictor variables, and p is the number of predictor variables. We implemented this analysis in the *lmertest* package (Kuznetsova et al. 2017) in R (R Core Team 2018), which also provides p values for the F and t tests.

We formulated four random intercept models, all with 'cost of off-road transportation and processing, incl. felling' (C_{OP}) [CHF m^{-3}] as the response variable. The first (Mod#01) and second (Mod#02) models used the predictors 'harvesting method [REF, BEST]' and 'labour-cost scenario' (0 vs -15% for Mod#01 and 0 vs -30% for Mod#02). Mod#03 and Mod#04 contained further predictors in addition to those in Mod#02, which were introduced to identify other significant cost drivers. A backward (elimination) approach was used to identify the significant variables, in which non-significant variables were removed stepwise from the model. The R code formulation for all models can be found in the Appendix.

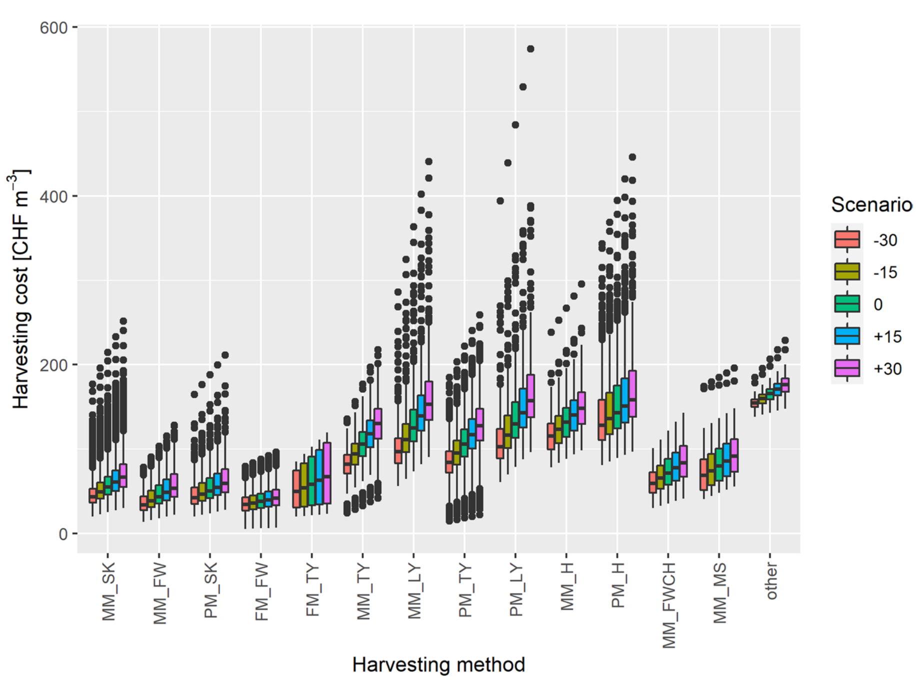

Fig. 1 Harvesting cost separated by labour-cost scenario and harvesting method currently applied in the Swiss National Forest Inventory (NFI) plots (REF). See Table 2 for descriptions of the harvesting methods

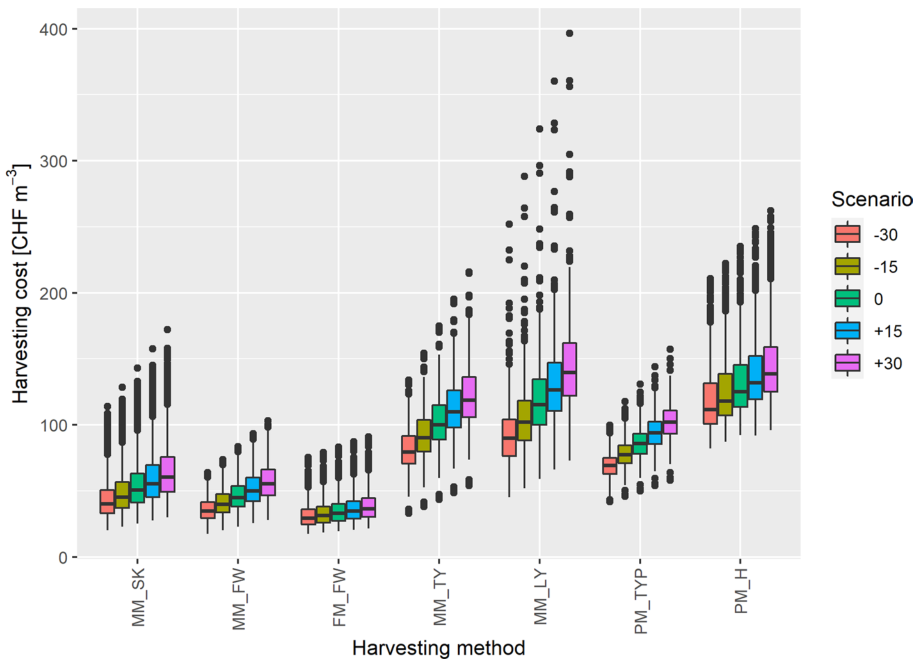

Fig. 2 Harvesting cost separated by labour-cost scenario and the best suitable harvesting method (BEST) in each Swiss National Forest Inventory (NFI) plot. See Table 2 for descriptions of the harvesting methods

Results

Costs of the harvesting methods

Irrespective of the harvesting method (REF and BEST), harvesting costs increased with increasing labour costs (REF: Fig. 1 and Table 4; BEST: Fig. 2 and Table 5). Fully mechanized harvesting methods, such as harvester and forwarder (FM_FW) in ground-based terrain and tower yarder processor (PM_TYP) in cable-based terrain, were more economical than low-mechanized or motor-manual harvesting methods (see Table 2 for descriptions of all harvesting methods). For example, where FM_FW was applied, costs were 31% (REF_0) or 36% ($BEST_0$) lower than where motor manual felling and processing and logging with a skidder

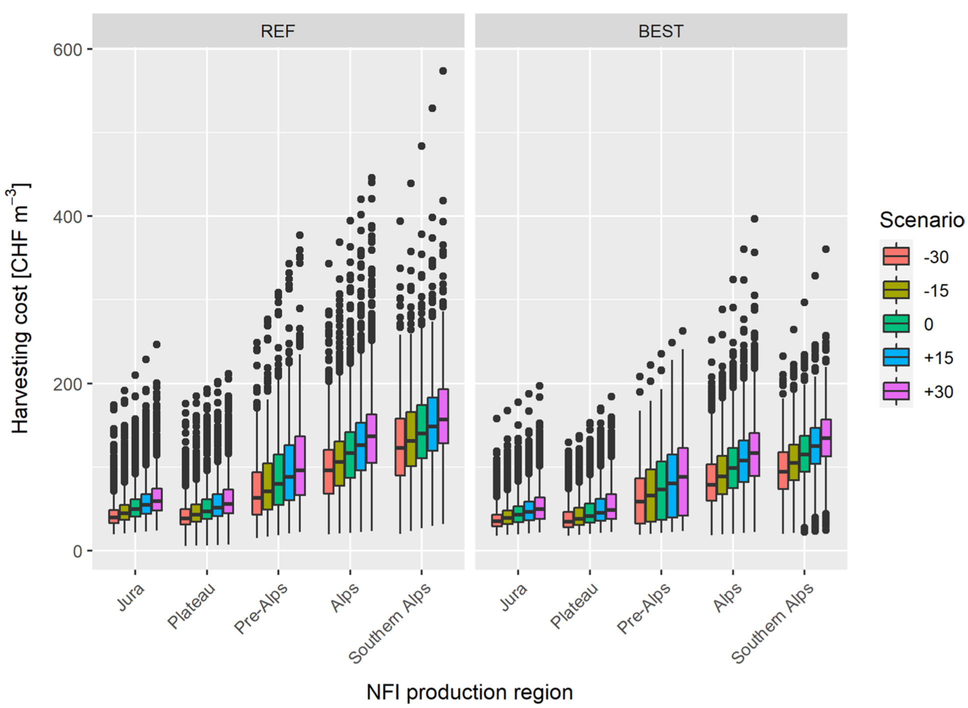

Fig. 3 Harvesting cost separated by labour-cost scenario, production region, and calculation method (left: based on NFI-survey REF, right: based on best suitable timber harvesting method BEST)

Table 4 Harvesting cost [CHF m^{-3}] with standard error [%], separated by labour-cost scenario and harvesting method, based on the currently applied harvesting methods (REF)

