forests

MDPI

Article

Comparison of A Cable-Based and a Ground-Based System in Flat and Soil-Sensitive Area: A Case Study from Southern Baden in Germany

Janine Schweier [1,*] and Christian Ludowicy [2,3]

[1] Research Group Sustainable Forestry, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, 8903 Birmensdorf, Switzerland

[2] Institute of Forest Sciences, University of Freiburg, 79085 Freiburg, Germany; christian.ludowicy@forstbw.de

[3] State Forest Administration of Baden-Württemberg (ForstBW), District Baar-Hegau, 72469 Meßstetten, Germany

* Correspondence: Janine.schweier@wsl.ch

Received: 30 April 2020; Accepted: 25 May 2020; Published: 29 May 2020

check for updates

Abstract: The results of this study showed that the application of cable-based systems in flat terrain must not necessarily be more cost intensive than its application in other terrains. In recent years, criteria other than purely economic ones have been taken into account in forest management decisions, with the aim of avoiding ecosystem damage and promoting better ecosystem services. Since precipitation in winter is becoming more intensive and weeks with frozen soils are becoming rare, one option might be the use of cable-based instead of ground-based extraction systems. Both vary in terms of economy and flexibility. Thus, it is important to make reliable estimates of potential costs and benefits before an operation is conducted. The aim of this study was to analyze a cable-based and a ground-based extraction system that could be applied to a forest stand in a flat and soil-sensitive area. The study, based on a cable-based operation, was conducted in a mixed forest stand that was vulnerable to traffic. Furthermore, we modeled an alternative operation focusing on a ground-based system, addressing the soil vulnerability by considering manual felling, processing, and use of a combi-forwarder for extraction. In the cable-based system, yarding productivity was high ($20.3\ m^3_{ub}/PMH_{15}$) due to several reasons, such as a high share of larger dimension timber, the fact that heavy timber was partially de-limbed and processed motor-manually in the stand, the fact that a mini forestry crawler was used for pre-winching the material and finally due to the experience of the operators. Resulting costs for harvesting and extraction were on average €27.8/m^3_{ub}. In the ground-based system, costs were on a comparable level (€28.30/m^3_{ub}). In our case, the application of a cable yarder in flat terrain was a good alternative and should be considered in future forest management to support environmentally friendly operations and allow independent planning of the operation.

Keywords: soil protection; vulnerable soil; wet area; horizontal yarding; extraction; combi-forwarder; bogie tracks; productivity; costs; uncertain planning

1. Introduction

Forest operations (FO) commonly involve the use of machinery in the forest environment. This, however, might result in environmental impacts in cases where soils are sensitive to machine traffic [1]. In particular, some studies have shown that machine-induced soil compaction can persist for periods ranging from several years to decades, depending on the severity of the impact, soil properties, and level of biological activity [2–5]. In recent years, a number of criteria have been taken into account in forest management decisions in order to avoid ecosystem damage and promote better ecosystem services, including but not limited to economic criteria (e.g., [6–11]). As such, issues other than solely wood production have been considered, including for example social aspects [12], biodiversity [13], and soil protection (c.f. [14]).

Furthermore, shorter periods in which soils are frozen [15], as well as increased and more intensive precipitation, in winter [16] are now expected. Lehtonen et al. [17] estimated that the wintertime bearing season in Finland will be approximately one month shorter for the period 2021–2050. An increase in sensitivity toward traffic of harvest stands is expected. To give an example, in the Southwest German federal state Baden-Württemberg (BW), around 30% to 41% of forest soils in state forests are expected to be sensitive to traffic in future [18,19], with most of them being located in flat terrain [18].

Both aspects, the inclusion of environmental criteria into decision-making processes and the increasing share of forest areas that are vulnerable to traffic, have substantial impacts on forest management. In view of this and the fact that forest traffic is influenced by slope, ground-bearing capacity, and ground roughness [20], some federal states of Germany have set limits for acceptable track depth. The overall aim is to protect the soils and preserve the durability of skid roads in the long term. In BW, the limit has been set to 40 cm, which can only be exceeded on a maximum of 10% of all tracks in one forest stand [21]. Planners are now legally required in their planning deliberations to consider expected impacts on soil. This is highly important because it might lead to the fact that the use of classic mechanized cut-to-length systems are no longer permitted and FO need to be based on motor-manual felling and processing.

One option to reduce soil disturbance from mechanized FO is the use of ground-based cable extraction systems with winch-assisted hauling machines that are equipped with bogie tracks. Of increasing interest is a machine that can be used for extraction of either long or short logs, a so-called combi-forwarder (e.g., Welte 210, HSM 208F, John Deere 1210 E). Resulting productivities depend on given conditions; in the case of Bacher-Winterhalter [22], 26 m^3 per productive hour was reached, and costs were 4.6 €/m^3 for the extraction process and 18–19 €/m^3 for felling and extracting. Depending on the machine type, hourly costs are approximately between 75 € and 90 € per productive hour (excluding additional equipment, such as bogie tracks). Another option is the use of cable crane systems, which completely eliminates ground-based traffic and reduces soil compaction, soil surface damage, and erosion [23]. Studies analyzing yarders that were, however, applied to all directions (but mostly uphill), reported productivities of 10–15 m^3 per productive hour [24–26]. Resulting costs were 30–40 €/m^3 for the whole process chain, from manual felling to processing. Since both systems, the ground-based and the cable-based, vary in terms of economy and flexibility, it is important to make reliable estimates of potential costs and benefits beforehand.

In order to support forest managers, the aim of this study was to incorporate their perspectives and to (i) identify a ground-based and a cable-based harvesting and hauling operation that could be applied to a forest stand located in a flat and soil-sensitive area; (ii) analyze and compare the FO in terms of productivity and cost; and (iii) derive recommendations that are valid for comparable stands.

2. Materials and Methods

2.1. Study Approach

We found a mixed forest stand where ground-based systems have continued to be applied. Practitioners described the area as consistently sensitive to traffic. However, the soil appeared to have become even more vulnerable than before because of warm and rainy conditions during the scheduled winter harvesting period. For the first time on this site, the FO was therefore done by using a cable-based system, a commercial FO, conducted in March 2019. We accompanied the FO and collected time-related data in order to calculate productivity and cost. Furthermore, in order to compare two systems, we also collected site- and stand-related information to estimate the likely productivity and cost of using a ground-based system for the same site. The study was supported by (i) the leader of the operation (data about machines and systems); (ii) the local forester (information about the area and previous FO); and (iii) the State Forest Administration of Baden-Württemberg (ForstBW) (provision of GIS and other data being necessary to simulate the ground-based system, e.g., the size of the area).

2.2. Study Site

The study was carried out in the German southwestern federal state BW, namely in the South-Baden area north-west of the city Schwörstadt (47°36′15″ N; 7°50′47″ E, 400–450 m a.s.l.). The growth area belongs to the Upper Rhine Lowland, the mean annual temperature is 9.6 °C, and the annual precipitation reaches 900 mm [27]. The forest site of the 12.7 ha study area is flat with a slightly undulating (5–15%) relief. There is one exception in the southeastern area at the forest edge, where it is comparably steep. Fine, layered, and dolomite weathering clay were dominating on this site, together with a relatively small fraction of colluvial silt clay [28]. As such, the site is generally sensitive to traffic [29]. The beech/conifers-mixed forest has a continuous forest cover [30]. The site is well maintained, trees have large crowns, and natural regeneration can be found in the overall area. The dominating tree species of the harvested trees was hardwoods (65%, mainly beech and 5% ash), and softwoods (35%, mainly larch and spruce and 5% pine). The tree diameter at breast height (DBH) of the harvested trees was on average 50 cm, and the main assortment contained standard lengths.

