

## Article

# Evaluation of Salvage Logging Productivity and Costs in the Sensitive Forests of Bulgaria

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**Abstract:** Steep terrain harvesting can only be implemented by a limited set of operational alternatives; therefore, it is important to be efficient in such conditions, in order to avoid incurring high costs. Harvesting abiotically-disturbed forests (salvage harvests caused by wet snow), which is becoming common these days, can significantly impact the operational efficiency of extraction operations. This study was implemented in order to evaluate the performance of truck-mounted uphill cable yarding operations in salvage logging deployed in coniferous stands. A time study was used to estimate the productivity and yarding costs, and predictive models were developed in order to relate the time consumption and productivity to the relevant operational factors, including the degree of wood damage. The average operational conditions were characterized by an extraction distance of 101 m and a lateral yarding distance of 18 m, resulting in a productivity rate of 20.1 m<sup>3</sup> h<sup>-1</sup>. In response to different kind of delays, the productivity rate decreased to 12.8 m<sup>3</sup> h<sup>-1</sup>. Under the prevailing conditions, lateral yarding accounted for 32% of the gross work cycle time, and for 50% of the delay-free work cycle time of the machine. Decreasing the lateral yarding distance and increasing the payload volume to the maximum capacity of the machine would eventually lead to a yarding productivity of close to 30 m<sup>3</sup> per SMH (scheduled machine hour). The calculation of the gross costs of uphill yarding showed that the labor costs (35.7%) were slightly higher than the fixed costs (32.9%), and twice as high compared to the variable costs (17.7%). The remote control of the carriage, mechanical slack-pulling mechanisms, and radio-controlled chokers are just some of the improvements that would have led to increments in operational efficiency.

**Keywords:** steep terrain; windbreak; windthrow; Natura 2000; cable yarder; performance



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## 1. Introduction

Abiotic and biotic factors are causing important damage in European forests, and windstorms are the dominant factor causing them [1]. Such forest disturbances are becoming common due to the current trends in the climate, and their severity has increased in many forest ecosystems, including those in the Northern Hemisphere [2]. For instance, wet snow and ice cause damage to forests by bending or breaking the tree branches and tops. This happens when the weight of frozen precipitation exceeds the buckling load of the tree part bearing the load. In such circumstances, bending can occur, and it can result in permanent internal wood damage without any external exhibition of such damage. When they are left in forests, broken and uprooted trees favor insect outbreaks. A common way to minimize these effects by forest management is salvage logging [2], an activity that gained considerable interest and importance in those cases when disturbances occur in sensitive

forest areas, and which is needed in recovering the economic value of timber in damaged forests, even in those locations which otherwise are spared from regular logging [3,4].

Salvage logging can be described as the harvesting of dead, damaged, or infested trees, aiming to recover the maximum value prior to the wood's deterioration [5]. Such operations require supplementary concerns to plan and adapt the harvesting system and safety to the site-specific characteristics and degree of damage [6–8]. When salvage logging is in question, the most suitable harvesting solutions are those guaranteeing the safety of the operators while yielding acceptable productivities and costs [3,8]. The problem is more challenging when these disturbances occur in sensitive areas, because the interventions must be consistent with the natural disturbance regime [9,10], which is known to contribute to biodiversity [11], while salvage logging may alter it [12] by causing changes in the structure, soil, microclimatic, and vegetation conditions in the harvested areas [13]. Still, salvage logging is a management option which is used in many European national parks [14,15].

Among the existing protected areas, the Natura 2000 network was established with the purpose of preserving Europe's most valuable and threatened species and habitats [16]. Currently, it protects approximately 18% of the European Union's land [17]; in these areas, it is of fundamental importance to regulate human-caused disturbance so as not to alter the natural conditions and to preserve the habitats, including by the correct implementation of the salvage logging operations. In fact, in several sensitive areas, such operations are not implemented, or are limited due to ecological reasons [18,19]. In addition, the economic factors may prohibit such operations, making them unfeasible due to low timber prices, causing situations in which the damaged timber is often left in the forests [20,21]. These reasons have led, in some regions, to a decrease in the implementation of salvage logging operations [22].

As an option, ground-based harvesting systems require a dense extraction infrastructure which may generate increased costs when they are developed in steep terrain. For slopes of 40% or higher, cable extraction is expected to cause less environmental impact compared to ground-based systems [23,24]. In addition, it is a desirable alternative to ground-based equipment when dealing with sensitive sites [25]. As such, cable yarding causes the least damage to soil [8], and minimizes the impact in environmentally sensitive areas. Hence, it could support biodiversity goals, and could be integrated into ecosystem management plans [26,27], based also on its competitiveness in terms of CO<sub>2</sub> emissions [28] and on its potential of using gravity [29] compared to other partly- or fully-mechanized ground-based harvesting systems. In fact, the natural level of biodiversity can be preserved by avoiding soil disturbance, which is enabled by the use of the suspended transportation of wood, enabling cable logging operations to preserve the succession of species that depend on undisturbed soil [2,30,31]. In the past, cable yarders were considered to be more complex and expensive than ground-based harvesting, mainly due to their purchasing costs and challenging setup operations, making cable-yarding operations more costly. Fortunately, most of the modern yarders are referred to as mobile equipment integrating a steel tower [8], making them less resource-intensive in setup and dismantling operations [32,33]. On steep terrain, they were found to be a more efficient alternative to building an extensive [34,35], costly [23], and environmentally-damaging [36,37] network of skidding roads. During the last few decades, different yarder models have been used in those conditions in which the terrain prohibits the use of other timber extraction equipment [38,39].

The current knowledge on the performance of salvage logging is mainly based on studies which have been carried out in order to evaluate it for harvesters, forwarders, and skidders. Dvůrák et al. [40] found that the time consumption of harvesting broken stems increased by 33% in Norway spruce forests affected by windthrow compared to regular operational conditions. Brzózko et al. [41] suggested that the productivity of operations in wind-damaged forests is 40–60% lower compared to normal conditions. Bodaghi et al. [42] evaluated the productivity of skidding operations deployed in wind-damage forests for skidders and farm tractors. Borz et al. [43] developed a survey on

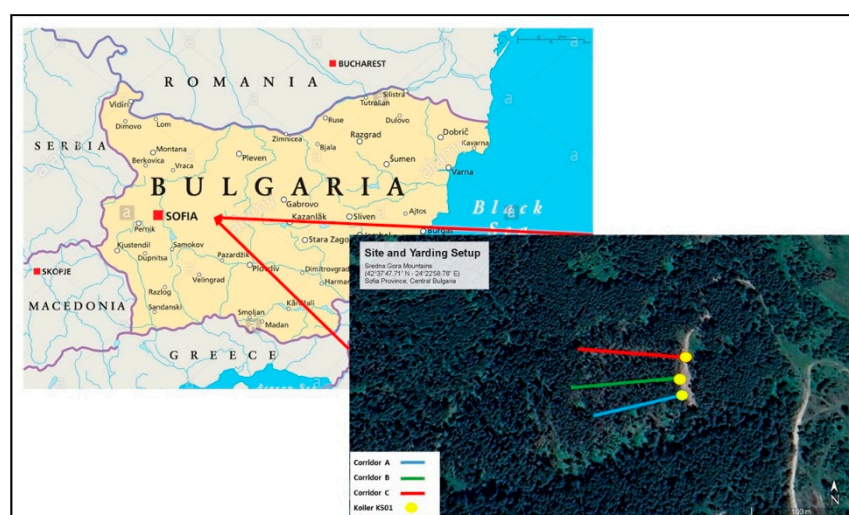
the skidding performance in difficult conditions characterized by low access and wind-damaged forests. Cadei et al. [7] evaluated the forwarding productivity in salvage logging deployed in the difficult terrain of the Italian Alps, in a forest area affected by windthrow caused by the Vaia storm. Kärhä et al. [3] carried out a comparative study and analyzed the productivity of a harvester–forwarder system in salvage operations deployed in Finnish windfallen forests. Cákša [44] evaluated the influence of sawlog volume production on the recovered timber assortments, in order to provide the information necessary to support salvage logging decisions. However, no studies have been identified to address the problem of cable yarding salvage logging operations. For this reason, this paper aimed at filling the knowledge gap related to cable yarding productivity in salvage operations. Based on the above, the objectives of this research were: (i) to evaluate the influence of selected operational factors on time consumption by a statistical modeling approach, and (ii) to improve our understanding on the operational efficiency of mobile cable-yarders in the salvage logging of coniferous stands. The efficiency improvement concerned the analysis of the time consumption, productivity, and costs, as these performance metrics are useful to integrate cable yarding operations in order to achieve the economic and environmental efficiency of timber harvesting in forests disturbed by abiotic factors.