Harvesting method	REF_{-30}	REF_{-15}	REF_0	REF_{15}	REF_{30}
MM_SK	47.69 ± 0.6	53.89 ± 0.59	60.1 ± 0.59	66.3 ± 0.58	72.5 ± 0.58
MM_FW	36.45 ± 1.05	41.87 ± 1.06	47.29 ± 1.07	52.71 ± 1.08	58.13 ± 1.08
PM_SK	47.62 ± 2.08	52.1 ± 2.05	56.58 ± 2.03	61.06 ± 2.01	65.55 ± 1.99
FM_FW	37.15 ± 1.2	39.2 ± 1.2	41.25 ± 1.19	43.3 ± 1.19	45.36 ± 1.18
FM_TY	52.06 ± 14.61	56.69 ± 15.24	61.32 ± 15.79	65.96 ± 16.26	70.59 ± 16.67
MM_TY	81.74 ± 1.03	93.83 ± 1.03	105.92 ± 1.03	118.01 ± 1.03	130.1 ± 1.02
MM_LY	103.71 ± 1.21	119.21 ± 1.2	134.71 ± 1.19	150.21 ± 1.19	165.71 ± 1.18
PM_TY	84.84 ± 0.84	95.65 ± 0.83	106.46 ± 0.82	117.28 ± 0.81	128.09 ± 0.8
PM_LY	111.85 ± 1.46	126.59 ± 1.43	141.34 ± 1.41	156.08 ± 1.39	170.82 ± 1.37
MM_H	118.66 ± 1.21	127.05 ± 1.2	135.44 ± 1.2	143.82 ± 1.2	152.21 ± 1.2
PM_H	138 ± 0.56	145.96 ± 0.56	153.93 ± 0.55	161.89 ± 0.55	169.86 ± 0.54
MM_FWCH	60.48 ± 3.57	66.65 ± 3.6	72.81 ± 3.62	78.98 ± 3.65	85.15 ± 3.66
MM_MS	78.45 ± 6.6	83.59 ± 6.17	88.73 ± 5.79	93.87 ± 5.47	99.02 ± 5.19
Other	155.65 ± 0.76	161.3 ± 0.87	166.95 ± 0.97	172.6 ± 1.06	178.24 ± 1.15

See Table 2 for descriptions of the harvesting methods

(MM_SK) was applied. These values (FM_FW and PM_TYP) were also less sensitive to labour costs, e.g. sensitivity was 10% with FM_FW but about 20% with MM_SK (Table 6).

The percent change in harvesting costs with the fully mechanized harvesting method using a harvester and forwarder (FM_FW) was 10%, with a 30% reduction in labour costs, and was thus the least sensitive method (Table 6). Air-based systems had the next lowest sensitivity, with changes around 10–12%. Next were partially mechanized ground-based systems (PM_TYP, PM_SK) and fully mechanized cable-based systems (FM_TY), with effects between 15 and 17%. Low-mechanized and motor-manual ground-based systems (MM_FW, MM_SK), as well as partially and low-mechanized cable-based systems (MM_LY, MM_TY, PM_TY, PM_LY) had a rather high labour-cost sensitivity of > 20%. Among these systems, it is difficult to give an exact order, as the standard error for these values for all these methods was in the range of 1 to 1.5 percentage points (see Appendix). Methods that appeared only seldom in the NFI interview survey (MM_MS, MM_FWCH and FM_TY) are not discussed because they had large standard errors (5%–15%). Differences in the sensitivity between REF and BEST were small (< 1%), except for MM_TY, which had a difference of 2.4%. These differences arose because the harvesting methods were not necessarily applied to the same plots in the BEST and the REF approaches; as a result, different input variables flowed into the productivity models in terms of forest composition and extraction path. Even if the same harvesting procedures on the same plot had been calculated once with BEST and once with REF, however, differences could have occurred because the extraction paths could have differed (length, steepness). In addition, the plots could have been assigned to different harvesting methods for the different labour-cost scenarios in the BEST calculation. This occurred especially in cable-based terrain.

Regional means of harvesting costs

The effects of different labour-cost scenarios on regional harvesting costs were considerably smaller if calculated with BEST methods rather than with the currently applied (REF) methods (Fig. 3). For the whole of Switzerland, costs were 93.3 CHF m^{-3} (REF_0) vs 76.7 CHF m^{-3} ($BEST_0$).

With REF methods, varying salaries (labour costs) by ± 30% caused the average harvesting costs to vary between 78 CHF m^{-3} and 109 CHF m^{-3} (93.34 CHF m^{-3}, − 16.71%/ + 16.71%) over the whole of Switzerland (Table 7). Salaries were linearly related to harvesting costs, i.e. increasing and decreasing salaries by the same amount resulted in a symmetric increase and decrease in costs, with regionally varying magnitude. While a 30% increase

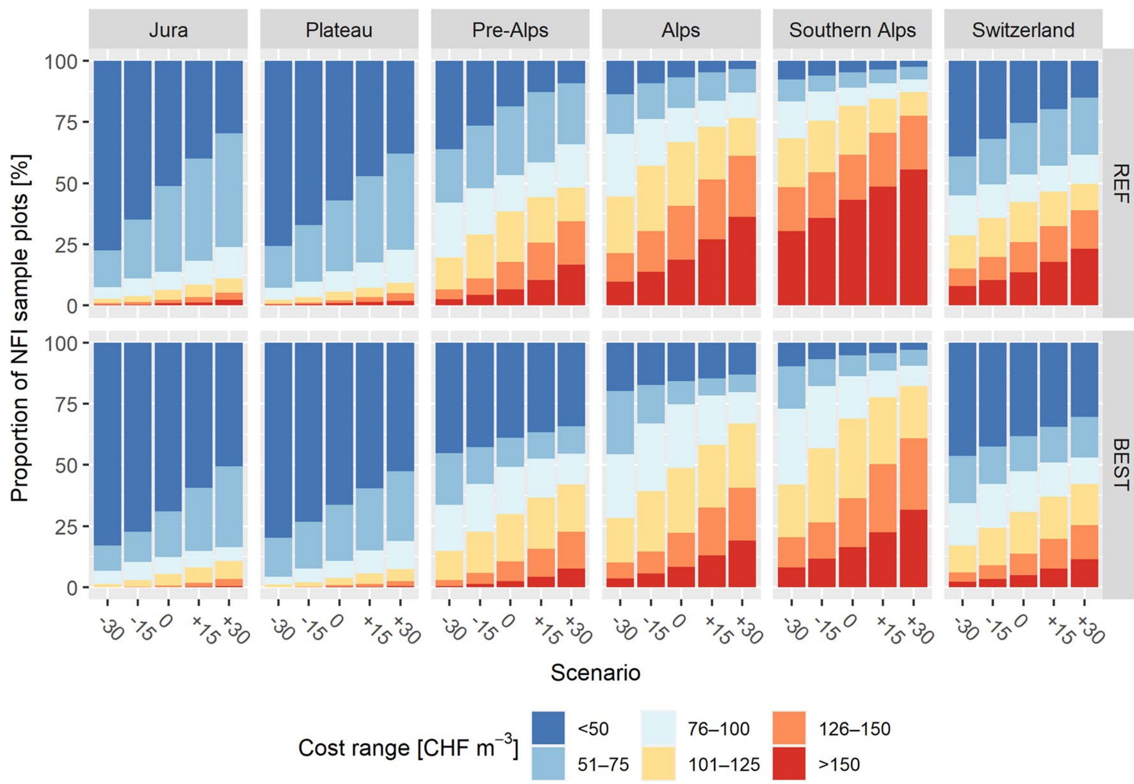

Fig. 4 Distribution of NFI sample plots in different cost classes, separated by harvesting method (BEST, REF), NFI production region, and labour-cost scenario

Table 5 Harvesting cost [CHF m^{-3}] with standard error [%], separated by labour-cost scenario and harvesting method, based on the best suitable harvesting methods (BEST)

Harvesting method	REF_{-30}	REF_{-15}	REF_{0}	REF_{15}	REF_{30}
MM_SK	44.22 ± 0.8	49.61 ± 0.79	55.14 ± 0.79	60.53 ± 0.79	65.97 ± 0.78
MM_FW	36.2 ± 0.77	41.58 ± 0.78	46.79 ± 0.77	52.15 ± 0.78	57.51 ± 0.78
FM_FW	31.41 ± 0.57	33.39 ± 0.58	35.23 ± 0.58	37.13 ± 0.59	39.1 ± 0.59
MM_TY	81.45 ± 0.51	92.43 ± 0.52	102.3 ± 0.54	112.59 ± 0.57	122.1 ± 0.63
MM_LY	93.6 ± 0.91	106.98 ± 0.98	121 ± 1.05	134.21 ± 1.16	148.75 ± 1.31
PM_TYP	69.59 ± 0.4	78.16 ± 0.41	86.38 ± 0.41	94.37 ± 0.4	102.34 ± 0.4
PM_H	118.91 ± 0.48	125.8 ± 0.46	132.4 ± 0.43	138.84 ± 0.4	145.19 ± 0.38

See Table 2 for descriptions of the harvesting methods

or decrease in labour costs resulted in a 12.3% increase or decrease in harvesting costs in the Southern Alps, it resulted in a 19.2% and 19.1% increase or decrease in harvesting costs in the Jura and the Pre-Alps, respectively, with the other production regions in between (Plateau: 18.3%, Alps: 16.9%; Table 8).