2.3. Applied: Cable-Based System

The FO in use applied a tower yarder with a mounted processor. It was employed in the following operational setup (Figure 1): motor-manual felling, extraction of (mainly) full trees, and processing by processor.

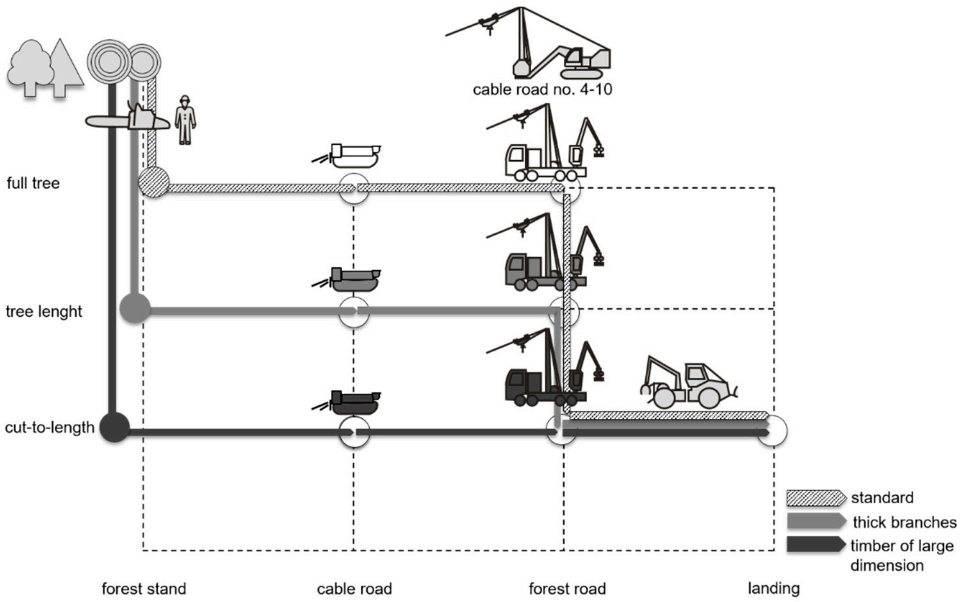

Figure 1. Operational setup of the cable-based system: working steps include motor-manual felling, extraction of (mainly) full trees, and processing by processor. An excavator with tail spar function was used in cable roads nos. 4–10.

After instruction, ten cable corridors (Table 1) were planned and prepared, and anchor trees and intermediate supports were determined. An excavator with tail spar function was used as an anchor (Liebherr-International AG, Switzerland, Type 924) in seven out of ten cable roads (Table 1). Subsequently, trees were felled and partially top-cut, both motor-manually by a team of two experienced forest workers. Very heavy timber, i.e., hardwoods with thick branches, was de-limbed, processed, and cut into assortments to reduce pressure on the processor aggregate. In most cases, felled trees were pre-winched with a radio-controlled mini forest crawler to the cable corridor (Wicki Forst AG, Switzerland, Type 50.6 b). The crawler was operated by the forest workers. Ideally, pre-winching happened at acute angles to the next cable road, with butts ahead of the corridor to concentrate the trees before employing the tower yarder system. The tower yarder (Koller Forsttechnik GmbH, Austria, Type K507) was mounted on a truck and worked with a three-cable system in horizontal yarding direction. Trees were further processed at the forest road. Finally, the different assortments were piled at the landing along the forest road by using a grapple skidder (Welte, Germany, Type 150W) before on-road transport (Figure 1).

Table 1. Number and length of cable roads, amount of intermediate supports (IS), use of excavator with tail spar function, and amount of harvested biomass in the applied cable-based system.

Cable Road No.	Length (m)	IS	Excavator with Tail Spar	Volume (m^3_{ub})
1	122.7	0	0	66.2 *
2	173.9	0	0	93.9 *
3	208.3	1	0	112.4 *
4	371.7	3	1	200.6 *
5	371.3	2	1	183.9
6	339.1	2	1	120.8
7	320.6	1	1	105.9
8	348.6	1	1	57.1
9	235.2	1	1	58.4
10	210.8	1	1	226.2
Sum	2702.2	12	7	1,225.5

IS = intermediate supports; m^3_{ub} = cubic meter under bark; * it was not possible to allocate timber from cable roads 1–4 to the origin cable road. In total, 473.2 m^3_{ub} was extracted from the cable roads nos. 1 to 4, and we here report the calculated average value per cable road in relation to its length.

It was not possible to apply this system to the edges of the forest stand, in addition to the steeper southeastern area. Instead, those trees were felled and de-limbed motor-manually, the first partly supported by the mini forest crawlers (Wicki Forst AG, Switzerland, Type 50.6 b). The extraction of the assortments to the forest road and piling was conducted by using the same grapple skidder (Welte, Germany, Type 150W).

2.4. Simulated: Ground-Based System

A potential alternative ground-based FO system could use a combi-forwarder for extraction. This machine can be used either for long logs in skidding mode with a clambunk or for short logs in forwarding mode with a stake cage and is of increasing interest to the forest operations profession generally, owing to its increased functionality and reliability; the operating company in question did in fact own one. All assumptions and calculations considered the same conditions that were given in the cable-based system (e.g., site- and stand-related data, but also availability of the technical equipment owned by the company).

The system could have been employed in the following operational setup (Figure 2): motor-manual felling and de-limbing, assisted by mini forest crawler, extraction of full trees by combi-forwarder to skid road, and final extraction to landing. In this setup, a team of two forest workers fell the trees (if possible) in the design of a fishbone at an acute angle to the next skid road or forest road. Within the boom reach, stems are processed and cut into standard lengths. A radio-controlled mini forestry crawler (Wicki Forst AG, Switzerland, Type 50.6 b) is used to support the felling process. Outside the boom reach, trees are felled, cut into double lengths, and pre-winched into the boom reach, using the crawler. A powerful 8-wheeled combi-forwarder (Deere & Company, Illinois, Type John Deere 1210 E) equipped with bogie tracks is used for the extraction to the next skid road or forest road, where double lengths are cut into standards. Due to the size of the forest site this system requires four forest workers (2 chainsaws and 2 crawlers). Finally, a second, smaller, 6-wheeled combi-forwarder (without bogie tracks) is used to extract the assortments from the forest road to the landing (Welte, Germany, Type W210) (Figure 2).

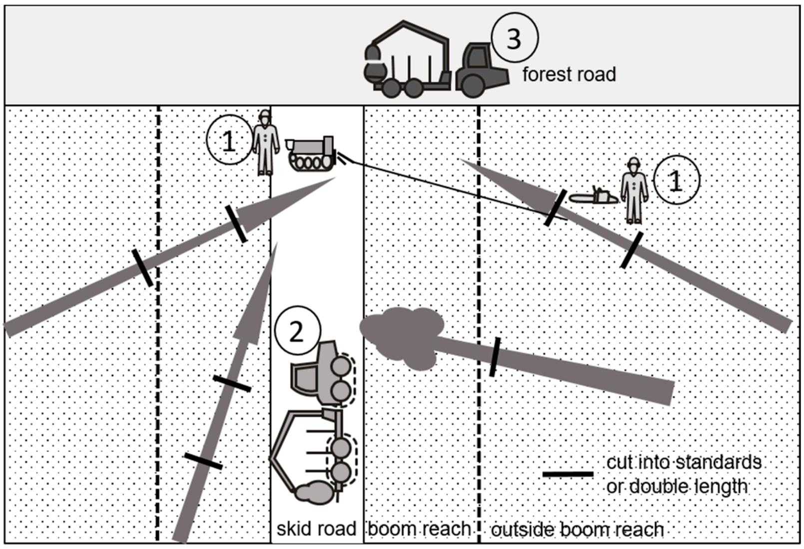

Figure 2. Operational setup of the simulated ground-based system: working steps include (1) motor-manual felling and de-limbing, assisted by mini forest crawler, (2) extraction of full trees by combi-forwarder to skid road, and (3) final extraction to landing.