## 2. Materials and Methods

Most Bulgarian forests (approximately 60%) are located in mountainous areas, on steep slopes and complex terrain configurations, while 23.6% of the national territory is protected within the framework of the Natura 2000 network. Bulgaria is not affected by Atlantic storms, but snow-breaks, wind-blows, and forest fires occur frequently; the statistical data indicates that traces of natural catastrophes/disturbances may be found on about 3% of the Bulgarian forest land [39].

### 2.1. Description of the Site and Yarding Setup

The study was carried out in the Sredna Gora Mountains ( $42^{\circ}37'47.71''$  N– $24^{\circ}22'58.76''$  E), near the city of Koprivshitsa, Sofia Province, Central Bulgaria (Figure 1). A description of the forest site and the operational characteristics is given in Table 1.



**Figure 1.** Site map of the study and the schematic layout of the corridors during the cable-yarding operations.

The forest chosen for the study is a part of the Natura 2000 network, designated by the function codes BG 0002054 and BG 0001389, listed under the Birds and the Habitats Directives, respectively. The type of habitat, by its code, is 91CA Rila-Rhodope and Balkan Mts. Scots pine forests. Such forests are dominated by *Pinus sylvestris* L., on mountain slopes with sun exposure, mainly on silicate and (more limitedly) on calcareous terrains.

They have a diverse structure and rich species composition. The participation of other tree species, in different proportions, is a sign of the dynamic status of a large part of the pine forests. This is why cable yarding was used as a more environmentally-friendly extraction solution while the studied forest was affected by wet snow and subsequent windbreaks and windthrow. Broken and uprooted trees are commonly described to generate additional difficulties for felling and extraction, mainly due to the fact that they are subjected to intense and complex tensions within the wood [8]. This makes both the tasks of identifying and taking safe positions by the workers, as well as for the cuts to be performed, more challenging because of the potential hazards.

**Table 1.** Characteristics of the test site.

Site	Kriva reka, subcompartment 9019-a1
Elevation	1200 m asl
Protection function/designation	Natura 2000: BG 0001389, BG 0002054, habitat 91CA
Species composition	Scots pine ( <i>Pinus sylvestris</i> L.)
Stand age (years)	40
Stand type by age	Even-aged
Stand density (trees ha <sup>-1</sup> )	1784
Logging operation	Salvage cutting after wet snow, windbreaks and windthrow damage
Average tree height (m)	15
Average DBH of tree (cm)	24
Site volume (m <sup>3</sup> over bark)	540
Removal volume (m <sup>3</sup> over bark)	175
Altitudinal difference between the corridor endpoints (m)	45
Average sag (m)	12
Average lateral yarding distance (m)	17.8

Three yarding corridors (A, B, and C) were designated on terrain slopes of 18° (32%) on corridor A, 16° (29%) on corridor B, and 14° (25%) on corridor C; each corridor had a length of approximately 200 m. Most of the damaged trees were located on the site specific to corridor A. The field observations were designed to cover the minimum required number of 30 complete yarding work cycles (turns) on each corridor [45]. The extraction was performed in the uphill direction, and the trees were manually felled. A single-span layout was rigged on each corridor, and the proportion of undamaged standing trees was 50%. A total number of 892 trees were removed from the stand, out of which 64 were removed from the cable yarding corridors. The removed trees were distributed as follows: 437 trees (about 49%) on the site of corridor A, 277 trees (31%) on the site of corridor B, and the remaining of 178 trees (20%) on the site of corridor C. The classification of the damaged trees was performed according to the system described by Kärhä [3]; accordingly, the types of damage corresponded to code 1A—uprooted whole tree with stump, code 1B—hang-up whole tree, code 1C—uprooted and broken tree with separate butt and top sections, and code 1D—broken tree section. The damaged trees coded by 1A were dominant in the site corresponding to corridor A, while in the sites of corridors B and C, the dominant damage type was 1D.

## 2.2. Description of the Cable Yarder Unit and Work Team

The study was performed on a Koller K501 truck-mounted tower yarder (Table 2–Figure 2). The work team consisted of the yarder operator, a second worker who unhooked, delimbed, and bucked the trees, and a choker-setter at the yarding site. The workers were 35 to 45 years old, and all of them had an extensive experience of cable yarding operations. They were informed in advance on the study objectives and the intended use of the data, and they agreed to be observed. The observed yarder was designed for uphill extraction. It was a powerful machine, and it was mainly used in selective cuts and for other common

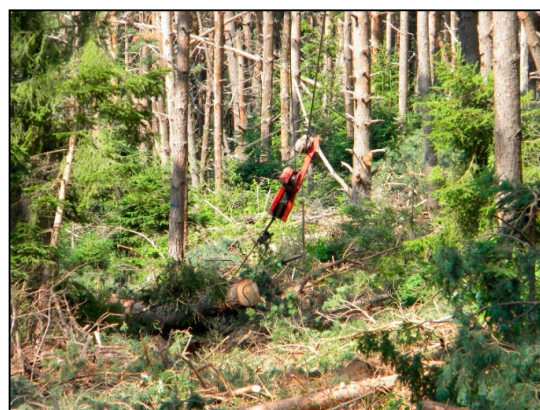
wood harvesting operations. During the observed operations, it was equipped with a SKA 2.5 (KOLLER Forsttechnik GmbH, Schwoich, Austria) carriage that supports payloads of up to 2.5 t. The mass (9800 kg) was distributed on the rear axle of a Mercedes-Benz truck equipped with special reinforced frames. The logs were yarded laterally to the carriage using the power of the mainline winch and active skyline clamps.

**Table 2.** Technical characteristics of the cable crane.

Parameter	Value
Skyline capacity 600 m, $\varnothing$ 24 mm	120 kN (tension section)
Mainline 600 m, $\varnothing$ 14 mm	43 kN (average drum)
Guylines	$4 \times 75 \text{ m}^2$ , $\varnothing$ 16 mm/ $2 \times 15 \text{ m}^2$ (extension)
Foldable telescopic tower, height	13.5 m
Power station	Autonomous engine and hydrostatic transmission
Engine power	250 kW (340 HP)
Skyline	Manually actuated band brake
Mainline	Hydraulically actuated band brake
Operation	Hydro-mechanical/electro-hydraulic single lever operation with dead-man's control
Carriage	Koller SKA-2.5, manual slack-pulling carriage
Choker system	Bardon choker
Lifting moment	270 kNm
Carrier	$6 \times 4$ Mercedes-Benz truck



(a)



(b)

**Figure 2.** Koller K501 yarder during the operations: (a) view from the landing site; (b) view from the lateral yarding.

