# Productivity analysis and costs of wheel cable skidder during salvage logging in European beech stand

Stanimir Stoilov,[1] Salvatore F. Papandrea,[2] Georgi Angelov,[1] Delyan Oslekov,[1] Giuseppe Zimbalatti,[2] Andrea R. Proto[2]

[1]Department of Technologies and Mechanization of Forestry, University of Forestry, Sofia, Bulgaria; [2]Department of Agraria, Mediterranean University of Reggio Calabria, Italy

## Abstract

Salvage logging is increasing in Central Europe because of the growth of severe meteorological events, and timber harvesting in these conditions is challenging in terms of both productivity performances and safety of the operations. In recent years, with the increase of natural calamities, several researchers studied machinery productivity performances regarding salvage logging carried out by ground-based systems. In fact, a common post-disturbance management approach is salvage logging which consists of the widespread removal of damaged trees. In this research, system productivity and the cost of salvage logging are analysed in European beech stands affected by wet snow. The accretion of heavy wet snow poses the greatest risk to forests in the Northern Hemisphere. This type of snow attaches more effectively to tree crowns and branches when temperatures are close to freezing at the time of precipitation. As a result, trees may break or bend and may be uprooted when the soil is unfrozen. This study has been implemented to evaluate the productivity and cost-effectiveness of extraction in salvage logging deployed with a skidder in beech stands affected by two different types of wet snow damage. The results show that the productivity of the four-wheel-drive cable skidder, despite operating in salvage cutting with a removal intensity of 10%, is 14.73 $m^3 \cdot SMH^{-1}$, similar to skidder performances in 'ordinary' cuttings. Skidder's productive time was 86% of the scheduled time, whereas the delays were due to organisational reasons, mechanical delays, and adverse weather conditions. The mean travel speed of the cable skidder obtained in this study is close to the results obtained from other studies on similar machines. The costs per unit are lower than effective cost consumptions for the other cable skidders and agricultural tractors, adapted for skidding operated in hardwood salvage logging. Therefore, under the given conditions, the operation of the four-wheel-drive cable skidder is viable from a silvicultural, technical, and economic point of view in the salvage operation logging.

Correspondence: Salvatore F. Papandrea, Department of Agraria, Mediterranean University of Reggio Calabria, Feo di Vito snc, 89122 Reggio Calabria, Italy.
Tel.: +39.0965.1694202.
E-mail: salvatore.papandrea@unirc.it

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## Introduction

Severe natural disturbances are common in many forest ecosystems, particularly in the Northern Hemisphere (Thorn *et al.,* 2017). Forest disturbances have caused noticeable damage to European forests over the last few decades (Schelhaas *et al.,* 2003). Different abiotic and biotic disturbances are expected to become more common in the future due to a warming climate. In particular, ice storms could trigger physical damage to forests and, therefore, significantly affect forest structures and functions (Carbaugh and Hensle, 2005; Kramer *et al.,* 2014; Zhu *et al.*, 2022). In detail, wet snow or ice causes bending or breakage of branches and tree tops, and this occurs when the weight of frozen precipitation exceeds the buckling load of the portion of the tree bearing the load (Stoilov *et al.*, 2021; Thorn *et al.*, 2017). In order to prevent biological diseases (fungi and insects) and to foster active forest restoration, forest managers apply salvage logging in affected stands with the intent of recovering maximum value prior to deterioration (Stokes *et al.,* 1989). These interventions differ from the common planned logging activities for the higher harvesting intensity (Schmiegelow *et al.,* 2006; Cadei *et al.,* 2021; Stoilov, 2021) or for their higher difficulties found during harvesting operations. For these reasons, post-disturbance salvage logging is becoming more predominant to recover economic value from timber in disturbed forests (Kärhä *et al.,* 2018; Magagnotti *et al.,* 2013), and this purpose motivated several studies in recent years to determine productivity models and cost assessments to support a correct decision in choosing between alternative wood harvesting systems. These aspects are particularly important in salvage logging because of difficulties due to irregularly positioned fallen trees in forest areas and due to particular aspects related to the absence of work planning (Bodaghi *et al.,* 2018).