2.5. Geo-Based Data

In order to get site-related data (e.g., size and shape) and to estimate transport distances used in the alternative ground-based system (e.g., length of skid trails), it was necessary to have access to digital maps. They were provided by the business area "forest geo-information" by ForstBW [31]. Required data were mostly exported from ForstBW's forest GIS program "FoGIS". In addition, a mobile handheld data collector was used on-site (Trimble Inc, California, Type Geo 7x) to determine the exact position of the cable roads and involved machines, as well as the forest road network, in particular old skid trails and truck-accessible forest roads. Data were further edited by using ArcGIS (ESRI Inc., California, version 10.6.1).

2.6. Harvested Volume

It was not possible to measure the DBH before conducting the FO. Therefore, the height of approximately 70 fresh stumps was measured, on a sample basis, to estimate the average cutting height, which was 29 cm, taking seven tree species into account. Next, about 100 stems lying close to the stumps were measured at a length of approximately 100 cm. In this way, it was possible to reconstruct the DBH of all removed trees. At the same time, other relevant data were recorded (e.g., species). For safety reasons, it was not possible to collect data in the forest stand while the tower yarder was running. Therefore, all timber was measured and recorded as soon as it was piled at landing. Any missing information was provided by the operator. The following data were recorded per pile: pieces of logs, log length, log diameter, assortment, species, treatment (i.e., tower yarder vs. motor-manual), and origin (i.e., number of respective cable road). Timber extracted from cable roads 5–10 was allocated to the origin cable road (Table 1).

In the case of cable roads nos. 1–4, however, this was not possible. Resulting data allowed an estimate of the average length, diameter, and stem of mean basal area per assortment, as well as the average volume per assortment. This was done separately for the larger part, which was extracted by using the tower yarder, and the smaller one, which was extracted by using the grapple skidder. The resulting volumes of biomass extracted during the FO were used as reference for further calculations of both systems, namely the applied cable-based system and the simulated alternative ground-based system.

2.7. Working Productivity

For the applied cable-based system, working and machine hours were recorded by the forest workers and machine operators, including the number of hours spent on each working step, for every working day. The regular weekly working time spent in the forest was 37.5 h. The mini forest crawler was used on the overall study site, namely in the larger part, where extraction was done by the tower yarder, and the smaller one, where extraction was done by the grapple skidder. Neither the daily travel of the forest workers to the forest stand nor the transport of the machines was included in the working-time calculation. The productivity was calculated by dividing the working time with the amount of processed timber.

In contrast, for the simulated alternative ground-based system, working times, productivity, and costs were estimated by using the model HeProMo (WSL, Switzerland, versions 2.3 and 2.4) [32]. The Java-based calculation tool, which is currently used by research and forest enterprises, allowed the productivity of different working processes to be estimated. It was necessary to provide some further data for the calculation: (1) Based on information given by the operator, a time requirement of 4.5 h was assumed for installation of the bogie tracks on the combi-forwarder that was used for the first extraction process. This time was distributed proportionally to the working times of the skidder (35%) and the forwarder (65%). (2) In principle, the operator was asked to extract one assortment per forwarder cycle. However, this was not 100% feasible because of the high number of assortments. Therefore, it was assumed that, on average, 1.2 assortments were extracted per forwarding cycle. (3) The average extraction distances and slopes of the cable roads were estimated by using GIS data. The local forester identified the forest road network that was used in the previous ground-based operations that have been conducted at this site, and the calculated distances refer to this former network. On average, the extraction distance was 153 m when the powerful 8-wheeled combi-forwarder was operating on skid roads (no machine entered the stands), and it was 55 m for the second extraction process, from forest road to landing. Again, neither the daily travel of the forest workers to the forest stand nor the transport of the machines was included in the calculation.

2.8. Production Costs

Based on productivity results, standard cost rates (Table 2) were used to calculate costs of both systems, in order to keep results comparable. This is important because the cost rates used by ForstBW could differ from the rates used in this study. The costs for the transport of forest workers and machines were not considered.

Table 2. Standard cost rates of used machines (in Euros); wages include non-wage costs.

Component	Costs	Unit
Forest workers	30.40	€/h
Operation manager	38.00	€/h
Machine operators	32.00	€/h
Chainsaw	8.40	€/PMH_{15}
Mini forestry crawler	30.00	€/PMH_{15}
Tower yarder mounted on truck	145.00	€/PMH_{15}
Excavator (plus tail spar)	35.00 (+25.00)	€/PMH_{15}
Grapple skidder	65.00	€/PMH_{15}
8-wheeled combi-forwarder	89.00	€/PMH_{15}
Bogie tracks	1.50	€/$m^3{}_{ub}$
6-wheeled combi-forwarder	77.00	€/PMH_{15}

€ = Euro; $m^3{}_{ub}$ = cubic meter under bark; PMH_{15} = productive machine hours, including delays up to 15 min.

3. Results

3.1. Tested: Cable-Based FO

3.1.1. Harvested Volumes

In total, an amount of 1397.3 cubic meters under bark (m^3_{ub}) were harvested (Table 3). Of this, 12% (171.7 m^3_{ub}) were harvested from the edges and the southeastern part of the site, where felling was conducted by chainsaw and extracting by ground-based grapple skidder. The tower yarder was applied over the majority of the site (88%, 1225.6 m^3_{ub}). Overall, most assortments were hardwoods (65%) (Table 3). Specifically, the most frequent assortment was industrial wood from beech (28%, 390 m^3_{ub}), followed by stem wood from beech (17%, 234 m^3_{ub}), and industrial wood from other hardwoods (10%, 142 m^3_{ub}) (Table 3).

Table 3. Volumes, species, and assortments of the harvested area.

Assortment	Additional Information	Volume Grapple (m^3_{ub})	Volume Yarder (m^3_{ub})	Total (m^3_{ub})
Stem wood beech		42.1	191.8	233.9
Stem wood oak	Large dimensioned	20.6	26.6	47.2
Stem wood oak		4.8	27.0	31.9
Stem wood oak		0.9	11.1	11.9
Stem wood spruce	Large dimensioned	8.0	86.3	94.3
Stem wood spruce		2.3	266.4	268.7
Stem wood spruce	Low quality	2.8	37.1	39.9
Industrial wood beech		52.4	337.9	390.3
Industrial wood o.hw.		28.8	113.3	142.1
Wood for chipping		9.0	64.0	73.0
Stem wood larch/pine	Long	0.0	41.8	41.8
Stem wood larch/pine	Short, high quality	0.0	3.3	3.3
Stem wood larch/pine	Short, low quality	0.0	16.0	16.0
Unknown		0.0	3.0	3.0
Sum		171.7	1225.6	1397.3

Grapple = grapple skidder; m^3_{ub} = cubic meter under bark; o.hw. = other hardwoods.