Changes in harvesting costs due to the different labour-cost scenarios varied less among regions when the BEST method was applied. The average harvesting cost varied between 64 and 89 CHF m^{-3} (76.68 CHF m^{-3}, − 17.0%/ + 16.2.2%) over the whole of Switzerland (Table 7). In contrast to the REF method, labour-cost changes were not exactly linearly related to changes in harvesting costs, as the distribution of the harvesting methods varied among the different combinations of BEST methods and labour-cost scenarios (Fig. 8, Appendix).

Economically feasible forested area

Regarding the effect of labour cost on the percentage of timber volume and forested area for which harvesting is economically feasible, over the entire country 47% (REF) to 52% (BEST) of the NFI samples could be economically harvested under the current labour costs and assuming an

Table 6 Percent change in harvesting cost depending on the labour-cost scenario (– 30% for REF and – 30% BEST compared with REF_0 and $BEST_0$)

Harvesting Method	REF_{-30} (%)	$BEST_{-30}$ (%)	Difference (percent points)	Normalized (%*)
Other	*– 6.8*			0.23
FM_FW	– 10.0	– 10.8	0.8	0.33
PM_H	– 10.3	– 10.2	– 0.1	0.34
MM_MS	*– 11.6*			0.39
MM_H	– 12.4			0.41
FM_TY	*– 15.1*			0.50
PM_SK	– 15.8			0.53
PM_TYP		– 19.4		0.65 (based on BEST)
MM_FWCH	*– 16.9*			0.56
PM_TY	– 20.3			0.68
PM_LY	– 20.9			0.70
MM_SK	– 20.6	– 19.8	– 0.8	0.69
MM_FW	– 22.9	– 22.6	– 0.3	0.76
MM_TY	– 22.8	– 20.4	– 2.4	0.76
MM_LY	– 23.0	– 22.6	– 0.4	0.77

*Change in total harvesting cost per 1% change in labour costs, based on REF unless indicated otherwise

Note that the harvesting methods are ordered according to increasing percent change. Italic indicates methods that appeared only seldom in the NFI interview survey (MM_MS, MM_FWCH and FM_TY) with a large standard error. See Table 2 for descriptions of the harvesting methods

average timber price of 75 CHF m^{-3} (Fig. 4). If labour costs were to decrease by 30%, these percentages would increase to 55% and 65% for REF and BEST, respectively. In contrast, if labour costs were to increase by 30%, only 38% (REF) to 47% (BEST) could be harvested economically. These values differed greatly by region. In the Jura and Swiss Plateau, 86% (REF, Jura and REF, Plateau), 88% (BEST, Jura), or 89% (BEST, Plateau) could be harvested economically, whereas in the Southern Alps, the area share for an economical forest operation amounted to only 11% (REF) or 14% (BEST) (under current labour costs).

Figure 5a depicts the empirical cumulative distribution of the sample plots as a band for ± 30% (the interval between + 30% and -30%) labour cost. REF and BEST are both plotted and the two intervals between + 30% and -30% are overlapping. Beginning with costs (C_{OP}) of 50–125 CHF m^{-3}, the upper curve of the REF interval (REF_{-30}, solid blue line) is equal to or slightly above the centre of the BEST interval ($BEST_0$, dashed green line). This means that the impact of a lower labour cost by 30% (REF_{-30}) was slightly larger than that of switching from REF_0 to $BEST_0$. Figure 5b shows the width of the interval for ± 30% varying labour cost. For both REF and BEST the impact of labour cost variation on the economically feasible forest area was neither regular nor symmetrical. At timber costs (C_{OP}) of 50–125 CHF m^{-3}, changing labour costs by ± 30% impacted the economically feasible forest area by 5–15 percent points for both REF and BEST (Fig. 5b).

The distribution for the volume fraction is shown in Fig. 10 in the Appendix. The distribution and sensitivities were almost identical to those of the area share and are therefore not discussed separately.

The spatial distribution of harvesting costs across Switzerland was clearly controlled by the topography and thus the accessibility and harvesting method (Fig. 6). Generally, the northern half of Switzerland (Swiss Plateau and Jura regions) is less expensive to harvest than the southern half, which is dominated by alpine landscapes. In contrast to the reference scenario (REF_0), reducing labour costs by 30% and applying BEST methods resulted in many sample plots in the main valleys of the cantons of Grisons (east) and Valais (southwest) being harvestable for < 100 CHF m^{-3} and thus becoming more accessible for economically feasible forest management.

Labour-cost sensitivity and switch of harvesting method

In the case of a 15% reduction in labour costs, the effect of switching the harvesting method (REF vs BEST; 10.5 CHF m^{-3}) was larger than the effect of changing the labour-cost scenario (7.1 CHF m^{-3}). In contrast, a labour cost reduction of 30% had a larger effect (14.4 CHF m^{-3}) than switching from REF to BEST (10.0 CHF m^{-3}; Mod#02, see Appendix).

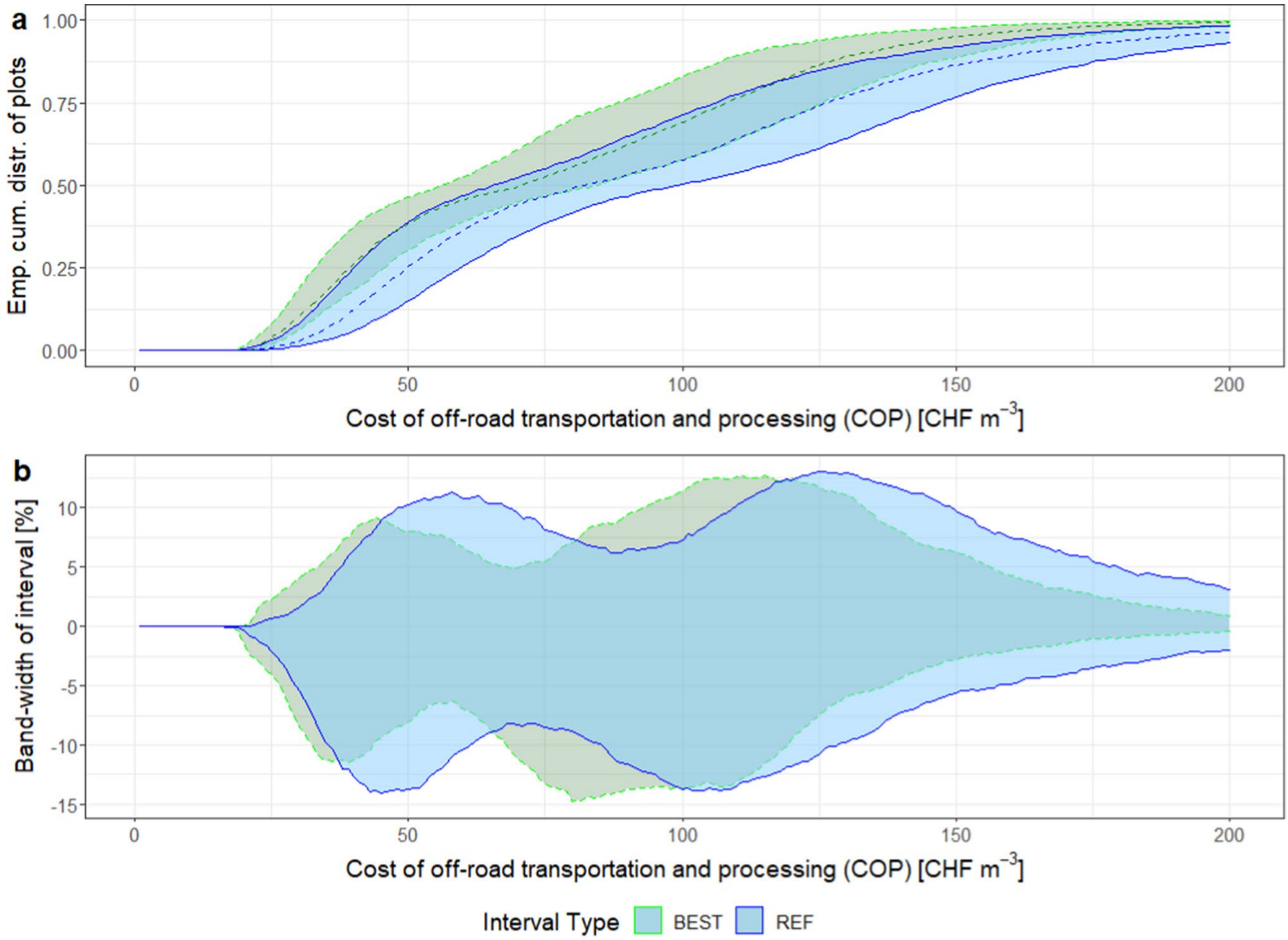

Fig. 5 **a** Range (±30% labour costs) of the empirical cumulative distribution of the sample plots for BEST and REF. Sample plots with costs ≥ CHF 200 were removed for better visualization. Note: y-axis values indicate the proportion of sample plots. **b** Corresponding band-width of the interval. BEST: best suitable harvesting method; REF: currently applied harvesting method

The model including slope (*slope25*), basal area share of conifers (*bfantndh*), standing volume (*volume*), quadratic mean diameter (*kfm*), square root of the distance to the next forest road (trafficable at least for 3-axle trucks with a 26-ton total weight, *sdist_a*), labour-cost scenario (0, -30%), and harvesting method (REF, BEST) had all factors as significant (Mod#03, see Appendix). Here as well, the effect of switching to the BEST method (-10.0 CHF m^{-3}) was smaller than that of reducing labour cost by 30% (-14.3 CHF m^{-3}). According to this model, the effect of decreasing labour cost by 30% (-14.3 CHF m^{-3}) equalled the effect of increasing the slope by 17.5 percentage points (labour-cost effect/ slope effect = 14.3 CHF m^{-3} / 0.816 CHF m^{-3} = 17.5).