These interventions required valid operational planning according to the site's characteristics to ensure high productivity and greater safety for forestry workers. According to the steep slope condition, low road density, and the structure and tree volume, ground-based systems are the main extraction methods for logs, which are felled and processed by chainsaws (Cataldo *et al.,* 2020). This semi-mechanised system represents the most suitable technological solution for rapid post-disturbance wood harvesting. In particular, the productivity of logging machines depends on many factors, such as forest disturbance types, logging intensity, the number of trees per hectare, machine type, tree size, terrain conditions, operator skills, silvicultural treatment, and distances between skid roads (Wang *et al.,* 2004; Proto *et al.,* 2016, 2018).

In recent years, with the increase of natural calamities, several researchers studied machinery productivity performances regarding salvage logging carried out by ground-based systems, based mainly on adapted agricultural tractors with related logging equipment such as winches, as well as wheel cable skidders (Borz *et al.,* 2013; Bodaghi *et al.,* 2018; Cadei *et al.,* 2020). Compared to agricultural forestry tractors, skidders have greater mobility, and being specially built, they meet the ergonomic and safety standards imposed by the wood industry. For these reasons and not only all over the world, the skidder is one of the primary machines used for timber extraction operations (Georgiev and Stoilov, 2007). The skidders may successfully replace modified farm tractors without requiring any substantial changes in the conventional harvesting methods (Proto *et al.,* 2018). Wheel cable skidders are used in many harvesting systems on slopes prohibitive for farm tractors due to their better longitudinal and lateral stability, mobility, and long winch cable (80-100 m), giving a better opportunity to access marked trees and enhanced productivity. Currently, there are a few studies on the work cycle, productivity rates, and costs of cable skidders in salvage logging in different silvicultural systems, damage type, and terrain conditions. The influence of different operational and technical parameters in salvage logging was studied by Bodaghi *et al.* (2018), who monitored the productivity and costs of wheeled skidders and farm tractors under two different stand conditions. In Romanian Carpathians, Borz *et al.* (2013) evaluated the efficiency of two different skidder models during timber skidding in reduced accessibility conditions caused by wind-fallen trees. Such studies have been needed to evaluate the application of typical wheel cable skidders in salvage logging in sensitive sites from a silvicultural, technical, and economic point of view. However, the available knowledge when dealing with salvage logging is still limited in productivity and costs for different harvesting types of equipment, including the association between chainsaws and skidders, as different damage types (wind-storm, ice-storm, *etc.*). For this reason, the study aims to partially fill the lack of knowledge of skidder productivity in salvage logging operations in two different types of damages caused by wet snow disturbance. The aims of the present study propose: i) to determine productivity rates and extraction costs using conventional cable skidder in salvage cutting in deciduous stands; and ii) to develop skidding time and productivity prediction models in European beech high forests damaged.

## Materials and Methods

### Study site and work organisation

The study was conducted in Vitinya State Hunting Range, Sofia Province, in Western Balkan Mountains, Bulgaria. Stand and operation characteristics are shown in Table 1. The wet snow disturbance damaged a European beech (*Fagus sylvatica,* Linnaeus, 1753) stand, and the proportion of damaged trees with respect to the total number of trees was 10%. There were 981 damaged trees in the stand, and the type of damages corresponded to code 1A Uprooted whole tree with stump (the standing tree had lodged, felling a whole stem) and 1D Broken tree section (a broken tree with a separate butt section or top broken sections) (Kärhä *et al.*, 2018). The stand was divided into two approximately equal parts (Figure 1): site A (upper part) with damages corresponding to code 1D and site B (lower part) with damages described with code 1A. The skidding direction was downhill, and trees were motor-manually felled. A wheel cable skidder transported the logs as semi-suspended stem sections. The work team consisted of the skidder operator, a second worker who unhooked the stems at landing, and the other two were chainsaw operators at the cutting area. A chain-