3.1.2. Distribution of Working Times

In total, 655 worker-hours were necessary to conduct the FO (Table 4). Of this, 16.5% (108 h) was required for the edges and the southeastern part of the site, where felling was conducted by chainsaw and extracting by ground-based grapple skidder. The remaining 83.5% (547 h) was required for all other parts of the site where the tower yarder was used for extraction. There, the most time-consuming process was manual felling and partial de-limbing (30%), followed by yarding and processing (26.5%), instruction and machine installation (24.5%), extracting and piling (9%), pre-winching (8%), and tracing (2%). The machine installation included the setting up and dismantling of the tower yarder, as well as the installation of the excavator with tail spar function.

A total of 362.5 productive machine hours, including delays up to 15 min (PMH_{15}), were necessary to conduct the FO (Table 4). Of this, 21% (75 PMH_{15}) was employed on the small part of the site, where felling was conducted by chainsaw and extracting by ground-based grapple skidder. The remaining 79% (287.5 PMH_{15}) was employed on the area where the tower yarder was used for extraction. There, the most time-consuming process was felling and partial de-limbing (34%), followed by yarding and processing (21%), anchoring with excavator with tail spar function (16%), pre-winching (15%), extracting and piling (9%), and instruction and machine installation (5%). For the excavator with tail spar function, we assumed the same productivity as for the yarding process. Thus, the excavator was used for 47.0 PMH_{15} in the cable roads nos. 4–10 (referring to 953 m^3_{ub}, Table 1).

Table 4. Required labor and machines for the different working steps in the cable-based FO.

Site	Working Step	Labor Hours (h)	Machine Hours (PMH_{15})
Yarder	Instruction and machine installation [1]	133.0	14.0
Yarder	Tracing	10.0	0.0
Yarder	Manual felling and partial processing	163.5	97.1
Yarder	Pre-winching with crawler	45.4	42.5
Yarder	Yarding and processing with yarder	144.5	60.5
Yarder	Anchoring with excavator and tail spar	0.0	47.0
Yarder	Extracting and piling with grapple skidder	50.6	26.0
Grapple	Preparation and others	26.0	0.0
Grapple	Manual felling	36.0	32.9
Grapple	Supporting and pre-winching with crawler	5.1	5.0
Grapple	Extracting and piling with grapple skidder	40.9	37.5
Sum	All working steps	655.0	362.5

[1] This includes instruction, setup, and dismantling of the tower yarder and the excavator with tail spar function; grapple = grapple skidder, refers to the small part of the site where felling was conducted motor manually; PMH_{15} = productive machine hours including delays up to 15 min.

3.1.3. Working Productivity

The resulting productivity of the different working steps is shown in Table 5. The yarding productivity was 20.3 m^3_{ub}/PMH_{15}. To calculate the productivity of the machine installation (128.0 h in total), the amount of cable roads can be considered (10 cable roads). On average, the productivity was 12.8 h/cable road. Alternatively, the length of the cable road could also be used as reference, as noted by Erber et al. (2017) [25]. In our case, the time consumption for setting up and dismantling the tower yarder was 0.05 h/m cable road.

Table 5. Resulting productivity of the different working steps in the cable-based FO.

Site	Working Step	Volume (m^3_{ub})	Labor Productivity (m^3_{ub}/h)	Machine Productivity (m^3_{ub}/PMH_{15})
Yarder	Instruction and machine installation [1]	1225.6	9.2	87.5
Yarder	Tracing	1225.6	122.6	n.a.
Yarder	Manual felling and partial processing	1225.6	7.5	12.6
Yarder	Pre-winching with crawler	919.2	20.2	21.6
Yarder	Yarding and processing with yarder	1225.6	8.5	20.3
Yarder	Anchoring with excavator and tail spar	952.9	n.a.	20.3
Yarder	Extracting and piling with grapple skidder	1164.3	23.0	44.8
Grapple	Preparation and others	171.7	6.6	n.a.
Grapple	Manual felling	171.7	4.8	5.2
Grapple	Supporting and pre-winching with crawler	171.7	33.7	34.3
Grapple	Extracting and piling with grapple skidder	171.7	4.2	4.6

[1] Installing includes the setup and dismantlement of the tower yarder and the excavator with tail spar function; [2] we assumed the same productivity for the excavator as for the winching process; grapple = grapple skidder, refers to the small part of the site where felling was conducted motor-manually; PMH_{15} = productive machine hours, including delays up to 15 min; n.a. = not applicable.

3.1.4. Production Costs

Total production costs were €38,760. Of this, 16% (€6’118) applies to the small part of the site, where felling was conducted by chainsaw and extracting by ground-based grapple skidder. The remaining

84% (€32′662) applies to the area where the tower yarder was used for extraction. Overall, 52% of the costs refer to labor and 48% to machines (Table 6).

Table 6. Resulting labor, machine, and total costs of the different working steps in the cable-based FO, in €.

Site	Working Step	Labor Costs (€)	Machine Costs (€)	Total Costs (€)
Yarder	Instruction and machine installation [1]	4054.0	490.0	4544.0
Yarder	Tracing	380.0	0.0	380.0
Yarder	Manual felling and partial processing	4970.4	815.6	5786.0
Yarder	Pre-winching with crawler	1380.2	1275.0	2655.2
Yarder	Yarding and processing with yarder	4392.8	8772.5	13165.3
Yarder	Anchoring with excavator and tail spar	0.0	2822.6	2822.6
Yarder	Extracting and piling with grapple skidder	1619.2	1690.0	3309.2
Grapple	Preparation and others	790.4	0.0	790.4
Grapple	Manual felling	1000.2	276.4	1276.5
Grapple	Supporting and pre-winching with crawler	155.0	150.0	305.0
Grapple	Extracting and piling with grapple skidder	1308.8	2437.5	3746.3
Sum	All working steps	20,051.0	18,729.6	38,780.6

On a relative scale, costs were on average €27.8/$m^3_{ub.}$ The most cost-intensive working steps were yarding and processing (34%, €9.4/m^3_{ub}), followed by manual felling and partial processing (15%, €4.1/m^3_{ub}), instruction and machine installation (12%, €3.3/m^3_{ub}), extracting and piling with grapple skidder in the small part (10%, €2.7/m^3_{ub}), and the larger part (9%, €2.4/m^3_{ub}) of the site. All other working steps were responsible for the remaining 21% of the costs.

When looking at the yarder site only, the average cost was €26.7/m^3_{ub} (referring to 1225.6 m^3_{ub}). Again, the most cost-intensive working steps were yarding and processing with yarder (40%, €10.7/m^3_{ub}), followed by manual felling and partial processing (18%, €4.7/m^3_{ub}), instruction and machine installation (14%, €3.7/m^3_{ub}), extracting and piling with grapple (10%, €2.7/m^3_{ub}), anchoring with tail spar (9%, €2.3/m^3_{ub}), pre-winching with crawler (8%, €2.2/m^3_{ub}), and tracing (1%, €0.3/m^3_{ub}).

When looking at the edges and the southeastern part of the site only where felling was conducted by chainsaw and extracting by ground-based grapple skidder, the average costs were €35.6/m^3_{ub} (referring to 171.7 m^3_{ub}). The most cost-intensive working steps were extracting and piling with a grapple skidder (61%, €21.8/m^3_{ub}), followed by manual felling (21%, €7.4/m^3_{ub}), preparation and others (13%, €4.6/m^3_{ub}), and support and pre-winching with a crawler (5%, €1.8/m^3_{ub}).