If only sample plots in mountainous areas (production regions Pre-Alps, Alps and Southern Alps) were included (Mod#04, see Appendix), the effect observed in the previous models was confirmed. The effect of switching to the BEST method (− 12.7 CHF m^{-3}) was smaller than the effect of reducing labour cost by 30% (− 17.2 CHF m^{-3}). Both effects were larger in the Alps than in the 'country as a whole'.

Discussion

Effect of labour costs on the cost of the harvesting method

Our calculations indicate that a 1% change in labour costs affected the harvesting cost by 0.3–0.8%, depending on the harvesting method applied. As expected, changes in labour costs had a larger influence on harvesting methods that involve a large share of motor-manual work. The impact of labour cost was lower when fully mechanized harvesting methods were applied, for example harvester and forwarder use on trafficable terrain. This outcome was expected, as the incidence of labour costs is lower in fully mechanized

Table 7 Average harvesting cost [CHF m^{-3}] with standard error (%), separated by labour-cost scenario and production region

Calculation method	Labour-cost scenario	Jura (CHF m^{-3}; SD)	Swiss Plateau	Pre-Alps	Alps	Southern Alps	Switzerland
REF	− 30%	44.61 ± 1.43	43.48 ± 1.37	71.36 ± 1.51	97.4 ± 0.94	125.33 ± 1.46	77.74 ± 0.77
REF	− 15%	49.92 ± 1.41	48.35 ± 1.36	79.77 ± 1.47	107.34 ± 0.91	134.13 ± 1.4	85.54 ± 0.74
REF	0	55.23 ± 1.39	53.21 ± 1.35	88.17 ± 1.45	117.28 ± 0.89	142.93 ± 1.35	93.34 ± 0.72
REF	15%	60.54 ± 1.39	58.08 ± 1.35	96.58 ± 1.43	127.22 ± 0.88	151.73 ± 1.31	101.14 ± 0.71
REF	30%	65.84 ± 1.38	62.94 ± 1.36	104.99 ± 1.42	137.16 ± 0.87	160.53 ± 1.28	108.94 ± 0.7
BEST	− 30%	39.9 ± 1.45	39.3 ± 1.32	61.71 ± 1.62	81.14 ± 1	96.52 ± 1.49	63.62 ± 0.75
BEST	− 15%	44.13 ± 1.47	43.48 ± 1.34	68.01 ± 1.62	89.7 ± 0.98	105.92 ± 1.39	70.22 ± 0.74
BEST	0	48.36 ± 1.5	47.63 ± 1.36	74.16 ± 1.62	97.98 ± 0.97	115.19 ± 1.32	76.68 ± 0.74
BEST	15%	52.54 ± 1.53	51.75 ± 1.38	80.06 ± 1.62	106.02 ± 0.96	124.39 ± 1.27	82.98 ± 0.73
BEST	30%	56.69 ± 1.54	55.84 ± 1.39	85.77 ± 1.61	113.81 ± 0.96	133.43 ± 1.24	89.14 ± 0.73

Table 8 Percent change in harvesting cost, separated by production region, for REF_{-30} (currently applied harvesting method with a 30% reduction in labour costs) and $BEST_{-30}$ (best suitable harvesting method with a 30% reduction in labour costs) compared with REF_0 and $BEST_0$ (no change in labour costs) and the corresponding normalized value [percent change in total harvesting cost per 1% change in labour costs]

Production region	REF_{-30} [%]	$BEST_{-30}$ [%]	Normalized REF	Normalized BEST
Jura	− 19.2	− 17.5	0.64	0.58
Swiss Plateau	− 18.3	− 17.5	0.61	0.58
Pre-Alps	− 19.1	− 16.8	0.64	0.56
Alps	− 16.9	− 17.2	0.56	0.57
Southern Alps	− 12.3	− 16.2	0.41	0.54
Switzerland	− 16.7	− 17.0	0.56	0.57

systems with expensive machinery and high costs of machine operation and maintenance (Enache et al. 2016).

The labour cost effect was generally greater for cable-based systems than for ground-based systems, especially when motor-manual felling and processing was required. This can be explained by the large share of motor-manual work that is required in steep terrain, even with highly mechanized systems. These results are in line with those of Schweier et al. (2022), where 55.1% of the overall harvesting cost was attributed to labour and 44.9% to machines for a tower-yarder processor (Koller K 507; PM_TYP), and with those of Schweier and Ludowicy (2020), where 52% of the costs were attributed to labour and 48% to machines, also for tower-yarder-based extraction (PM_TYP). The results of our study also support the findings of Zhang et al. (2016) for the use of a fully mechanized harvesting method, where operating costs (consisting mainly of labour costs) contributed 20–30% to total cost.

Helicopter yarding has a low sensitivity to labour costs for two reasons. First, helicopter machine costs are quite high (60 CHF min^{-1}) compared with the cost of employing forestry labourers. Second, due to methodological aspects, only the labour cost of the forestry labourers, not that of the helicopter company staff, was varied in our analysis. However, where helicopter yarding is necessary (in protective forest), harvesting costs are not decisive anyway. The interventions are necessary to ensure protection of infrastructure against natural hazards and are thus carried out almost independent of the cost required.

Effect of labour costs on regional mean harvesting costs

Over the entire country, changing labour costs by 1% impacted the total harvesting cost by 0.56% (REF) or 0.57% (BEST), but with variations across the different regions. The currently

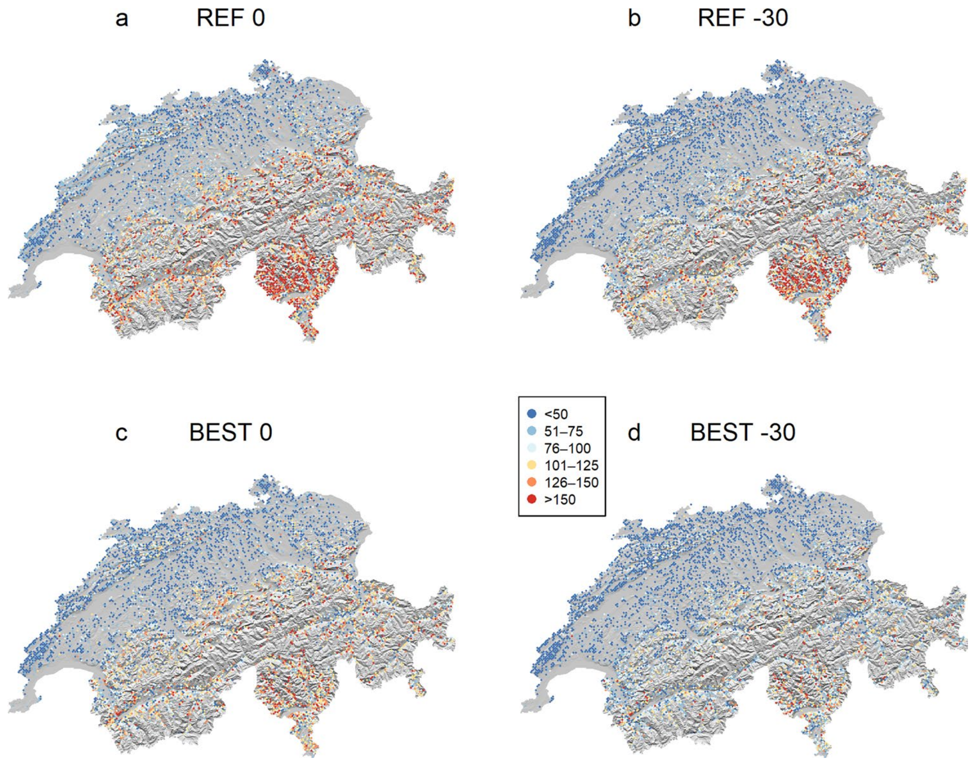

Fig. 6 Mapped National Forest Inventory (NFI) sample plots in Switzerland. Sample plots are colour-coded according to harvesting cost class (CHF m^{-3}). Panels **a**–**d** show the labour-cost scenarios "0" (panels a and c) and "− 30%" (panels b and d) based on the REF (panels a and b) and BEST harvesting method (panels c and d). BEST: best suitable harvesting method; REF: currently applied harvesting method

applied harvesting methods (REF) show the highest sensitivity to labour costs in the Jura, Swiss Plateau and Pre-alps (> 60%). Despite the steeper terrain and poorer accessibility in the Southern Alps, the sensitivity was considerably lower there (41%). This can be explained by the large share of helicopter logging (REF: 52%) that would, according to the NFI interview survey with local foresters, be applied in the Southern Alps in case of a management intervention. A large part of this region has not been managed for > 50 years and is likely to remain unmanaged for the foreseeable future, due to poor accessibility (Portier et al. 2021). Surprisingly, labour-cost sensitivity is also relatively high in the Swiss Plateau, where fully mechanized systems can be widely applied. A possible reason is that the mechanization potential is not completely realized in this region and many motor-manual processes are still used, as shown in Fig. 7 (share of all motor-manual methods (*MM_***) = 66%).