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

| **Location** | **N 42.77810779; E 23.67989894** |
|---|---|
| Elevation | 1150 m asl |
| Function | Natura 2000: BG 0001043, habitat 9150 (Medio-European limestone beech forests of the Cephalanthero-Fagion) |
| Species composition | European beech (*Fagus sylvatica*, L) 100% |
| Stand age | 90 years |
| Stand type | High natural forest |
| Total area | 15.4 ha |
| Stand density | 640 trees $ha^{-1}$ |
| Relative stocking | 0.7 |
| Logging operation | Salvage cutting, removal intensity 10% |
| Average tree height | 21 m |
| Average DBH of tree | 26 cm |
| Average slope gradient | 26° (49%) |
| Growing stock | 298 $m^3 \cdot ha^{-1}$ |
| Allowable cut | 30 $m^3$ $ha^{-1}$, 64 trees·$ha^{-1}$ |
| Extraction direction | Flat and uphill |
| Average slope gradient of the skidding road | 4.72° (8.26%) |

saw operator outhauls the main cable and hooks stem sections. The work team had at least 5 years of experience with logging, and the age of the operators ranged between 35 and 55 years. An articulated four-wheel-drive TAF-690 PE (SC Irum SA, Reghin, Romania) double-drum cable skidder was used for the tests (Figure 2 and Table 2).

## Productivity study and costs

The time and motion study was conducted to estimate the duration of work elements and productivity of the cable skidder, and field observations were carried out on 60 work cycles (turns). A work cycle was assumed to be composed of repetitive elements (Olsen *et al.*, 1998). The work cycle of the skidder was composed of the following repetitive elements: i) travel unloaded along skidding trail (UT); ii) bunching - time for winching and gathering the tree load, including the time for manoeuvres and choice of position. Bunching can be divided into manoeuvring (M), outhaul of the main cable, hook (OH), and inhaul the load to the skidder (I); iii) travel loaded along skidding trail (TL); iv) unload the stems (U); v) delays (D).

During the study, the skidding distance, bunching distance, slope, and volume of the stems, were measured. Each work cycle was individually measured by a stopwatch and productive time was separated from delay time. Skidding distance and slop gradient of the skidding road were measured by GPS - receiver with Digital Terrain Model using GIS software. Bunching distances and terrain slopes were measured with a Nikon Forestry Pro II (Nikon Vision Co. Ltd, Tokyo, Japan) professional laser range finder with a clinometer. Load volume was determined by measuring the length and the mid-length diameter of all logs from each load. The machine costs were calculated using the COST model proposed by Ackerman *et al.* (2014). In order to calculate the production cost for 1 m$^3$ of timber, the cost analysis was based on the following parameters: the number of operators, the hourly cost of an operator, the hourly cost of machines, the volume of extracted timber, and the productive machine hours (excluding all delay times). The

**Table 2.** Technical data of studied TAF-690 PE double-drum cable skidder.

| Parameter | Value |
|---|---|
| Engine | Perkins 1104D-44T |
| Engine power | 70kW at 2300 rpm |
| Dimensions | |
| Length | 5800±50 mm |
| Width | 2500±50 mm |
| Height | 2700±50 mm |
| Wheelbase | 2830±50 mm |
| Track | 2050±50 mm |
| Ground clearance | 450±20 mm |
| Blade width | 2140±50 mm |
| Shield width | 2000±50 mm |
| Weights | |
| Weight (with no load) | 7500 kg |
| On the front axle | 4285 kg |
| On the rear axle | 3215 kg |
| Maximum permissible semi-suspended load | 5000 kg |
| Maximum permissible load weight | 9300 kg |
| Maneuverability | |
| Minimum turning radius | 2.9 m |
| Turning angle of the chassis | ±40° |
| Oscillation of front axle | ±12° |
| Winch | TA2-AM |
| Cables, number/diameter | 2/13 mm |
| Cable length | 70 m |
| Tractive force | 70 kN |