3.2. Simulated: Ground-Based FO

3.2.1. Harvested Volumes

The same harvesting volumes and similar distribution of the assortments were assumed to be extracted in both systems (~1400 m^3_{ub}).

3.2.2. Distribution of Working Times

By using the model HeProMo, we estimated that a total of 785 worker-hours would have been necessary to conduct the FO (Table 7). The most time-consuming processes were manual felling and de-limbing (including sorting and other necessary tasks) (43%) and pre-winching into the boom with the crawler (43%), followed by extracting to the next forest road with the eight-wheeled combi-forwarder (8%) and extracting to landing and piling with the six-wheeled combi-forwarder (6%).

The combi-forwarder operated 61–65% of the time in forwarding mode (second and first extraction process, respectively) and 35–39% of the time in skidding mode (first and second extraction process, respectively). The high use as forwarder can mostly be explained by the assortments (Table 3).

Table 7. Required labor and machines for the different working steps in the ground-based FO.

Working Step	Labor Hours (h)	Machine Hours (PMH_{15})
Manual felling and de-limbing	339.1	169.5
Pre-winching into the boom with crawler	339.1	144.1
Extracting to next road [1]		
Skidder	18.8	17.1
Forwarder	35.5	32.3
Bogie tracks	4.5	n.a.
Extracting to landing and piling [2]		
Skidder	18.8	17.1
Forwarder	28.9	26.3
All working steps	784.7	406.4

[1] Extracting to next forest road with eight-wheeled combi-forwarder equipped with bogie tracks; [2] extracting to landing and piling with six-wheeled combi-forwarder; n.a. = not applicable.

In terms of machine hours, 406 PMH_{15} was necessary to conduct the FO (Table 7). Again, the most time-consuming processes were manual felling and de-limbing (42%), followed by pre-winching into the boom with the crawler (36%), extracting to next forest road with the eight-wheeled combi-forwarder (12%), and extracting to landing and piling with the six-wheeled combi-forwarder (10%). Similar to the labor hours, the combi-forwarder operated 61–65% of the time in forwarding mode (second and first extraction process, respectively) and 35–39% of the time in skidding mode (first and second extraction process, respectively).

3.2.3. Working Productivity

The resulting productivity of the different working steps is shown in Table 8. In the first extraction process to the next forest road, the productivity varied depending on the applied mode of the combi-forwarder: extracting long logs in skidding mode resulted in lower productivity compared to the extraction of short logs in forwarding mode (21.9 vs. 31.7 m^3_{ub}/PMH_{15}, respectively; Table 8). The latter was about 50% higher, since almost three-times-more volume was extracted in the forwarding mode (Table 3), which had a significant positive effect on the machine productivity. A similar pattern was shown in the final extraction process to the landing. There, productivity in the forwarding mode was even higher (38.9 m^3_{ub}/PMH_{15}; Table 8) because timber was already preconcentrated on piles and the machine operated mostly on forest roads.

Table 8. Resulting productivity of the different working steps in the ground-based FO.

Working Step	Volume (m^3_{ub})	Labor Productivity (m^3_{ub}/h)	Machine Productivity (m^3_{ub}/PMH_{15})
Manual felling and de-limbing	1397.8	4.1	8.2
Pre-winching into the boom with crawler	1188.1	3.5	8.2
Extracting to next forest road [1]			
Skidder	374.2	19.9	21.9
Forwarder	1023.3	28.8	31.7
Bogie tracks	1397.5	n.a.	n.a.
Extracting to landing and piling [2]			
Skidder	374.2	19.9	21.9
Forwarder	1023.3	35.4	38.9

[1] Extracting to next forest road with eight-wheeled combi-forwarder equipped with bogie tracks; [2] extracting to landing and piling with six-wheeled combi-forwarder; n.a. = not applicable.

3.2.4. Production Costs

Total production costs were €39,607. Of these, 61% were for labor and 39% for machines (Table 9). The main drivers for the labor costs were the two forest workers (felling, processing, etc.) and the two additional forest workers for pre-winching with the crawler. The main driver for the machine costs was the eight-wheeled combi-forwarder equipped with bogie tracks, in particular when it operated in forwarding mode (Table 9). The costs for the bogie tracks were included, namely €1.50/m^3_{ub} (Table 2), with 4.5 hours for their installation.

Table 9. Resulting labor, machine, and total costs of the different working steps in the ground-based FO, in €.

Working Step	Labor Costs (€)	Machine Costs (€)	Total Costs (€)
Manual felling and de-limbing	10,308.6	1423.8	11,732.4
Pre-winching into the boom with crawler	10,308.6	4323.0	14,631.6
Extracting to next forest road [1]			
Skidder	601.9	1521.9	2123.8
Forwarder	1136.0	2874.7	4010.7
Bogie tracks	144.0	2096.3	2240.3
Extracting to landing and piling [2]			
Skidder	601.9	1316.7	1918.6
Forwarder	924.8	2025.1	2949.9
Sum	24,025.9	15,581.5	39,607.4

[1] Extracting to next forest road with eight-wheeled combi-forwarder equipped with bogie tracks; [2] extracting to landing and piling with six-wheeled combi-forwarder.

On a relative basis, average costs were €28.3/m^3_{ub}. Of these, 61% (17.2 €/m^3_{ub}) was for labor and 39% (€11.1/m^3_{ub}) for machines. The most expensive working steps were pre-winching into the boom reach (37%, €10.5/m^3_{ub}), followed by manual felling and de-limbing (30%, €8.4/m^3_{ub}), extracting to next forest road (21%, skidder €1.5/m^3_{ub}, forwarder €2.9/m^3_{ub}, bogie tracks €1.6/m^3_{ub}) and final extracting to landing and piling (12%, skidder €1.4/m^3_{ub}, forwarder €2.1/m^3_{ub}).

When looking at the extraction processes only in considering the extracted volumes, results showed that, in the first extraction process, the skidding mode (374 m^3_{ub}) was rather inefficient (€7.30/m^3_{ub}) compared to the forwarding mode (€5.5/m^3_{ub}). The same was true for the second extraction process (skidding mode €5.1/m^3_{ub}, forwarding mode €2.9/m^3_{ub}, results refer to 1023 m^3_{ub}).

4. Discussion

We compared a cable-based and a ground-based FO in flat terrain. The latter was applied at the study site in recent decades, but the respective forest stand is soil sensitive to traffic. That has been a problem from both a technical and an environmental viewpoint. The vulnerability also increased in the harvesting year because of high winter precipitation. Thus, the use of a classic fully mechanized harvester-forwarder system was no option.

The regional forester decided for the first time to apply a cable-based system. This decision was taken in order to address the soil sensitivity, consider the environmental soundness in decision-taking, and plan independently from many system-influencing factors, such as the weather. The system was employed in the following setup: Trees were felled motor-manually, pre-winched by a radio-controlled mini forestry crawler, and extracted by tower yarder with a mounted processor (Figure 1). The Koller K507 worked with a three-cable system in horizontal yarding direction and processed stems at the forest road, where they were piled at the landing by using a grapple skidder. Due to the shape and slope of the site, it was necessary to apply another system in a small area for 12% of the harvested volume. There, trees were felled and de-limbed motor-manually, partly supported by mini forestry crawlers, and extracted with a grapple skidder.