When switching to BEST methods, the sensitivity decreased for the Jura, Plateau and Pre-Alps and increased for the Alps and Southern Alps, but overall, the differences between the different regions were low and ranged from 0.54 to 0.58 (percent change in harvesting costs per 1% change in labour cost). The decrease in sensitivity is because BEST methods are more mechanized. For example, the share of all motor-manual methods (*MM_***) in the Swiss Plateau is 56% with $BEST_0$ (Fig. 7). Labour costs generally have a smaller influence on the total cost with these more mechanized methods (see above).

The increase in labour-cost sensitivity (Alps, Southern Alps) was caused by a shift from air-based systems towards cable-based systems in steep terrain. For example, the share of air-based system amounted to 52% for REF (all scenarios) and 45% for $BEST_{+30}$, 41% for $BEST_0$, and 39% for $BEST_{-30}$ for the Southern Alps. An economic benefit from a shift towards more mechanized harvesting methods has also been observed in other studies (e.g. Kühmaier and Stampfer 2010).

Overall, the differences in the impact of labour-cost on total harvesting cost between the regions were rather small, except for REF and the Southern Alps. This is caused by the fact that in the Southern Alps harvesting is dominated by air-based systems.

Economically feasible forested area

The share of the economically feasible forested area was heavily dependent on the production region. The lowest values occurred in the Southern Alps, with values in the other regions ascending in the following order Alps, Pre-Alps, Jura and Swiss Plateau.

Over the entire country, assuming an average timber price of 75 CHF m^{-3} (which was a reasonable market price in 2022), the difference in the share of the economically forested area ($SEFA_{75}$) over the whole country with a labour-cost change of ± 30% was around -11 and + 8 percentage points for REF and -5 and + 13 percentage points for BEST.

Changing the method from REF to BEST led to an increase in the economically feasible forested area from 47 to 52% (+5 percentage points). The relationships in this case were not symmetrical and can only be generalized with certain restrictions, as depicted in Fig. 5.

When the labour costs increased by 30% and the harvesting method switched from REF to BEST ($BEST_{+30}$), the area share ($SEFA_{75}$) remained the same (47%) as for REF_0. On the other hand, reducing labour costs by 30% led to a slightly larger area share ($SEFA_{75}=55\%$) with REF_{-30} than with $BEST_0$ ($SEFA_{75}=52\%$), whereas REF_{-15} had a slightly smaller area share of 50%. These results indicate that applying a more suitable harvesting method had an impact on the share of economically feasible forest area that was comparable to changing the labour costs by between 15 and 30%.

Effect of both labour-cost and switching of harvesting methods

The fourth question of interest was whether labour costs or switching from REF to BEST had a larger influence on the overall harvesting cost. It has already been observed (e.g. forest area, see Sect. "Economically feasible forested area") that the choice of method (BEST vs REF) had an influence on the harvesting cost similar to that of a labour cost reduction of 15–30%. This observation was confirmed by our models, in which the estimate of the regression coefficient for the method (10.0 / 10.5 CHF m^{-3}) was between the two corresponding coefficients for the labour-cost change (14.4 CHF m^{-3} for a 30% labour-cost change and 7.1 CHF m^{-3} for a 15% change). This statement was also confirmed by Mod#03 and Mod#04 and still applied if only the Alps were considered (see Appendix for model output). Unfortunately, these results cannot be placed in a broader context because comparable studies are not available. Our results show that there are theoretically two possible ways to improve the efficiency of timber harvesting or to increase the timber potential: a reduction in salaries or a change of the harvesting method towards more mechanized systems.

Conceptual framework

In a first view, the results of the sensitivity analysis are somewhat obvious. The impact of an eventual labour cost increase (or decrease) is larger for labour intensive systems than for the others, that is: proportional to the incidence of labour cost on total cost. Thus, the relative labour cost sensitivity without considering a switch of the systems, could have been also estimated in a much simpler way, i.a. just by checking the proportion of labour cost over total cost in a general way. When calculating the ratio C_L / C_{Tot} by using Eqs. 1-6, then the input from the productivity models (PMH_{15}) disappears. However, the reason for this complex framework was, that an objective of this study was also to achieve absolute values in CHF, that are representative for the regions and the whole county and to include the effect of switching the system, which depends on the specific properties of the plots.

Conclusion

In this purely theoretical study, we have shown, first, that a 1% change in labour costs affects harvesting costs by 0.33–0.77%, depending on the harvesting method applied. The effect is larger for systems that involve a larger share of motor-manual work and for cable-based systems. The smallest influence was observed with fully mechanized ground-based systems (harvester and forwarder, 0.33%) and air-based systems (0.34%). Second, changing labour costs by 1% impacted the total harvesting costs by 0.56% (REF) or 0.57% (BEST) for the whole of Switzerland, whereas effects were between 0.41% and 0.64% (REF) and 0.54% and 0.58% (BEST) for individual regions. Third, changing labour costs by ±30% affected the share of area for which timber harvesting is economically feasible, by between 5 and 15 percentage points. In this respect, reducing labour costs by 30% had a slightly larger effect than switching from REF to BEST methods. Fourth, switching to a BEST method had an effect on the total harvesting cost comparable to that of reducing labour costs by 15–30%. This applied for the whole country and for the Alps (Pre-Alps, Alps and Southern Alps) only.

To our knowledge, this study is the first attempt to simultaneously consider both the impact of labour costs and the application of alternative harvesting methods (switching methods) on timber harvesting costs. In addition, the method has been linked to a representative dataset of 6500 sample plots, so that the full range of possible stands, topographic constraints and access situations have been considered. Eventhough this study is purely theoretical, it provides the framework and the basis for a proper analysis and discussion and can therefore contribute to a debate that is often based on emotions rather than on reliable data. This study provides the conceptual figures that should be at the base of any such debate.

Our findings have several implications for the public sector, as well as for administrators and practitioners. For example, this study can be used to quantify the productivity gain from the use of BEST methods and to relate it to labour costs. It can be deduced, for example, how much salaries can be increased while switching to other methods without compromising productivity.

Our results apply to Switzerland. In principle, the results are also valid for other Central European countries, as long as the harvesting methods used and the forests (species, silviculture) are comparable. The conceptual framework can be

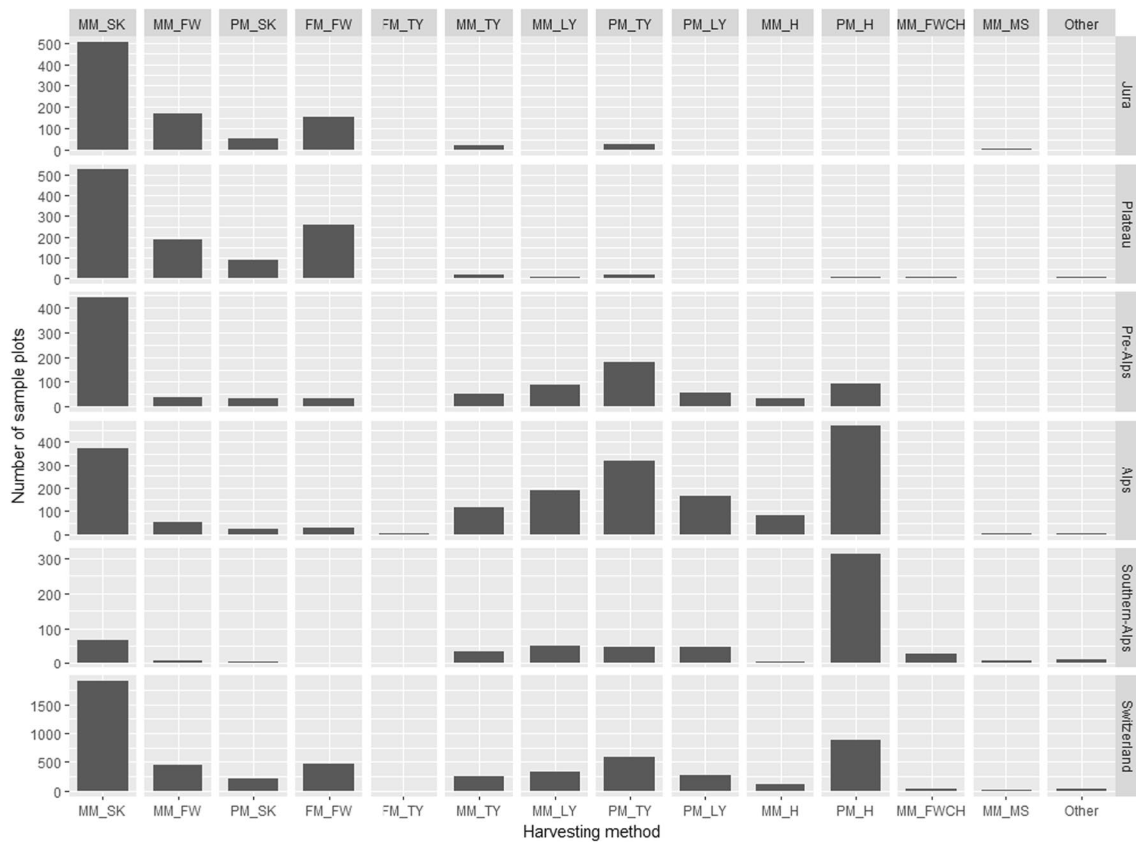

Fig. 7 Distribution of the currently applied harvesting methods (REF) for the whole of Switzerland and the different production regions, as reported in the interview survey with local foresters conducted as part of the Swiss National Forest Inventory (NFI), See Table 2 for descriptions of the harvesting methods