### 2.3. Time Study

An elemental time study was carried out in order to estimate the time consumption and productivity of the cable yarder in the observed conditions. The elemental composition of a work cycle was assumed to be that described in the related scientific literature [35,46,47], and the operational variables were accounted for in order to check their effect on the variation of the work cycle time. Each yarding work cycle was individually timed by a stopwatch (Hanhart<sup>®</sup> Stratos 2) to account for the scheduled machine hours (SMH). Following the field observations, the productive time was separated from the delay time, and the time shares and harvesting productivity were estimated based on a productive machine hours (PMH) approach. The yarding distance and the terrain slope were measured by a professional laser range-finder (Bushnell<sup>®</sup> V5). The payload volume was estimated by measuring the length and the mid-length diameter of all of the logs from each load. Six

work elements were separated and taken into account in order to estimate the work cycle time [48]; they were similar to those described by Proto et al. [24,35,49]:

1. Carriage outhaul (CO) begins when the operator is ready to move the empty carriage from the landing out to the stump, and ends when the choker-setter touches the chokers.
2. Lateral outhaul (LO) begins at the end of carriage outhaul, and ends when the choker-setter has completed the hooking of the chokers and signals to begin yarding.
3. Lateral inhaul (LI) and hook begins at the end of the hook up, and ends when the turn is pulled up to the carriage and the carriage begins to move up the corridor.
4. Carriage inhaul (CI) begins at the end of the lateral inhaul, and ends when the load has reached the deck where it can be directly unhooked at the landing.
5. Unhook (U) begins at the end of the carriage inhaul, and ends when the chokers have returned to the carriage.
6. Delay time (D) includes the rest, personal delays, organizational delays, service, and repair.

#### 2.4. Economic Evaluation

The objective of developing hourly costs for the yarder and operators (machine rate) should be to achieve a value that is the most accurate, standing for a good representation of the work performed under the existing operating conditions and the accounting system in use. The machine rate includes cost categories such as the fixed, operating (variable), and labor costs. The machine costs were estimated using the COST model proposed by Ackerman et al. [50]. The hourly costs were reported by considering the productive machine hours (excluding delays) as well as the scheduled machine hours. The investment in machine purchasing and salaries required by the cost calculations were obtained from catalogues and accounting records. The wages were set at 37.87 € SMH<sup>-1</sup>, and they included all indirect salary costs. The fuel consumption was measured by the commonly used method of refilling to full. The machine's salvage value was set at 10%, and the Value Added Tax (VAT) was excluded from the calculations. The economic evaluation was based on the assumption that the company worked for 200 days in the year, and the depreciation period was set at 10 years.

#### 2.5. Data Analysis

The prediction of the work cycle time and productivity were performed by statistical modeling, which involved the use of regression analysis. The variables used as predictors were the yarding distance ( $L$ , m), lateral yarding distance ( $l$ , m), payload per cycle ( $Q$ , m<sup>3</sup>), terrain slope angle ( $i$ , °), and the number of trees per payload ( $n$ ). In addition, the tree damage type ( $dt$ ) was used as an indicator (dummy) variable to enhance the discrimination of the time prediction models. The models describing the time consumption and productivity were defined in Equations (1) and (2):

$$T_{net} = f(L, l, Q, i, dt) \quad (1)$$

$$P_{PMH} = \frac{3600 Q}{T_{net}} \quad (2)$$

where  $T_{net}$  = the productive time separated from the delay time, and  $P_{PMH}$  = the harvesting productivity based on a productive machine hours approach.

The preliminary statistical steps consisted of the exclusion of outliers, and a correlation analysis which was run for the predictors in order to check their appropriateness in the models. The correlation analysis was based on a threshold set at 0.75 for the correlation coefficient to exclude predictors based on a pair-by-pair comparison. The reason for this approach was the avoidance of an artificial inflation of the determination coefficients in the developed models, which is an approach which has been used in similar studies. Then, the main descriptive statistics were estimated, and least-square multiple linear regression was used by a stepwise backward approach to develop predictive models of the time

consumption and productivity as a function of the predictors kept in the analysis. The predictive models were developed using a confidence threshold set at 95% ( $\alpha = 0.05$ ) by assuming a probability of  $p < 0.05$ . Under these assumptions, the predictors are significant for a given model when  $p < 0.05$ , i.e., there is a strong presumption against the neutral hypothesis. The software used to process and analyze the data was Statistica 8 (StatSoft Inc., Tulsa, OK, USA).

### 3. Results

The field observations covered, in total, 14 h, and within this time, the cable crane completed 30 cycles for each corridor. Under the studied conditions, the largest share (33%) of the delay-free work cycle time was spent during the lateral outhaul and hooking, with some differences that were characteristic to each corridor (A, 28%; B, 36%; C, 24%), followed by the lateral inhaul (17% in general, and 14, 18, and 15% for corridors A, B and C, respectively). These shares were related to the work deployed on moderately steep terrain, as well as to the specific distribution of crossed, thrown, and broken trees. The work elements of the carriage outhaul, unhooking, and carriage inhaul accounted for shares of 19%, 18%, and 13%, respectively. Regarding the total scheduled time, delays accounted for the most time: 46% for site A, 31% for site B, and 47% for site C. For comparison, Huyler and Ledoux [48] found a time share of approximately 35% for delays caused by operational, mechanical, and non-productive time on steep slopes of approximately 40–50% in the US Northeast. In this study, the delay time recorded at each site was related mainly to the operation of the yarder. In fact, the processing of the yarded trees into logs was a work task performed by the worker who unhooked, delimbed, and bucked the trees, whereas the yarder operator piled the logs by hydraulic crane on landing, during which the yarding work was interrupted. The lateral outhaul and hook accounted for about 15% (site A), 25% (site B), and 13% (site C), respectively. According to Dimitrov [51], in order to increase the productivity of tower yarders operated in Southwest Bulgaria, the time consumption for lateral outhaul (28%), inhaul (21%), and unhook (13%), as well as the ineffective time covering the spare and delays of workers (16%) should be minimized.

The remaining work elements had an approximately equal share in the time consumption. The carriage outhaul accounted for 12% (11, 12, and 13% in corridors A, B and C, respectively), unhook accounted for 12% (11, 11, and 12%), and lateral inhaul accounted for 11% (8, 13, and 8%); the carriage inhaul accounted the smallest time share, which was 8% (9, 8 and 8%). The work tasks related to the lateral yarding (the lateral pull of the main line, the chocking, and the extraction of the load to carriage) accounted for 32% of the gross study time (21, 38, and 21% for corridors A, B, and C, respectively), and for 50% (general), 42% (A), 54% (B), and 39% (C) of the delay-free work cycle time. Due to the short yarding distance, moderate terrain slope, and small loads per turn (2.2 trees and 1.1 m<sup>3</sup>, on average), where the latter did not load the carriage at its full capacity, the lateral yarding distance had a high impact on the work cycle time. Also, it is worthwhile to note that the running time of the empty carriage was longer compared to the loaded running, a fact that was controlled by the operator of the yarder, and which depended on the operator's availability for certain tasks. The yarding productivity for an average yarding distance of 100.7 m and for an average lateral yarding distance of 17.8 m, excluding and including the delays, was estimated at 20.1 and 12.8 m<sup>3</sup> h<sup>-1</sup>, respectively. The increase of the lateral and corridor extraction distances resulted in significant variations of the work cycle time. The results indicate a good efficiency of the extraction system, but there are many organisational issues which could be addressed in order to fully utilize the potential of the tested cable yarding system [49]. If the remote control of the carriage had been available, it could have been controlled by the choker-setter. Another option to reduce the choker-setter's fatigue and to decrease the time for the lateral outhaul and hook would have been to use a carriage equipped with a mechanical slack-pulling device. Tables 3 and 4 and Figure 3 show the main descriptive statistics related to the time consumption and yarding distances, which are given at the site and corridor level.