In the frame of this study, we accompanied the operation conducted in early 2019 and analyzed the yarder K507 applied to flat and soil sensitive terrain in the southern part of Baden-Württemberg close to Switzerland. In sum, 1400 $m^3{}_{ub}$ was extracted.

Many of the literature studies analyze productivity, costs, and various other (mainly technical) aspects of cable-based systems in steep terrain (e.g., [25,33–36]). It is well-known that the productivity of a cable crane is influenced by log volume and its characteristics, length of skyline, silvicultural prescription, and extraction distance. In addition, it is known that terrain slope, stand density, and direction of the yarding (uphill/downhill) have an influence on the extracted volume per time (e.g., [25,34,37–39]), as well as professional training (e.g., [40]) and log presentation (e.g., [39]).

With regard to productivity, Erber et al. [25] analyzed the same yarder as the one analyzed in this study (K507 by Koller Forsttechnik GmbH, Austria). The machine was applied in the Bavarian State Forests, which is the neighbor federal state of Baden-Württemberg. Based on a nine-year data collection, the average yarding productivity reported was 10.1 m^3 per productive system hours, including delays up to 15 min (PSH_{15}). Recently, Schweier et al. [26] reported an average productivity of 13.3 ± 2.6 $m^3{}_{ub}/PMH_{15}$ for the same yarder (K507), based on a six-year data collection. Stampfer et al. [24] analyzed a comparable yarder (Wanderfalke by Mayr-Melnhof, Austria) and reported average productivities of 12.1–12.5 m^3 per productive system hours, excluding delays (PSH_0) (with radio-controlled and standard choker, respectively).

However, studies referring to the use of cable-based systems in flat terrain are scarce. Some rare examples include the tractor-mounted cable crane Syncrofalke (Type 4.0 by MM Forsttechnik GmbH, Austria) that was presented by KWF in Germany in 2013 [41]. Working in combination with the Woody aggregate for crane processing (Type 60 H by Konrad Forsttechnik GmbH, Austria,) it reached an average productivity of 9.0 m^3/PMH_{15} for yarding and piling (Ø DBH 30 cm). In 1995, Brown [42] analyzed an earlier model of the Koller yarder (K501) in Oregon, USA. A three-rope system was used to bring the short wood to the forest road. The average yarding productivity of the 16-hectare site was 15.3 m^3/PMH_{15}. The productivity of the subsequent processor was 20.8 m^3/PMH_{15}. Recently, Erber and Spinelli [43] collected information about manufacturers' experience with customers working on flat terrain and reported an increasing interest, particularly in Germany. Klein et al. [44] analyzed the productivity of the Koller yarder (K507) used in Southwest Germany with regard to yarding direction. The productivity tended to be a bit lower in an uphill direction (12.9 ± 2.4 m^3/PMH_{15}) compared to a horizontal direction (14.5 ± 2.8 m^3/PMH_{15}).

Here, results showed that, on average, the productivity of manual felling and partial processing was 12.6 $m^3{}_{ub}/PMH_{15}$, of yarding and processing 21.6 $m^3{}_{ub}/PMH_{15}$ and of extracting and piling with grapple skidder 44.8 $m^3{}_{ub}/PMH_{15}$. Additionally, in about 75% of the cases, a mini forestry crawler was used additionally to pre-winch the material to the cable roads, with an average productivity of 21.6 $m^3{}_{ub}/PMH_{15}$.

The resulting yarding productivity was quite high. From our perspective, the following drivers led to these results. First, a high share of timber with larger dimension (Ø DBH 50 cm) was extracted (law of piece-volume). Second, the operators were very experienced with horizontal yarding: Schweier et al. [26] reported that they extracted more than 3000 m^3 in horizontal yarding direction between 2013 and 2018. Third, heavy timber, for example, with thick branches, was partially de-limbed and processed motor-manually in the stand, thus the yarder could focus on the yarding process. Finally, it has been proven that pre-winching the material by mini forestry crawler has a significant positive impact on the yarding productivity [26]. The high piece-volumes also led to high productivity in the pre-winching and extracting processes.

Beside high productivity, our results showed that the application of cable-based systems in flat terrain must not necessarily be more cost intensive than its application in other terrain. Resulting costs included all process steps being required from felling until timber was ready to be sold at roadside and were on average €27.8/$m^3{}_{ub}$. At the edges and the southeastern part of the site, where felling was conducted by chainsaw and extracting by ground-based grapple skidder, average costs were

€35.6/m^3_{ub}. At the yarder part of the site, it was on average €26.7/m^3_{ub}. These results can be considered good. The high share of pre-winching by the crawler allowed the yarder to operate cost-efficiently. The fact that 13% of the total working time was required for installation processes shows, however, that good planning is necessary. It should be noted that transportation of machines and manpower to and from the site was not included. On the other hand, it is worth mentioning that we analyzed selective logging in a mixed forest [45], and 14 different assortments of varying qualities have been extracted (Table 3).

The question of whether, and to what extent, the applied cable-based system could be considered better than a ground-based system remains to be answered. In this respect, "better" was defined as fulfillment of the foresters' requirements (addressing vulnerability of soils, and therefore addressing environmental soundness, as well as assuring an independent planning). At the same time, the system should be as cost-efficient as possible and preferably less expensive than the ground-based system. This question was justified because it is commonly hypothesized that a cable-based system is more cost intensive compared to a ground-based system [43].

We modeled an alternative with a ground-based system by using HeProMo. The approach was to offer to the responsible forester and the state forest administration a realistic comparison of two alternative systems, both of which could have been applied in the forest stand. This means, in our case, that a fully mechanized system was no option. Much more, we were looking for a system based on manual felling and processing being adapted to work on sensitive soil (e.g., pre-winching). With respect to common practices in the study area, given stand conditions and machine availability, the system was modeled in the following setup (Figure 2): within the boom reach, trees were felled and de-limbed motor-manually (assisted by mini forestry crawler). Outside the boom reach, trees were felled, cut into double lengths, and pre-winched into the boom reach. A powerful eight-wheeled combi-forwarder equipped with bogie tracks was used for the extraction to the next road, where trees were further processed. The final extraction process was conducted by a six-wheeled combi-forwarder.

The resulting productivity of all working steps related to felling (de-limbing, sorting, and chalking) was on average 8.2 m^3_{ub}/PMH_{15}. Productivity was also 8.2 m^3_{ub}/PMH_{15} for pre-winching into the boom reach. The productivity of the extraction processes differed strongly depending on the applied mode of the combi-machine and was much higher when it was operating in forwarding mode. This could be explained mainly by the higher processed volume in this mode. Regardless, with respect to the assortments, the skidding mode was justified because, here, long logs of larger dimension and high value were extracted for which high revenues could be expected (especially for hardwoods).

The biggest limitation of the study was that the ground-based system was calculated theoretically and not applied and proofed in reality. We tried to consider this aspect, for example, by using standard cost rates in the calculation of both systems, aiming to keep results comparable. Furthermore, harvesting volumes and assortments were measured in the cable-based system, and the same volumes and assortments were assumed as products of the ground-based system. This might have been a constraint because it would have been possible to extract more or less volume or to choose another sorting when applying the ground-based system. Regardless, we are convinced that the study is of importance, particularly at a time when soil protection is increasingly essential. Foresters take decisions for or against a system and often need to justify if a more cost-intensive system is applied, even if its environmental credentials are high. The reason is quite simple: The efficiency of timber extraction varies with the extraction method used (e.g., [25]).