easily transferred, but when transferring the results to other countries, it must be taken into account that Switzerland is one of the countries with the highest labour costs in the world. Previous studies confirm that logging rates are much higher in Switzerland than in the neighbouring countries sharing the same Alpine space, such as France, Germany, Italy and Slovenia (Spinelli et al. 2015). This should be considered in particular when using the absolute cost figures (with reported CHF) of this study outside Switzerland. In addition, with much lower labour costs overall, the influence of labour costs on total harvesting costs is smaller and therefore variation in labour costs has a smaller influence on total costs. Furthermore, the BEST method can also differ among countries.

An important driver of harvesting costs is the machine annual use. In this study, machine annual use was assumed to be high (850–1300 h). However, it is likely to be lower in reality, as not all contractors can always have an optimal machine annual use (Spinelli et al. 2011). In the case of a lower machine annual use, the costs of the more highly mechanized processes automatically increase and the advantage of the BEST method, involving a shift to more highly mechanized methods, is no longer so pronounced.

Moreover, our results apply only to a change in labour costs for forest workers and machine operators. The statements do not apply in the case of general inflation and rising labour costs in other industries. The machine costs also consist to a large extent of labour costs, be it for their production in factories or for their maintenance. If these labour costs increase, then machine costs would rise as well.

For this study, we assumed that workers' productivities remain the same at lower salaries as at higher salaries, an assumption that may not hold (Janzen and Sandberg 1998). Wages in the forestry sector are rather low compared with those in other industries. With lower wages it can be difficult to find well-qualified and motivated personnel, and the employment of poorly qualified personnel in turn tends to reduce productivity (Purfürst and Lindroos 2011; Schweier et al. 2022). Other problems can also arise from a lower quality of work, e.g. stand damage, more frequent machine breakdowns, and a higher risk of accidents (Axelsson 1998; Lindroos and Burström 2010; Tsioras et al. 2014), which in turn contribute to rising costs. Therefore, from our point of view, the scenarios with lower labour costs presented here are only theoretical, and we strongly advise against decreasing salaries. Indeed, our results show how an increase in productivity and efficiency can be reached with higher salaries. Overall, our results show that labour costs play a minor role in fully mechanized systems and that costs can be reduced by switching to a more mechanized system. Further mechanization is recommended for forestry to become more independent of salary costs, thus allowing better remuneration of labour, to the benefit of easier recruitment, increased professionalism and higher retention.

Appendix

Distribution of the harvesting methods

We present the distribution of the harvesting methods here, as this information is relevant for understanding the results even if not part of our specific research questions. Figure 7 depicts the distribution of the current harvesting methods as reported in the NFI survey. The harvesting methods remain unchanged for all labour-cost scenarios. In the Alps and Southern Alps the backbone of harvesting lies in cable- and air-based systems. In the Southern Alps the share of air-based systems (MM_H & PM_H) amounts to 52%.

In contrast to with the REF harvesting methods, the distribution does not remain constant for the different combinations of best suitable harvesting methods (BEST) and labour-cost scenarios (Fig. 8). Depending on the chosen scenario, a shift between cable-based and air-based methods can be observed. If labour costs are high, the share of air-based methods increases. Further, a shift towards more mechanized systems occurs when BEST methods are applied

Sensitivity of the harvesting cost depending on the labour-cost scenario

See Tables 9, 10.

Table 9 Percent change in harvesting cost depending on the labour-cost scenario for the currently applied harvesting method (REF)

Harvesting method	REF_{-30}	REF_{-15}	REF_{+15}	REF_{+30}
MM_SK	– 20.6	– 10.3	10.3	20.6
MM_FW	– 22.9	– 11.5	11.5	22.9
PM_SK	– 15.8	– 7.9	7.9	15.8
FM_FW	– 10.0	– 5.0	5.0	10.0
FM_TY	– 15.1	– 7.6	7.6	15.1
MM_TY	– 22.8	– 11.4	11.4	22.8
MM_LY	– 23.0	– 11.5	11.5	23.0
PM_TY	– 20.3	– 10.2	10.2	20.3
PM_LY	– 20.9	– 10.4	10.4	20.9
MM_H	– 12.4	– 6.2	6.2	12.4
PM_H	– 10.3	– 5.2	5.2	10.3
MM_FWCH	– 16.9	– 8.5	8.5	16.9
MM_MS	– 11.6	– 5.8	5.8	11.6
other	– 6.8	– 3.4	3.4	6.8

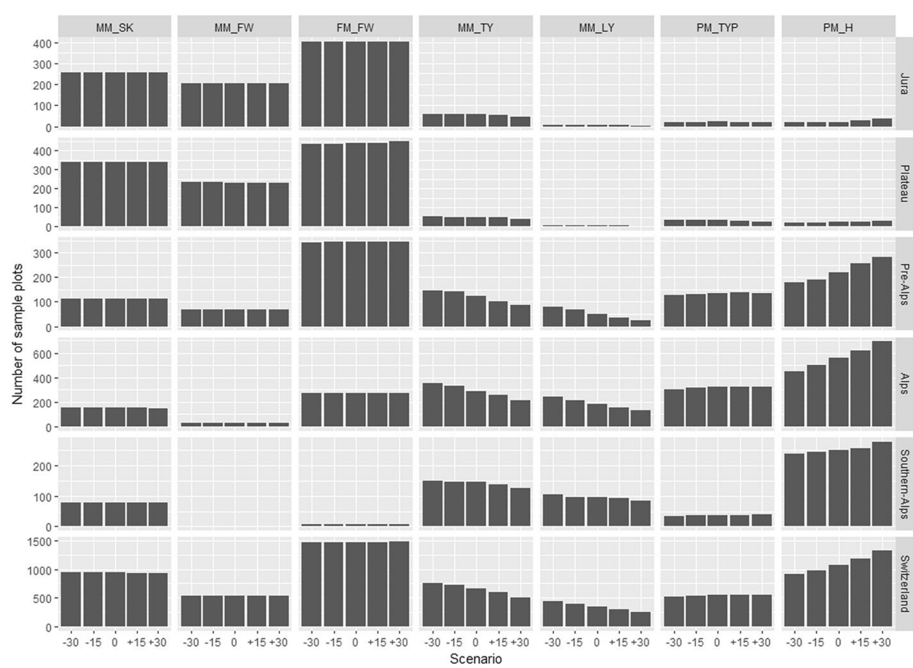

Fig. 8 Distribution of the best suitable harvesting methods (BEST) for the different labour-cost scenarios and production regions. See Table 2 for descriptions of the harvesting methods

Table 10 Percent change in harvesting cost depending on the labour-cost scenario for the best suitable harvesting method (BEST)

Harvesting method	$BEST_{-30}$	$BEST_{-15}$	$BEST_{+15}$	$BEST_{+30}$
MM_SK	-19.8	− 10.0	9.8	19.6
MM_FW	− 22.6	− 11.1	11.5	22.9
FM_FW	− 10.8	− 5.2	5.4	11.0
MM_TY	− 20.4	− 9.6	10.1	19.4
MM_LY	− 22.6	− 11.6	10.9	22.9
PM_TYP	− 19.4	− 9.5	9.2	18.5
PM_H	− 10.2	− 5.0	4.9	9.7

Empirical cumulative distribution of costs by labour-cost scenario and calculation method

See Figs. 9, 10.