Table 3. Descriptive statistics of the time consumption and operational distances.

Yarding Time Consumption Variables	Cycle Time, s			Distance, m		
	Mean Value $\pm$ St. Dev.	Min	Max	Mean Value $\pm$ St. Dev.	Min	Max
<b>Carriage Outhaul</b>	<b>39.5 <math>\pm</math> 10.0</b>	<b>22</b>	<b>70</b>	<b>100.7 <math>\pm</math> 31.8</b>	<b>60</b>	<b>130</b>
Corridor A	39.5 $\pm$ 10.2	22	70	96 $\pm$ 31.2	60	130
Corridor B	39.5 $\pm$ 10.3	22	70	96 $\pm$ 31.2	60	130
Corridor C	39.6 $\pm$ 9.6	22	60	108.4 $\pm$ 28.7	60	130
<b>Lateral outhaul and hook</b>	<b>69.2 <math>\pm</math> 51.8</b>	<b>20</b>	<b>200</b>	<b>17.8 <math>\pm</math> 11.3</b>	<b>9</b>	<b>42</b>
Corridor A	83.0 $\pm$ 58.6	20	200	20.8 $\pm$ 12.8	9	42
Corridor B	36.5 $\pm$ 25.3	20	180	14.7 $\pm$ 4.1	7	22
Corridor C	44.0 $\pm$ 25.3	20	120	12.1 $\pm$ 2.5	9	19
<b>Lateral inhaul</b>	<b>36.0 <math>\pm</math> 25.3</b>	<b>15</b>	<b>100</b>	<b>17.8 <math>\pm</math> 11.3</b>	<b>9</b>	<b>42</b>
Corridor A	41.5 $\pm$ 28.7	15	100	20.8 $\pm$ 12.8	9	42
Corridor B	41.3 $\pm$ 28.7	15	100	14.7 $\pm$ 4.1	7	22
Corridor C	27.7 $\pm$ 17.6	15	100	12.1 $\pm$ 2.5	9	19
<b>Carriage Inhaul</b>	<b>28.3 <math>\pm</math> 7.2</b>	<b>15</b>	<b>45</b>	<b>100.7 <math>\pm</math> 31.8</b>	<b>60</b>	<b>130</b>
Corridor A	33.5 $\pm$ 7.2	15	45	96 $\pm$ 31.2	60	130
Corridor B	26.6 $\pm$ 4.7	20	35	96 $\pm$ 31.2	60	130
Corridor C	24.8 $\pm$ 6.0	20	35	108.4 $\pm$ 28.7	60	130
<b>Unhook</b>	<b>38.3 <math>\pm</math> 11.1</b>	<b>10</b>	<b>60</b>			
Corridor A	38.2 $\pm$ 11.1	10	60			
Corridor B	38.1 $\pm$ 11.3	10	60			
Corridor C	38.9 $\pm$ 11.1	10	60			
<b>Delay</b>	<b>120.0 <math>\pm</math> 131.1</b>	<b>0</b>	<b>550</b>			
Corridor A	109.7 $\pm$ 131.1	0	525			
Corridor B	102.9 $\pm$ 127.8	0	525			
Corridor C	142.7 $\pm$ 136.8	0	550			
<b>Total cycle time</b>	<b>331.3 <math>\pm</math> 120.9</b>	<b>151</b>	<b>715</b>			
Corridor A	345.4 $\pm$ 127.8	154	690			
Corridor B	331.6 $\pm$ 114.1	151	695			
Corridor C	317.4 $\pm$ 135.3	154	715			
<b>Delay-free cycle time</b>	<b>211.3 <math>\pm</math> 77.5</b>	<b>135</b>	<b>430</b>			
Corridor A	235.7 $\pm$ 88.7	145	430			
Corridor B	228.7 $\pm$ 85.4	140	421			
Corridor C	317.4 $\pm$ 135.4	140	330			

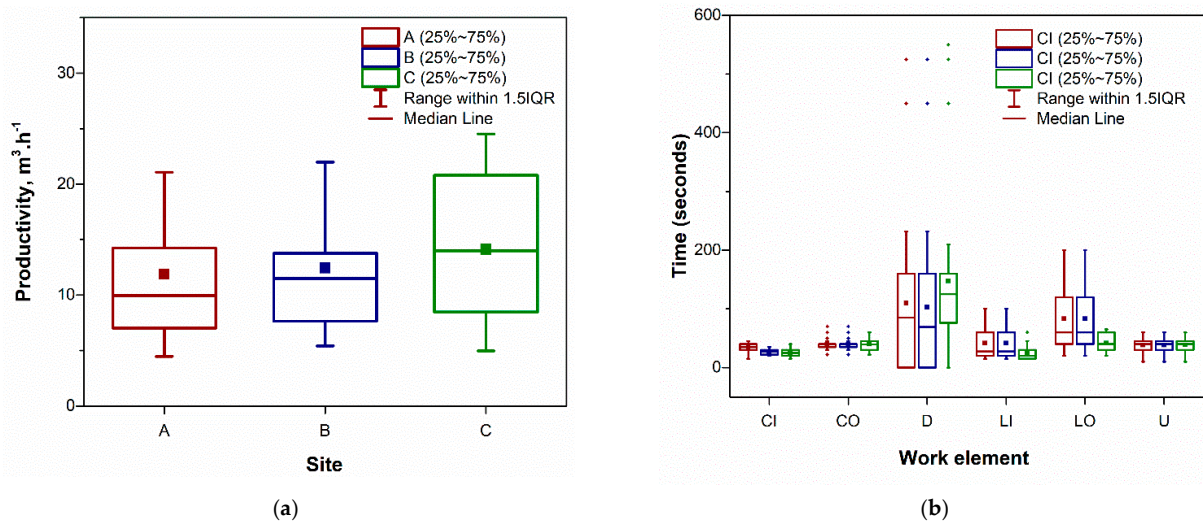
The regression analysis used the time study data with the aim to develop prediction equations to estimate the yarding work cycle time. The significant variables, which were retained in the models, were the lateral yarding distance ( $l$ , m) and slope ( $i$ ,  $^\circ$ ). The general regression equation for the delay-free cycle time  $T_{net}$  (s, seconds), which was developed in order to reflect the performance at the site level, along with its significant variables, are shown in Table 5. According to Equation (1), the minimum values of the delay-free cycle time ( $T_{net}$ , productive machine hours; PMH) may be reached when the lateral yarding distance ( $l$ , m) and the terrain slope ( $s$ ,  $^\circ$ ) are small, in conjunction with damage type 1A ( $dt = 1$ ). For such a case, it was easier to laterally yard the trees, because of the presence of



fewer obstacles. The damage type  $dt = 2$  (code 1D, broken tree section prevailed) involves lateral outhaul among the broken tree sections, which may stand as serious obstacles. Besides the general model, which enables a differentiation between the condition of the yarded trees, the equations in Table 6 show the cases specific to the three corridors, in which the lateral yarding distance  $l$  (m) was found to be the only significant variable affecting the variation of the delay-free work cycle time. As shown by the regression coefficients, the effect of the lateral yarding distance on the delay-free work cycle time was the strongest in the case of corridor B compared to the specifics of corridors A and C; this was due to the aforementioned operational conditions. As was provided for the same lateral yarding distance, the time needed to yard the trees would be significantly less in corridors A and C compared to corridor B.