It has to be considered that, in general, travel speed might be slower on sites with wet and difficult terrain. In the case of Proto et al. [46], a forwarder was 57% slower on sites classified as difficult terrain compared to non-difficult terrain. In our case, the productivity in the first extraction process from the stand to the next road was much lower compared to the second extraction process to the landing. The main reason was that timber was piled before the second extraction process, but the terrain difficulty might have had an influence as well.

Regarding productivity, it needs to be considered that the ground-based system was modeled. However, our results can be considered realistic. Tiernan et al. [47] conducted a case study in Ireland on clear-felled sites classified as difficult terrain conditions and stated that the productivity for forwarding operations ranged from 15.9 to 27.5 m^3 per hour of productive system time. More recently, Cadei et al. [48] estimated the forwarder productivity in salvage logging in difficult terrain, based on studies conducted on three harvesting sites, and reported average productivity between 18.5 and 29.4 m^3/PMH_{15}. In our case, resulting costs included all process steps being required, from felling until timber was ready to be sold at the roadside, and were on average €28.3/$m^3{}_{ub}$ when applying the ground-based system. The increasing use of combi-forwarders can be explained mainly by the fact that it can operate as both skidder and forwarder, thus highly increasing the flexibility of the operator.

A limitation might be that the potential environmental impacts caused by the ground-based system on forest soils were not analyzed in the frame of this study. This was not possible because the ground-based system was not applied. Our main assumption was that the application of cable-based systems is always more favorable with regard to soil protection than ground-based systems [43]. Overall, the application of cable yarder in flat terrain was a good alternative in our case and should be favored when soils are sensitive or when the operation should be more independent from system-influencing factors.

5. Conclusions

Due to climate change, it can be expected that the wintertime bearing seasons will shorten. At the same time, the environmental soundness of forest operations is increasingly considered in decision processes. In the given case, the local forester aimed to respect the soil sensitivity, plan independently from system-influencing factors, and consider environmental aspects. These aims were reached by applying a cable-based system. Environmental aspects were not further analyzed, but one can assume that fewer damages to soils and remaining stands are caused by cable-based systems compared to ground-based systems. Results gave the evidence that the application of cable-based systems in flat terrain must not necessarily be more cost intensive than its application in other terrain.

Author Contributions: Conceptualization, C.L. and J.S.; methodology, C.L. and J.S.; validation, C.L. and J.S.; formal analysis, C.L. and J.S.; investigation, C.L. and J.S.; resources, C.L. and J.S.; writing—original draft preparation, J.S.; writing—review and editing, J.S.; supervision and project administration, J.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors thank the State Forest Administration of Baden-Württemberg (ForstBW) for permitting the data analysis and providing support. Further, we gratefully thank Wolfgang Zähringer who led the forest operation and supported the study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Gambi, M.; Certini, G.; Neri, F.; Marchi, E. The impact of heavy traffic on forest soils: A review. *For. Ecol. Manag.* **2015**, *338*, 124–138. [CrossRef]
2. Labelle, E.R.; Jaeger, D. Soil compaction caused by cut-to-length forest operations and possible short-term natural rehabilitation of soil density. *Soil Sci. Soc. Am. J.* **2011**, *75*, 2314–2329. [CrossRef]
3. Kleibl, M.; Klvač, R.; Lombardini, C.; Porhaly, J.; Spinelli, R. Soil compaction and recovery after mechanized final felling of Italian coastal pine plantations. *Croat. J. For. Eng.* **2014**, *35*, 63–71.
4. Jourgholami, M.; Khajavi, S.; Labelle, E.R. Recovery of Forest Soil Chemical Properties Following Soil Rehabilitation Treatments: An Assessment Six Years after Machine Impact. *Croat. J. For. Eng.* **2017**, *41*, 13. [CrossRef]
5. Mohieddinne, H.; Brasseur, B.; Spicher, F.; Gallet-Moron, E.; Buridant, J.; Kobaissi, A.; Horen, H. Physical recovery of forest soil after compaction by heavy machines, revealed by penetration resistance over multiple decades. *For. Ecol. Manag.* **2019**, *449*, 117472. [CrossRef]

6. MCPFE. MCPFE Expert Level Meeting. In Proceedings of the Improved Pan-European Indicators for Sustainable Forest Management as adopted by MCPFE Expert Level Meeting, Vienna, Austria, 7–8 October 2002.
7. Rametsteiner, E.; Mayer, P. Sustainable Forest Management and Pan: European Forest Policy. *Ecol. Bull.* **2004**, *51*, 51–57.
8. Blattert, C.; Lemm, R.; Thees, O.; Lexer, M.J.; Hanewinkel, M. Management of ecosystem services in mountain forests: Review of indicators and value functions for model based multi-criteria decision analysis. *Ecol. Indic.* **2017**, *79*, 391–409. [CrossRef]
9. Nocentini, S.; Buttoud, G.; Ciancio, O.; Corona, P. Managing forests in a changing world: The need for a systemic approach. A review. *For. Syst.* **2017**, *26*, 15. [CrossRef]
10. Marchi, E.; Chung, W.; Visser, R.; Abbas, D.; Nordfjell, T.; Mederski, P.S. Sustainable Forest Operations (SFO): A new paradigm in a changing world and climate. *Sci. Total Environ.* **2018**, *634*, 1385–1397. [CrossRef]
11. Bont, L.G.; Maurer, S.; Breschan, J.R. Automated cable road layout and harvesting planning for multiple objectives in steep terrain. *Forests* **2019**, *10*, 687. [CrossRef]
12. Harshaw, H.W.; Sheppard, S.R.J.; Lewis, J.L. A review and synthesis of social indicators for sustainable forest management. *BC J. Ecosyst. Manag.* **2007**, *8*, 17–36.
13. Kangas, J.; Kuusipalo, J. Integrating biodiversity into forest management planning and decision-making. *For. Ecol. Manag.* **1993**, *6*, 1–15. [CrossRef]
14. Schweier, J.; Magagnotti, N.; Labelle, E.R.; Athanassiadis, D. Sustainability Impact Assessment of Forest Operations: A Review. *Curr. For. Rep.* **2019**, *5*, 101–113. [CrossRef]
15. Kellomäki, S.; Maajärvi, M.; Strandman, H.; Kilpeläinen, A.; Peltola, H. Model Computations on the Climate Change Effects on Snow Cover, Soil Moisture and Soil Frost in the Boreal Conditions over Finland. *Silv. Fenn.* **2010**, *44*, 213–233. [CrossRef]
16. European Commission. *Regions 2020: The Climate Change Challenge for European Regions, Background Document to Commission Staff Working Document, Regions 2020: An Assessment of Future Challenges for EU Regions (SEC(2008) 2868 Final)*; Directorate-General for Regional Policy: Brussels, Belgium, 2009.
17. Lehtonen, I.; Venäläinen, A.; Kämäräinen, M.; Asikainen, A.; Laitila, J.; Anttila, P.; Peltola, H. Projected decrease in wintertime bearing capacity on different forest and soil types in Finland under a warming climate. *Hydrol. Earth Syst. Sci.* **2019**, *23*, 1611–1631. [CrossRef]
18. Berendt, F.; Fortin, M.; Jaeger, D.; Schweier, J. How Climate Change Will Affect Forest Composition and Forest Operations in Baden-Württemberg. A GIS-Based Case Study Approach. *Forests* **2017**, *8*, 298. [CrossRef]
19. Berleth, M.; Lelek, S.; Wolff, D. Wie sinnvoll sind weitere Gassenabstände? (How useful are larger distances between skid-trails?). *AFZ DerWald* **2016**, *71*, 56–59.
20. Erler, J. *Forsttechnik: Verfahrensbewertung*; Eugen Ulmer GmbH & Co.: Stuttgart, Germany, 2000.
21. Forst, B.W. *Konzept zur Sicherstellung der Dauerhaften Funktionsfähigkeit von Rückegassen für den Landesbetrieb ForstBW*; Version 1.0; Hg. v. Ministerium für Ländlichen Raum und Verbraucherschutz: Baden, Germany, 2012.
22. Bacher-Winterhalter, M. Optimierungsmöglichkeiten und Restriktionen eines mechani-sierten Holzerntesystems bei der Umsetzung moderner Waldbaukonzepte am Beispiel des Südschwarzwaldes (Optimization and restrictions of a mechanized harvesting system for modern silvicultural strategies in the southern black forest). Ph.D. Thesis, University of Freiburg, Freiburg, Germany, 2004.
23. Spinelli, R.; Magagnotti, N.; Nati, C. Benchmarking the impact of traditional small-scale logging systems used in Mediterranean forestry. *For. Ecol. Manag.* **2010**, *260*, 1997–2001. [CrossRef]
24. Stampfer, K.; Leitner, T.; Visser, R. Efficiency and ergonomic benefits of using radio controlled chokers in cable yarding. *Croat. J. For. Eng.* **2010**, *31*, 1–9.
25. Erber, G.; Haberl, A.; Pentek, T.; Stampfer, K. Impact of operational parameters on the productivity of whole tree cable yarding—A statistical analysis based on operation data. *Austrian J. For. Sci.* **2017**, *134*, 1–18.
26. Schweier, J.; Klein, M.-L.; Kirsten, H.; Jaeger, D.; Brieger, F.; Sauter, U.H. Productivity and cost analysis of tower yarder systems using the Koller 507 and the Valentini 400 in southwest Germany. *IJFE* **2020**, accepted. [CrossRef]
27. AM Online Projects Schwörstadt, Germany. Average Air Temperature and Precipitation in 2019. Available online: https://de.climate-data.org/search/?q=schw%C3%B6rstadt (accessed on 7 January 2019).