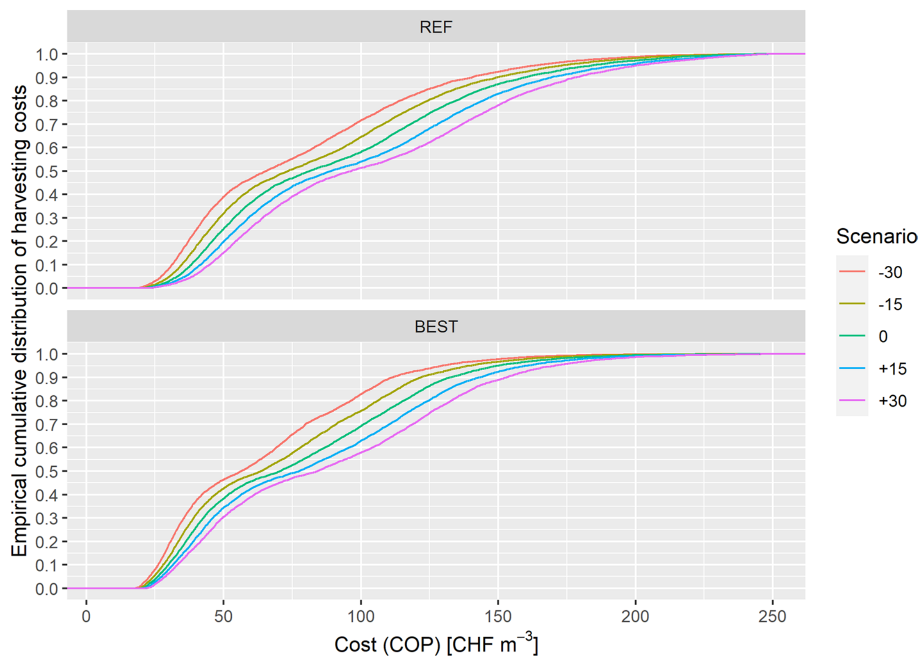

Fig. 9 Empirical cumulative distribution of harvesting costs by labour-cost scenario and calculation method (distribution of the sample plots). Sample plots with costs ≥ CHF 250 were removed for better visualization. Note: y-axis values indicate the proportion of the sample plots. BEST: best suitable harvesting method; REF: currently applied harvesting method. COP: Cost of off-road transportation and processing

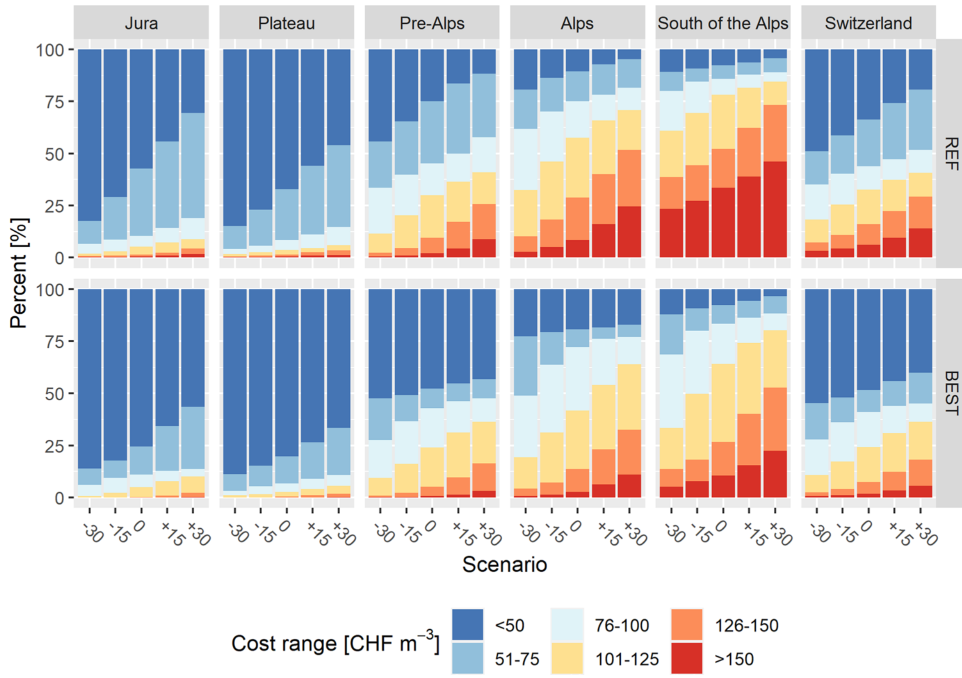

Fig. 10 Distribution of standing timber volume in different cost classes, separated by calculation method (BEST: best suitable harvesting method; REF: currently applied harvesting method), NFI production region, and labour-cost scenario

Distribution of standing timber volume in different cost classes by region and calculation method (BEST, REF)

R Code:

Mod#01

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: cost ~ scenario + system + (1 | clnr)
   Data: d.mm15

REML criterion at convergence: 210037.3

Scaled residuals:
    Min      1Q  Median      3Q     Max
-6.8181 -0.4426  0.0273  0.4083  7.8889

Random effects:
 Groups   Name        Variance Std.Dev.
 clnr     (Intercept) 2187.9   46.77
 Residual              202.9   14.24
Number of obs: 23040, groups:  clnr, 5937

Fixed effects:
              Estimate Std. Error         df t value Pr(>|t|)
(Intercept)    85.8677     0.6280  6404.8291  136.73   <2e-16 ***
scenario0       7.1480     0.1877 17035.7618   38.08   <2e-16 ***
systemBEST    -10.5090     0.1905 17080.3872  -55.16   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
           (Intr) scenr0
scenario0  -0.149
systemBEST -0.143  0.000
```

Mod#02

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: cost ~ scenario + system + (1 | clnr)
   Data: d.mm30

REML criterion at convergence: 209843.4

Scaled residuals:
    Min      1Q  Median      3Q     Max
-6.4855 -0.4428  0.0239  0.4192  8.2848

Random effects:
 Groups   Name        Variance Std.Dev.
 clnr     (Intercept) 2048.9   45.26
 Residual              205.1   14.32
Number of obs: 23040, groups:  clnr, 5937

Fixed effects:
              Estimate Std. Error         df t value Pr(>|t|)
(Intercept)    78.3597     0.6093  6438.8614  128.60   <2e-16 ***
scenario0      14.3648     0.1887 17028.2220   76.12   <2e-16 ***
systemBEST     -9.9913     0.1915 17076.1901  -52.16   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
           (Intr) scenr0
scenario0  -0.155
systemBEST -0.148  0.000
```

Mod#03

R output of model including all NFI sample plots

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: cost ~ scenario + system + volume + kfm + bfantndh + slope25 +
    sqrt(sdist_a) + (1 | clnr)
   Data: d.fullmodel

REML criterion at convergence: 203001.9

Scaled residuals:
    Min      1Q  Median      3Q     Max
-6.4397 -0.4489  0.0176  0.4268  8.3113

Random effects:
 Groups   Name        Variance Std.Dev.
 clnr     (Intercept) 885.3    29.75
 Residual             205.9    14.35
Number of obs: 22808, groups:  clnr, 5823

Fixed effects:
                Estimate Std. Error         df t value Pr(>|t|)
(Intercept)    6.874e+01  1.707e+00  5.801e+03   40.26  < 2e-16 ***
scenario0      1.428e+01  1.900e-01  1.688e+04   75.13  < 2e-16 ***
systemBEST    -9.971e+00  1.919e-01  1.694e+04  -51.97  < 2e-16 ***
volume        -2.962e-02  1.709e-03  5.709e+03  -17.33  < 2e-16 ***
kfm           -1.083e+00  3.742e-02  5.718e+03  -28.93  < 2e-16 ***
bfantndh       1.709e-01  1.032e-02  5.713e+03   16.56  < 2e-16 ***
slope25        8.158e-01  1.436e-02  5.731e+03   56.82  < 2e-16 ***
sqrt(sdist_a)  1.567e-01  1.942e-02  5.730e+03    8.07 8.49e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) scenr0 syBEST volume kfm    bfntnd slop25
scenario0   -0.056
systemBEST  -0.062  0.000
volume      -0.062  0.000 -0.004
kfm         -0.541  0.000  0.001 -0.414
bfantndh    -0.254  0.000  0.004 -0.102 -0.118
slope25     -0.470  0.000  0.009  0.094  0.018 -0.074
sqrt(sdst_) -0.539  0.000  0.010  0.001  0.008  0.061  0.141



Backward reduced random-effect table:

           Eliminated npar  logLik    AIC   LRT Df Pr(>Chisq)
<none>                  10 -101501 203022
(1 | clnr)          0    9 -111322 222661 19641  1  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Backward reduced fixed-effect table:
Degrees of freedom method: Satterthwaite

              Eliminated  Sum Sq Mean Sq NumDF   DenDF  F value    Pr(>F)
scenario               0 1162061 1162061     1 16876.4 5644.589 < 2.2e-16 ***
system                 0  555941  555941     1 16941.0 2700.428 < 2.2e-16 ***
volume                 0   61829   61829     1  5709.2  300.329 < 2.2e-16 ***
kfm                    0  172263  172263     1  5717.8  836.747 < 2.2e-16 ***
bfantndh               0   56444   56444     1  5713.0  274.169 < 2.2e-16 ***
slope25                0  664693  664693     1  5731.1 3228.679 < 2.2e-16 ***
sqrt(sdist_a)          0   13408   13408     1  5729.6   65.126 8.488e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Model found:
cost ~ scenario + system + volume + kfm + bfantndh + slope25 + sqrt(sdist_a) + (1 | clnr)
```

Mod#04

R output of model including only sample plots in production regions Pre-Alps, Alps and Southern Alps:

```
Linear mixed model fit by REML. t-tests use Satterthwaite's method ['lmerModLmerTest']
Formula: cost ~ scenario + system + volume + kfm + bfantndh + slope25 +
    sqrt(sdist_a) + (1 | clnr)
   Data: d.mountmodel

REML criterion at convergence: 131411.1

Scaled residuals:
    Min      1Q  Median      3Q     Max
-5.6259 -0.4471  0.0217  0.4364  7.3587

Random effects:
 Groups   Name        Variance Std.Dev.
 clnr     (Intercept) 984.9    31.38
 Residual             251.8    15.87
Number of obs: 14466, groups:  clnr, 3737

Fixed effects:
                Estimate Std. Error         df t value Pr(>|t|)
(Intercept)    8.307e+01  2.286e+00  3.723e+03  36.344  < 2e-16 ***
scenario0      1.716e+01  2.639e-01  1.066e+04  65.052  < 2e-16 ***
systemBEST    -1.270e+01  2.679e-01  1.072e+04 -47.389  < 2e-16 ***
volume        -3.448e-02  2.152e-03  3.656e+03 -16.025  < 2e-16 ***
kfm           -1.097e+00  4.825e-02  3.665e+03 -22.726  < 2e-16 ***
bfantndh       1.134e-01  1.397e-02  3.659e+03   8.118 6.39e-16 ***
slope25        6.427e-01  2.037e-02  3.667e+03  31.555  < 2e-16 ***
sqrt(sdist_a)  3.960e-01  2.647e-02  3.685e+03  14.960  < 2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Correlation of Fixed Effects:
            (Intr) scenr0 syBEST volume kfm    bfntnd slop25
scenario0   -0.058
systemBEST  -0.067  0.000
volume      -0.069  0.000 -0.006
kfm         -0.475  0.000  0.001 -0.398
bfantndh    -0.294  0.000  0.003 -0.080 -0.191
slope25     -0.547  0.000  0.008  0.091 -0.024  0.058
sqrt(sdst_) -0.433  0.000  0.017  0.010  0.020 -0.018  0.000



Backward reduced random-effect table:

           Eliminated npar logLik    AIC   LRT Df Pr(>Chisq)
<none>                  10 -65706 131431
(1 | clnr)          0    9 -71546 143110 11681  1  < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Backward reduced fixed-effect table:
Degrees of freedom method: Satterthwaite

              Eliminated  Sum Sq Mean Sq NumDF   DenDF F value    Pr(>F)
scenario               0 1065485 1065485     1 10656.7 4231.80 < 2.2e-16 ***
system                 0  565423  565423     1 10723.9 2245.70 < 2.2e-16 ***
volume                 0   64660   64660     1  3655.6  256.81 < 2.2e-16 ***
kfm                    0  130037  130037     1  3665.4  516.47 < 2.2e-16 ***
bfantndh               0   16595   16595     1  3659.0   65.91 6.385e-16 ***
slope25                0  250709  250709     1  3667.3  995.74 < 2.2e-16 ***
sqrt(sdist_a)          0   56350   56350     1  3685.2  223.81 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Model found:
cost ~ scenario + system + volume + kfm + bfantndh + slope25 + sqrt(sdist_a) + (1 | clnr)
```

Module inputs and harvesting method composition

Tables 11, 12

Table 11 Matrix showing the composition of the harvesting methods from its single modules, for the REF harvesting methods. (1*) The original REF computation according to Fischer and Stadelmann (2019) contains the module "Pre-Skidder" in the MM_FW harvesting method. As spatial data about the skidding road network are not available, the requirement of pre-skidding cannot be modelled with the BEST method. To ensure comparability, we chose an implementation without 'pre-skidding' in REF. (2*) An additional means of hauling was only applied in a few cases where the forest road was not trafficable with a truck. See Table 2 for descriptions of the harvesting methods

	HeProMo Module Name (Holm et al. 2020)	SimpleHelikopter2003	Simple-Hacker2018	SimpleRadharvester2014	SimpleForwarderRundholz2018	SimpleMobilseilkran1999	SimpleForwarder1997	SimpleHelikopter2003	SimpleHelikopter2003
	ID (Fischer and Stadelmann 2019)	1	2	3	4	5	6	7	8
	Module source (1 = HeProMo, 2 = NFI)	1	1	1	1	1	1	1	1
Code of harvesting method in NFI	Module name	Helicopter downhill (logs)	Mobile chipper	Harvester	Forwarder	Mobile tower yarder	Skidding with a forwarder (*2)	Helicopter uphill (logs)	Helicopter downhill (full tree)
1	MM_SK								
2	MM_FW				X				
3	PM_SK								
4	FM_FW			X	X				
5	FM_FW			X	X				
6	FM_TY			X		X			
7	MM_TY					X	X		
8	MM_LY						X		
9	PM_TY					X	X		
10	PM_LY						X		
11	PM_TYP								
12	MM_H	X					X		
13	MM_H						X	X	
14	PM_H						X		X
15	PM_H						X		
16	MM_FWCH		X				X		
17	MM_MS								
18	Other								

Table 11 (continued)

	SimpleHelikopter2003	SimpleSchlepper1992	SimpleSchlepper2014	SimpleSchlepper2014	SimpleKonventionellerSeilkran1999	SimpleMotormanuell2014	SimpleFaellenMotormanuell1978	RueckenAndereMittel	Reisten	Prozessor	SimpleKombiseilgeraet2018
	9	10	11	12	13	14	15	17	18	19	N
	1	1	1	1	1	1	1	2	2	2	1
Code of harvesting method in NFI	Helicopter uphill (full tree)	Pre-skidding	Skidder (*2)	Skidder	Long-distance cable yarder	MM felling and processing	Motor-manual felling	Skidding with other means	Hand skidding	Processor	Tower yarder processor
1				X		X					
2		(1*)				X					
3				X			X			X	
4											
5											
6											
7			X			X					
8			X		X	X					
9			X				X			X	
10			X		X		X			X	
11											X
12			X			X					
13			X			X					
14			X				X			X	
15	X		X				X			X	
16		X					X				
17						X			X		
18						X		X			

Table 12 Overview of the input variables for the module. Modified from Fischer and Stadelmann (2019). See Table 2 for descriptions of the harvesting methods

HeProMo module name (Holm et al. 2020)	SimpleHacker2018	SimpleRadharvester2014	SimpleForwarderRundholz2018	SimpleMobilseilkran1999	SimpleForwarder1997	SimpleHelikopter2003	SimpleSchlepper1992	SimpleSchlepper2014	SimpleKonventionellerSeilkran1999	SimpleMotormanuell2014	SimpleFaellenMotormanuell1978	RueckenAndereMittel	Reisten	Prozessor
Module name	Mobile chipper	Harvester	Forwarder	Mobile tower yarder	Skidding with a forwarder (additional)	Helicopter	Pre-skidding	Skidder (additional)	Long distance cable yarder	Motor-manual felling and processing	Motor-manual felling	Skidding with other means	Hand skidding	Processor
ID (Fischer and Stadelmann 2019)	2	3	4	5	6	1,7,8,9	10	11,12	13	14	15	17	18	19
Input variable														
Population element: tree			X										X	
Population element: living tree			X										X	
Extrapolation factor for each tree	X		X										X	
Diameter at breast height	X		X										X	
Broadleaved or coniferous tree	X		X											
Number of stems of living trees per hectare		X	X	X						X	X			X
Growing stock of living trees per hectare	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Table 12 (continued)

HeProMo module name (Holm et al. 2020)	Simple-Hacker2018	Sim-pleRadhar-vester2014	Simple-Forward-erRund-holz2018	Simp-leMobil-seilkran1999	SimpleFor-warder1997	Simple-Helikop-ter2003	Simple-Schlep-per1992	Simple-Schlep-per2014	SimpleKon-ventioneller-Seilkran1999	Simp-leMotorma-nuell2014	Simple-Faellen-Motorma-nuell1978	Rueck-enAnder-eMittel	Reisten	Prozessor
Dominant tree species with respect to basal area			X							X	X			
Dominant tree species group (broad-leaved/coniferous) with respect to basal area						X								
Mean volume of assortment	X			X			X	X	X					
Bole volume including bark	X		X											
Slope			X							X	X			
Obstacles for timber harvest	X		X	X			X	X		X	X		X	
Location of the mobile cable crane				X										
Length of cable crane line				X					X					
Skidding distance	X		X		X	X	X	X					X	

Table 12 (continued)

HeProMo module name (Holm et al. 2020)	SimpleHacker2018	SimpleRadharvester2014	SimpleForwarderRundholz2018	SimpleMobilseilkran1999	SimpleForwarder1997	SimpleHelikopter2003	SimpleSchlepper1992	SimpleSchlepper2014	SimpleKonventionellerSeilkran1999	SimpleMotormanuell2014	SimpleFaellenMotormanuell1978	RueckenAndereMittel	Reisten	Prozessor
Skidding technology					X	X	X	X						
Skidding direction			X						X					
Skidding route	X		X		X		X	X	X					

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Code availability The code is available upon request.

Declarations

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