**Table 4.** Payload and productivity metrics.

	Mean Value $\pm$ St. Dev.	Min	Max
<b>Payload per cycle (site), m<sup>3</sup></b>	<b>1.1 <math>\pm</math> 0.38</b>	<b>0.4</b>	<b>1.8</b>
Corridor A	1.04 $\pm$ 0.38	0.5	1.8
Corridor B	1.05 $\pm$ 0.38	0.5	1.8
Corridor C	1.10 $\pm$ 0.30	0.4	1.6
<b>Productivity (site), m<sup>3</sup> SMH<sup>-1</sup></b>	<b>12.8 <math>\pm</math> 6.40</b>	<b>4.47</b>	<b>29.45</b>
Corridor A	11.86 $\pm$ 6.11	4.47	29.45
Corridor B	12.45 $\pm$ 6.60	5.42	29.45
Corridor C	14.04 $\pm$ 6.40	4.97	24.51
<b>Productivity (site), m<sup>3</sup> PMH<sup>-1</sup></b>	<b>20.1 <math>\pm</math> 9.9</b>	<b>5.42</b>	<b>43.2</b>
Corridor A	17.8 $\pm$ 9.4	6.35	43.20
Corridor B	18.49 $\pm$ 9.9	5.42	43.20
Corridor C	23.73 $\pm$ 9.5	7.83	41.10
<b>Number of work cycles per SMH (site)</b>	<b>10.86</b>	<b>5.03</b>	<b>23.84</b>
Corridor A	10.42	5.22	23.38
Corridor B	10.84	7.18	23.84
Corridor C	11.34	5.03	23.38



**Figure 3.** Summary statistics of the yarding productivity for the three corridors (a) and of the elemental time consumption (b). Legend: A, B, and C stand for corridors A, B and C; CI, CO, D, LI, LO and U work elements are defined in Section 2.3.

**Table 5.** Summary of the work cycle time models at the site and corridor level.

Equations	F	R <sup>2</sup> <sub>adjusted</sub>	Std. Error	p-Value
$T_{net} = -0.575 L + 5.193 l + 17.017 i + 23.972 dt$	18.30	0.54	52.63	$p < 0.05$
$T_{net\_A} = 6.9005 l$	50.17	0.87	34.46	$p < 0.05$
$T_{net\_B} = 15.2073 l$	15.92	0.67	48.82	$p < 0.05$
$T_{net\_C} = 2.6206 l$	2.85	0.20	32.93	$p < 0.05$

**Table 6.** Summary of the productivity models developed for the site and corridor conditions.

Equations	F	R <sup>2</sup> <sub>adjusted</sub>	Std. Error
$P_{PMH} = 34.61 - 0.34 l + 17.46 Q - 1.58 i, (m^3 h^{-1})$	42.14	0.73	5.09
$P_{PMH\_A} = 14.20 + 0.08 l + 3.48 Q, (m^3 h^{-1})$	37.83	0.84	3.81
$P_{PMH\_B} = -0.71 l + 12.42 Q, (m^3 h^{-1})$	12.69	0.62	4.08
$P_{PMH\_C} = 18.83 - 1.13 l + 9.02 Q, (m^3 h^{-1})$	10.78	0.57	4.20
$P_{SMH} = 12.87 Q, (m^3 h^{-1})$	15.69	0.50	4.53
$P_{SMH\_A} = 13.827 Q, (m^3 h^{-1})$	9.60	0.54	4.13
$P_{SMH\_B} = -0.717 l + 12.428 Q, (m^3 h^{-1})$	12.69	0.62	4.08
$P_{SMH\_C} = 18.832 - 1.138 l + 9.027 Q, (m^3 h^{-1})$	10.78	0.57	4.20

The regression equations developed to describe the work cycle time including the delays (SMH) at the site and corridor (A, B, C) levels revealed no additional significant predictors, a fact that may be the effect of including the delays which are known to follow different statistical laws [52] and, therefore, to mask other important effects [53].

The variation of yarding productivity at the site level, which was estimated based on the delay-free time consumption, is given by the general regression equation reported in Table 6. Therefore, the factors that could contribute to the increment of the yarding productivity are the terrain slope and the lateral yarding distance  $l$ , by their minimization. In addition, the payload volume per work cycle ( $Q$ ) should be increased in order to enable higher productivities. The control over these factors is difficult to attain by engineering, as they are frequently a reflection of the given operational conditions. In regard to the productivity being estimated based on the total time, the general regression equation of yarding productivity indicates that the productivity for the given conditions depends solely on the volume of the payload, because no other factors acted as significant predictors. However, at the corridor level, the situation changed in the sense that the lateral yarding distance became a significant predictor of the productivity for corridors B and C. The models given in Table 6 also indicate that by decreasing the lateral yarding distance  $l$ , and by increasing the payload volume  $Q$ , one can increase the yarding productivity per scheduled machine hour; however, the control issues on such an attempt are similar to those presented in the case of time consumption models. Productivity did not depend significantly on the damage type.

The hourly costs of the studied tower yarder, as well as the labor costs, are summarized in Table 7. As shown, the gross costs for uphill whole tree yarding were estimated at 120.17 € PMH (productive machine hour). In the structure of the gross costs, the fixed costs (34%) were slightly higher than the labor (31%) and variable costs (24%). Therefore, for the productive time of the machine, the extraction costs were estimated at 5.72 € per m<sup>3</sup>. Different cost results were found by comparing the three different damage types. Corridor C, which was characterized by the damage code 1C, returned the lowest costs of wood harvesting, which were 25 and 22% lower compared to those of corridors A and B, respectively. In addition, an increase of the yarding productive time would lead to a decrease in the extraction costs, even though these costs are lower compared to those found

for a similar machine operating on moderate slopes to extract resinous wood for an outhaul distance of 125 m and a lateral yarding distance of 7 m, i.e., conditions in which the costs ranged between 12.910 and 14.690 US \$ per m<sup>3</sup> [54].

**Table 7.** Yarding costs (€) at the corridor level.

Costs Category	Costs per PMH	Costs per m <sup>3</sup>	% of Total	Costs per m <sup>3</sup>		
				Site A Code 1A	Site B Code 1B	Site C Code 1C
Fixed costs	40.38	1.91	33.46	2.27	2.18	1.70
Variable costs	29.05	1.40	24.45	1.63	1.57	1.22
Labor costs	37.87	1.80	31.38	2.13	2.05	1.60
Net costs (excluding profit)	107.30	5.11	89.29	6.03	5.80	4.52
Gross costs (including 12% profit)	120.17	5.72	100	6.75	6.50	5.06