28. FVA Baden-Wü. rttemberg. Standortinformationen mit Datenbezugsquelle FGeo. In *Regionale Gliederung*; FVA: Freiburg, Germany, 2017.
29. Ministerium für Ernährung und Ländlichen Raum, Baden-Württemberg (Ed.) *Richtlinie der Landesforstverwaltung Baden-Württemberg zur Feinerschließung von Waldbeständen*; Ministerium für Ernährung und Ländlichen Raum: Stuttgart, Germany, 2003.
30. Mason, B.; Kerr, G.; Simpson, J. What is Continuous Cover Forestry? In *Forestry Commission Information, 29*; Forestry Commission: Edinburgh, UK, 1999.
31. Ressel, W. Digital maps for analysis. Data for FGeo. Personal communication, Stuttgart, Germany, 16 May 2020.
32. Swiss Federal Institute for Forest, Snow and Landscape Research. *Productivity Models for Wood Harvesting Operations HeProMo, Version 2.4*; Swiss Federal Institute for Forest, Snow and Landscape Research: Birmensdorf, Switzerland, 2020.
33. Stampfer, K.; Visser, R.; Kanzian, C. Cable corridor installation times for European yarders. *IJFE* **2006**, *17*, 77. [CrossRef]
34. Lindroos, O.; Cavalli, R. Cable yarding productivity models: A systematic review over the period 2000–2011. *IJFE* **2016**, *27*, 79–94. [CrossRef]
35. Marchi, L.; Grigolato, S.; Mologni, O.; Scotta, R.; Cavalli, R.; Montecchio, L. State of the Art on the use of trees as supports and anchors in forest operations. *Forests* **2018**, *9*, 467. [CrossRef]
36. Kühmaier, M.; Harrill, H.; Ghaffariyan, M.R.; Hofer, M.; Stampfer, K.; Brown, M.; Visser, R. Using Conjoint Analyses to Improve Cable Yarder Design Characteristics: An Austrian Yarder Case Study to Advance Cost-Effective Extraction. *Forests* **2019**, *10*, 165. [CrossRef]
37. Ghaffariyan, M.R.; Stampfer, K.; Sessions, J. Optimal road spacing of cable yarding using a tower yarder in Southern Austria. *Eur. J. Forest Res.* **2010**, *129*, 409–416. [CrossRef]
38. Spinelli, R.; Magagnotti, N.; Visser, R. Productivity models for cable yarding in Alpine forests. *Eur. J. Forest Eng.* **2015**, *1*, 9–14.
39. Hoffmann, S.; Jaeger, D.; Schoenherr, S.; Lingenfelder, M.; Sun, D.; Zeng, J. The effect of forest management systems on productivity and costs of cable yarding operations in southern China. *For. Lett.* **2016**, *109*, 11–24.
40. Ottaviani Aalmo, G.; Talbot, B. Operator performance improvement through training in a controlled cable yarding study. *IJFE* **2014**, *25*, 5–13. [CrossRef]
41. KWF. Exkursionspunkt 1.12. Motormanuelle Fällung; Bringung und Aufarbeitung mit Gebirgsharvester Syncrofalke 4,0 t/Laufwagen Sherpa U 4t. In: Schmidt-Langenhorst T, Umweltgerechte Bewirtschaftung nasser Standorte. *AFZ-DerWald* **2013**, *18*, 48–49.
42. Brown, C.G. *The Deerhorn Case Study: A Production and Cost Analysis of a Single-Grip Harvester and Small Cable Yarder Performing a Thinning/Salvage Operation in Eastern Oregon*; Oregon State University: Corvallis, OR, USA, 1995.
43. Erber, G.; Spinelli, R. Timber extraction by cable yarding on flat and wet terrain: A survey of cable yarder manufacturer's experience. *Silva Fenn.* **2020**, *54*. [CrossRef]
44. Klein, M.-L.; Schweier, J.; Kirsten, H.; Jaeger, D.; Brieger, F.; Sauter, U.H. Produktivitäts- und Kostenanalyse der Seilkrananlage Koller 507 in verschiedenen Hiebsmaßnahmen. *AFZ DerWald* **2020**. upcoming.
45. Lewandowski, I.; Lippe, M.; Castro Montoya, J.; Dickhöfer, U.; Langenberger, G.; Pucher, J.; Schließmann, U.; Schmid-Staiger, U.; Derwenskus, F.; Lippert, C. *Primary Production*; Lewandowski, I., Ed.; Springer: Cham, Switzerland, 2018. [CrossRef]
46. Proto, A.R.; Macrì, G.; Visser, R.; Harrill, H.; Russo, D.; Zimbalatti, G. Factors a_ecting forwarder productivity. *Eur. J. For. Res.* **2018**, *137*, 143–151. [CrossRef]
47. Tiernan, D.; Zeleke, G.; Owende, P.M.O.; Kanali, C.L.; Lyons, J.; Ward, S.M. Effect of Working Conditions on Forwarder Productivity in Cut-to-length Timber Harvesting on Sensitive Forest Sites in Ireland. *Biosyst. Eng.* **2004**, *87*, 167–177. [CrossRef]
48. Cadei, A.; Mologni, O.; Röser, D.; Cavalli, R.; Grigolato, S. Forwarder productivity in salvage logging operations in difficult terrain. *Forests* **2020**, *11*, 341. [CrossRef]