#### 4. Discussion

As reported by similar studies [23,35,40,46,50,55], the comparison of productivity and costs across different countries, highly variable personnel costs, and contrasting environmental conditions is difficult, despite the similarity of the machines used. As such, the particular condition of the forest stand examined in this study and the lack of similar studies in which the cable yarder was used for salvage logging did not allow for a complete and exhaustive comparative analysis of the results. However, the objectives of this study were to check and find ways of improving the performance of cable yarding in salvage logging operations. For the neighbor country of Bulgaria, Romania, which shares a similar economic context, Munteanu et al. [29] evaluated the operational costs at 7.4 € m<sup>-3</sup> for the use of a gravity-driven Wyssen yarder. In their study, which was performed in a group shelterwood system by the use of a gravity-assisted downhill yarding, the extraction distance was 326 m, the lateral yarding distance was 43 m, and the payload per turn was 1.87 m<sup>3</sup>. In the Italian Alps, Spinelli et al. [56] estimated the costs of timber extraction and processing in the range of 9 to 40 € m<sup>-3</sup>. These previous studies proved that costs and productivity vary depending on the variables considered; in particular, the lateral yarding distance has an influence on productivity, while the costs are largely dependent on the productivity. Generally, the yarding productivity in this study was found to be higher than that reported by other studies on tower yarders [51,57,58]. Erber et al. [59] evaluated the performances of a Koller K507 in the conditions of Bavarian State Forests, and reported an average productivity of 10.1 m<sup>3</sup> h<sup>-1</sup>, identifying the terrain slope, stand density and yarding direction as the significant independent variables explaining the performance of the machine. Dimitrov [51] estimated that the productivity of the studied yarder was of 3.22 m<sup>3</sup> h<sup>-1</sup> in operational conditions characterized by a 33 m lateral yarding distance, and a 230 m outhaul distance, therefore the productivity figure estimated by him could be interpreted as moderate. Furthermore, our findings indicate higher productivities compared to those reported for Turkish coniferous forests, which were estimated at 6.6, 5.5, and 4.9 m<sup>3</sup> h<sup>-1</sup>, for extraction distances of 100, 200, and 250 m, respectively [60]. Tavankar et al. [61] reported that the volume of the fallen trees, harvested selectively, was twice as low as that from the protected forest stands of the Hyrcanian forest of Iran, a fact that may affect the productivity of salvage logging compared to conventional logging. The machines from the Processor Tower Yarder (PTY) class were evaluated as highly productive during our study, and are recommended for use in coniferous forests in order to fully use their functionality potential [32]; for these machines, the productivity increment is supported by technical features such as those of enabling tree processing, sorting, and piling after load lowering and releasing [62–65]. In addition, the use of radio-controlled chokers may help to decrease the unhooking time consumption by the elimination of this manual task at landing, and it could be supported by a remote controller mounted in the yarder's cab [66], improving the operations safety. Furthermore, the results of this study provide evidence that

cable yarding could be used effectively in salvage logging, complementing the commonly used harvesting systems, such as those including skidders [42]. In fact, nowadays, in steep terrain, there is no cost-efficient alternative to cable-based extraction. Schweier et al. [55] defined a winching distance of 50 m as the threshold value of winching operations performed by skidders. Higher productivities may support cost reduction when the extraction is carried out using a yarder. In particular, the costs analysis of this study produced values ranging from € 5.06 m<sup>-3</sup> to € 6.75 m<sup>-3</sup>, costs that are clearly lower than those of traditional ground-based salvage logging. The higher productivities and lower costs of this study may be related to the efficient forest operation planning during the cable yarder setup phase. The results confirmed that short operational distances influenced the productivity rate and, consequently, the operational cost. In addition, Bodaghi et al. [42] found no economic justification to harvest wind-fallen trees using ground-based wood extraction, due to lower productivities. As such, our opinions concur to consider the positive effects that salvage logging may have to overcome economic barriers; in fact, even if the salvage logging is frequently resource intensive in sensitive forest areas, these operations are important for the forests, as they can be used as a strategy to mitigate further damage outbreaks in coniferous forests [3]. In addition, some studies [67] have reported more conservative results on the impact of salvage logging, thereby supporting their implementation based on careful planning to protect the soil. The use of cable yarders holds the potential to reduce the damage and disturbances; in fact, if the operations are carefully planned and performed, then the resilience of seedlings and small trees is sustained [6]. In addition, there are several challenges to which the use of storm-damaged wood could respond, such as balancing the demand and supply of energy wood [13]. For other industrial purposes, the quality of such timber is in question, and should be researched further [68,69], and its use should also balance ecological, social, and economic needs [42].

## 5. Conclusions

Large-scale windstorms are increasingly frequent in European forests, and they may cause important losses, especially when they affect sensitive forests, for which there are problems related to the wood's recovery. This study was set up to evaluate the performance of wood extraction by tower yarders in such forests, by observing an operation done in the Bulgarian mountains. By its results, the study extended the existing knowledge on the productivity and costs of salvage logging operations. On the one hand, the damage type was found to produce significant variations in time consumption and productivity, mainly due to the amount of time needed to deal with different types of damaged trees. Similar to other findings, the limited payloads observed in this study have depended on the particular operational conditions, and not on the machine capacity. The preparation of the loads affected the efficiency of the extraction, in conjunction with delays, resulting in a decreasing trend of productivity, a situation for which better time management could be one of the improvement measures. Until extensive studies on the problem are developed, the results reported herein may be used as a baseline to plan and organize the production for similar operational conditions, because such information is needed at least to develop an equitable payment system for salvage logging operations. On the other hand, our findings complement the existing knowledge on the performance of salvage logging operations, which currently covers only ground-based harvesting systems.

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### Abbreviations

The following abbreviations are used in this manuscript:

asl	above sea level
CI	carriage inhaul time
CO	carriage outhaul
CO	carriage outhaul time
D	delay time
DBH	diameter at breast height
LO	lateral outhaul time
PMH	productive machine hours
PTY	processor tower yarder
SMH	scheduled machine hour
TNET	delay-free cycle time
U	unhook time

### References

- Schelhaas, M.J.; Nabuurs, G.J.; Schuck, A. Natural disturbances in the European forests in the 19th and 20th centuries. *Glob. Chang. Biol.* **2003**, *9*, 1620–1633. [\[CrossRef\]](#)
- Thorn, S.; Bässler, C.; Svoboda, M.; Müller, J. Effects of natural disturbances and salvage logging on biodiversity. *Lessons Bohemian For. For. Ecol. Manag.* **2017**, *388*, 113–119. [\[CrossRef\]](#)
- Kärhä, K.; Anttonen, T.; Poikela, A.; Palander, T.; Laurén, A.; Peltola, H.; Nuutinen, Y. Evaluation of Salvage Logging Productivity and Costs in Windthrown Norway Spruce-Dominated Forests. *Forests* **2018**, *9*, 280. [\[CrossRef\]](#)
- Lindenmayer, D.B.; Noss, R.F. Salvage logging, ecosystem processes, and biodiversity conservation. *Conserv. Biol.* **2006**, *20*, 946–948. [\[CrossRef\]](#)
- Stokes, B.J.; Ashmore, C.; Rawlins, C.L.; Sirois, D.L. *Glossary of Terms Used in Timber Harvesting and Forest Engineering*; Gen. Tech. Rep. SO-73, New Orleans; USDA Forest Service Southern Forest Experimental Station: Asheville, NC, USA, 1989.
- Kramer, K.; Brang, P.; Bachofen, H.; Bugmann, H.; Wohlgemuth, T. Site factors are more important than salvage logging for tree regeneration after wind disturbance in Central European forests. *For. Ecol. Manag.* **2014**, *331*, 116–128. [\[CrossRef\]](#)
- Cadei, A.; Mologni, O.; Röser, D.; Cavalli, R.; Grigolato, S. Forwarder productivity in salvage logging operations in difficult terrain. *Forests* **2020**, *11*, 341. [\[CrossRef\]](#)
- Oprea, I. *Tehnologia Exploatării Lemnului (Timber Harvesting Technology)*; Transilvania University Press: Brasov, Romania, 2008; p. 273. ISBN 978-973-598-301-7.
- Keeton, W.S. Managing for Late-successional/old-Growth Characteristics in Northern Hardwood-Conifer Forests. *For. Ecol. Manag.* **2006**, *235*, 129–142. [\[CrossRef\]](#)
- Keeton, W.; Chernyavskyy, M.; Gratzner, G.; Main-Knorn, M.; Shpylchak, M.; Bihun, Y. Structural Characteristics and Aboveground Biomass of old-growth spruce–fir Stands in the Eastern Carpathian Mountains, Ukraine. *Plant Biosyst.* **2010**, *144*, 148–159. [\[CrossRef\]](#)
- Lehnert, L.W.; Bässler, C.; Brandl, R.; Burton, P.J.; Müller, J. Conservation Value of Forests Attacked by Bark Beetles: Highest Number of Indicator Species is found in Early Successional Stages. *J. Nat. Conserv.* **2013**, *21*, 97–104. [\[CrossRef\]](#)
- Lindenmayer, D.B.; Burton, P.J.; Franklin, J.F. *Salvage Logging and Its Ecological Consequences*; Island Press: Washington, DC, USA, 2012.
- Wermelinger, B.; Moretti, M.; Duelli, P.; Lachat, T.; Pezzatti, G.B.; Obrist, M.K. Impact of windthrow and salvage-logging on taxonomic and functional diversity of forest arthropods. *For. Ecol. Manag.* **2017**, *391*, 9–18. [\[CrossRef\]](#)
- Jonášová, M.; Prach, K. The Influence of Bark Beetles Outbreak vs. Salvage Logging on Ground Layer Vegetation in Central European Mountain Spruce Forests. *Biol. Conserv.* **2008**, *141*, 1525–1535. [\[CrossRef\]](#)
- Michalová, Z.; Morrissey, R.C.; Wohlgemuth, T.; Bače, R.; Fleischer, P.; Svoboda, M. Salvage-Logging after Windstorm Leads to Structural and Functional Homogenization of Understorey Layer and Delayed Spruce Tree Recovery in Tatra Mts., Slovakia. *Forests* **2017**, *8*, 88.
- European Commission. Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. *Off. J. Eur. Union* **1992**, *206*, 7–50.

17. European Commission. NATURA 2000 Viewer User Guide. 2020. Available online: <https://natura2000.eea.europa.eu/#> (accessed on 30 November 2020).
18. Krejčí, F.; Vacek, S.; Bílek, L.; Mikeska, M.; Hejmanová, P.; Vacek, Z. The effects of climatic conditions and forest site types on disintegration rates in *Picea abies* occurring at the Modrava Peat Bogs in the Šumava National Park. *Dendrobiology* **2013**, *70*, 35–44. [[CrossRef](#)]
19. Vacek, S.; Moucha, P.; Bílek, L.; Mikeska, M.; Remeš, J.; Simon, J.; Hynek, V.; Šrůtka, P.; Schwarz, O.; Mánek, J.; et al. *Management of Forest Ecosystems in the Protected Areas of the Czech Republic*; Ministry of the Environment of the Czech Republic: Prague, Czech Republic, 2012.
20. Remeš, J.; Pulkrab, K.; Bílek, L.; Podrázský, V. Economic and production effect of tree species change as a result of adaptation to climate change. *Forests* **2020**, *11*, 431. [[CrossRef](#)]
21. Šimůnek, V.; Vacek, Z.; Vacek, S. Solar Cycles in Salvage Logging: National Data from the Czech Republic Confirm Significant Correlation. *Forests* **2020**, *11*, 973. [[CrossRef](#)]
22. Vacek, S.; Vacek, Z.; Bílek, L.; Hejmanová, P.; Štícha, V.; Remeš, J. The dynamics and structure of dead wood in natural spruce-beech forest stand—A 40 year case study in the Krkonoše national park. *Dendrobiology* **2015**, *73*, 21–32. [[CrossRef](#)]
23. Birda, M.; Borz, S.A. A comparison between tractor based and skyline based mechanized systems for timber logging. *Bull. Transilv. Univ. Bras. Ser. II For. Wood Ind. Agric. Food Eng.* **2012**, *5*, 19–24.
24. Proto, A.R.; Skoupy, A.; Macri, G.; Zimbalatti, G. Time consumption and productivity of a medium size mobile tower yarder in downhill and uphill configurations: A case study in Czech Republic. *J. Agric. Eng.* **2016**, *47*, 216–221. [[CrossRef](#)]
25. Visser, R.J.M.; Stampfer, K. Cable extraction of harvester felled thinnings an Austrian case study. *J. Eng.* **1998**, *1*, 39–46.
26. Huyler, N.K.; LeDoux, C.B. *Cycle-Time Equation for the Koller K300 Cable Yarder Operating on Steep Slopes in the Northeast*; Research Paper NE-705; US Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Radnor, PA, USA, 1997; p. 4.
27. Messingerova, V. *Analysis of Basic Parameters for Optimal Utilization of the Forestry Cable Yarding System*; Prace Komisji nauk rolniczych, leśnych i weterynaryjnych PAU, zv. Nr. 15; Polska Akademia Umiejętności: Krakow, Poland, 2011; pp. 177–186, ISSN 1733-5183.
28. Cosola, G.; Grigolato, S.; Ackerman, P.; Monterotti, S.; Cavalli, R. Carbon footprint of forest operations under different management regimes. *Croat. J. For. Eng.* **2016**, *37*, 201–217.
29. Munteanu, C.; Yoshida, M.; Iordache, E.; Borz, S.A.; Ignea, G. Performance and cost of downhill cable yarding operations in a group shelterwood system. *J. For. Res.* **2019**. [[CrossRef](#)]
30. Fischer, A.; Fischer, H.S.; Kopecky, M.; Macek, M.; Wild, J. Small changes in species composition despite stand-replacing bark beetle outbreak in *Picea abies* mountain forests. *Can. J. Res.* **2015**, *1171*, 1164–1171. [[CrossRef](#)]
31. Nováková, M.H.; Edwards-Jonášová, M. Restoration of Central-European mountain Norway spruce forest 15 years after natural and anthropogenic disturbance. *Ecol. Manag.* **2015**, *344*, 120–130. [[CrossRef](#)]
32. Borz, S.A.; Birda, M.; Ignea, G.; Oprea, I. Technological aspects regarding timber exploitation using Mouny 4100 cable yarder. *Bull. Transilv. Univ. Bras. Ser. II For. Wood Ind. Agric. Food Eng.* **2011**, *4*, 1–6.
33. Stampfer, K.; Visser, R.; Kanzian, C. Cable corridor installation times for European yarders. *Int. J. For. Eng.* **2006**, *17*, 71–77. [[CrossRef](#)]
34. Borz, S.A. A computational algorithm for cutting volumes determination with application in the tractor logging network design. *Bull. Transilv. Univ. Bras. Ser. II For. Wood Ind. Agric. Food Eng.* **2010**, *3*, 5–10.
35. Proto, A.R.; Sperandio, G.; Costa, C.; Maesano, M.; Antonucci, F.; Macri, G.; Scarascia Mugnozza, G.; Zimbalatti, G. A three-step neural network artificial intelligence modeling approach for time, productivity and costs prediction: A case study in Italian forestry. *Croat. J. For. Eng.* **2020**, *41*, 35–47. [[CrossRef](#)]
36. Borz, S.A.; Ignea, G.; Popa, B.; Spárchez, G.; Iordache, E. Estimating time consumption and productivity of roundwood skidding in group shelterwood system—A case study in a broadleaved mixed stand located in reduced accessibility conditions. *Croat. J. For. Eng.* **2015**, *36*, 137–146.
37. Duta, C.I.; Borz, A.; Salajan, A. Estimating current state of soil erosion induced by skid trails geometry in mountainous conditions. *Environ. Eng. Manag. J.* **2018**, *17*, 697–704.
38. 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](#)]
39. Findeisen, E.; Markoff, I.; Gluschkov, S. Fully mechanized logging in Bulgaria—First steps and prospects. In Proceedings of the 41th International Symposium on Forestry Mechanization, Schmallingenberg, Germany, 2–5 June 2008; German Center for Forest Work and Technology (KWF): Schmallingenberg, Germany, 2008. ISBN 978-3-9811335-2-3.
40. Dvůrák, J.; Walczyk, J.; Natov, P.; Hošková, P. Struktura času pracy harwesterów podczas pozyskania przygodnego (Structure of the operating time of the harvesters during casual logging). *Sylvan* **2015**, *159*, 300–306.
41. Brzózko, J.; Szereszewiec, B.; Szereszewiec, E. Productivity of machine timber harvesting at the wind-damaged site. *Ann. Wars. Univ. Life Sci. Sggw Agric.* **2009**, *54*, 41–49.
42. Bodaghi, A.I.; Nikooy, M.; Naghdi, R.; Venanzi, R.; Latterini, F.; Tavankar, F.; Picchio, R. Ground-based extraction on salvage logging in two high forests: A productivity and cost analysis. *Forests* **2018**, *9*, 1–18.

43. Borz, S.A.; Dinulică, F.; Bîrda, M.; Ignea, G.; Ciobanu, V.; Popa, B. Time consumption and productivity of skidding Silver fir (*Abies alba* Mill.) round wood in reduced accessibility conditions: A case study in windthrow salvage logging form Romanian Carpathians. *Ann. For. Res.* **2013**, *363–375*. [[CrossRef](#)]
44. Căkša, L.; Šenhofa, S.; Šnepsts, G.; Elferts, D.; Liepa, L.; Jansons, A. Effect of stem snapping on aspen timber assortment recovery in hemiboreal forests. *Forests* **2021**, *12*, 28. [[CrossRef](#)]
45. Ackerman, P.; Gleasure, E.L.; Ackerman, S.; Shuttleworth, B. Standards for time studies for the South African forest industry. *ICFR/FESA* **2014**. Available online: <https://natura2000.eea.europa.eu/#> (accessed on 9 September 2020).
46. Olsen, E.D.; Hossain, M.M.; Miller, M.E. *Statistical Comparison of Methods Used in Harvesting Work Studies*; College of Forestry, Forest Research Laboratory; Oregon State University: Corvallis, OR, USA, 1998; p. 45.
47. Munteanu, C.; Ignea, G.; Akay, A.E.; Borz, S. *Yarding Pre-Bunched Stems in Thinning Operations: Estimates on Time Consumption*; Special issue No. 1—2017 Series II—*Forestry, wood industry, agricultural and food engineering*; Transilvania University of Brasov: Brasov, Romania, 2017; Volume 10, ISSN 2065-2135.
48. Huyler, N.K.; LeDoux, C.B. Yarding cost for the Koller K300 cable yarder: Results from field trials and simulations. *North. J. Appl. For.* **1997**, *14*, 5–9. [[CrossRef](#)]
49. Proto, A.R.; Zimbalatti, G. Firewood cable extraction in the southern Mediterranean area of Italy. *For. Sci. Technol.* **2016**, *12*, 16–23, ISSN 2158-0103 (Print) 2158-0715. [[CrossRef](#)]
50. Ackerman, P.; Belbo, H.; Eliasson, L.; de Jong, A.; Lazdins, A.; Lyons, J. The COST model for calculation of forest operations costs. *Int. J. Eng.* **2014**, *25*, 75–81. [[CrossRef](#)]
51. Dimitrov, D. Investigation on work time and productivity of forest skyline Koller K 300 in Ograzhden Mountain. *For. Ideas* **2012**, *18*, 92–96.
52. Spinelli, R.; Visser, R.J.M. Analyzing and estimating delays in harvester operations. *Int. J. For. Eng.* **2008**, *19*, 36–41. [[CrossRef](#)]
53. Borz, S.A.; Ignea, G.; Popa, B. Modelling and comparing timber winching performance in windthrow and uniform selective cuttings for two Romanian skidders. *J. For. Res.* **2014**, *19*, 473–482. [[CrossRef](#)]
54. Kellogg, L.D.; Milota, G.V.; Miller, M., Jr. A Comparison of Skyline Harvesting Costs for Alternative Commercial Thinning Prescriptions. *J. For. Eng.* **1996**, *7*, 7–23. [[CrossRef](#)]
55. Schweier, J.; Klein, M.-L.; Kristen, 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. *Int. J. Eng.* **2020**, *31*, 172–183. [[CrossRef](#)]
56. Spinelli, R.; Magagnotti, N.; Visser, R. Productivity models for cable yarding in Alpine forests. *Eur. J. For. Eng.* **2015**, *1*, 9–14.
57. Melemez, K.; Tunay, M.; Emir, T. A comparison of productivity in five small-scale harvesting systems. *Small-Scale For.* **2014**, *13*, 35–45. [[CrossRef](#)]
58. Zimbalatti, G.; Proto, A.R. Cable logging opportunities for firewood in Calabrian forests. *Biosyst. Eng.* **2009**, *102*, 63–68. [[CrossRef](#)]
59. 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. Sci.* **2017**, *134*, 1–18.
60. Senturk, N.; Ozturk, T.; Demir, M. Productivity and costs in the course of timber transportation with the Koller K300 cable system in Turkey. *Build. Environ.* **2007**, *42*, 2107–2113. [[CrossRef](#)]
61. Tavankar, F.; Nikooy, M.; Picchio, R.; Venanzi, R.; Lo Monaco, A. Long-term effects of single-tree selection cutting management on coarse woody debris in natural mixed beech stands in the Caspian forest (Iran). *iForest* **2017**, *10*, 652–658. [[CrossRef](#)]
62. Stampfer, K. Perspectives on whole tree cable yarding systems for thinnings operations in Austria. In Proceedings of the Cable Yarding Suitable for Sustainable Forest Management, Idrija, Slovenia, 23 September 2004.
63. Bugoš, M.; Stanovský, M.; Lieskovský, M. Time analysis of the operations during yarding by Konrad Mounty 4000 mountain processor. *Acta Facultatis Xylologiae Zvolen* **2008**, *50*, 163–174.
64. Tajboš, J.; Slugeň, J.; Ilčík, Š. Popis lanovky Mounty 4000. In *Manažment podnikov*; Přeložil Mária LACIKOVÁ: Prešov, Slovenská, 2012; Volume 2, pp. 15–18.
65. Borz, S.A.; Bîrda, M.; Ignea, G.; Popa, B.; Cămpu, V.R.; Iordache, E.; Derczeni, R.A. Efficiency of a Woody 60 processor attached to a Mounty 4100 tower yarder when processing coniferous timber from thinning operations. *Ann. Res.* **2014**, *57*, 333–345. [[CrossRef](#)]
66. Visser, R.; Baker, S.; Sloan, H. Cable logging opportunities in the Appalachian Mountains. In Proceedings of the Workshop Proceedings New Trends in Wood Harvesting with Cable Systems for Sustainable Forest Management in the Mountains; Ossiach, Austria, 18–24 June 2001; Arzberger, U., Grimoldi, M., Eds.; Joint FAO/ECE/ILO Committee on Forest Technology, Management and Training with the participation of the IUFRO. FAO: Rome, Italy, 2003.
67. Peterson, C.J.; Leach, A.D. Limited Salvage Logging Effects on Forest Regeneration After moderate-severity Windthrow. *Ecol. Appl.* **2008**, *18*, 407–420. [[CrossRef](#)] [[PubMed](#)]
68. Donis, J.; Saleniece, R.; Krisans, O.; Dubrovskis, E.; Kitenberga, M.; Jansons, A. A Financial Assessment of Windstorm Risks for Scots Pine Stands in Hemiboreal Forests. *Forests* **2020**, *11*, 566. [[CrossRef](#)]
69. Picchio, R.; Proto, A.R.; Civitarese, V.; Di Marzio, N.; Latterini, F. Recent contributions of some fields of the electronics in development of forest operations technologies. *Electronics* **2019**, *8*, 1465. [[CrossRef](#)]