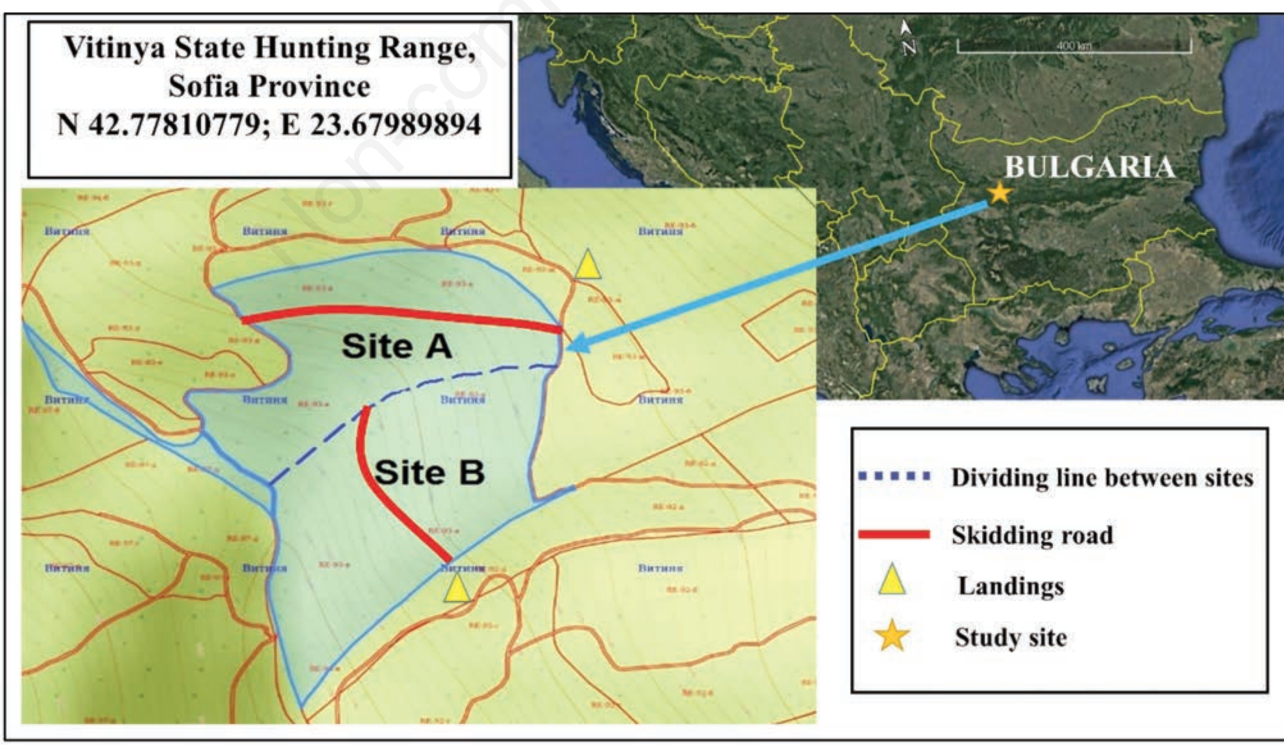


**Figure 1.** Stand map and schematic layout of sites and skidder roads.

machine costs per hour were reported as productive machine hours excluding delays and scheduled machine hours. The purchase prices and operator wages required by the cost calculations were obtained from accounting records (Borz *et al.,* 2014). Diesel fuel consumption was calculated using diesel fuel consumption norms. A salvage value of 10% of the purchase price was assumed, and the value added tax (VAT) was excluded.

Cost calculations were based on the assumption that companies worked for 150 working days in the year and a depreciation period of 10 years. The extraction work amounts to 130-150 working days per year (20-21 working days per month), at an average of 6-7 scheduled working hours per day (assuming one to two hours spent on lunch, rest, and other breaks). This yielded annual working times of 910-1050 SMHs with a 70% use coefficient (Spinelli and Magagnotti, 2011; Proto *et al.,* 2018).

## Data analysis

Regression analysis was performed on the experimental data to develop prediction equations for estimating the work cycle time and productivity. Variables in the modelling approach included skidding distance *L*, winching distance *l*, load volume per cycle *V*, slop gradient of skidding road *s*, and the load's number of trees *n*. In addition, the tree damage type *dt* was used as an indicator (dummy) variable to enhance the discrimination of the time prediction models. Therefore, the models describing the time consumption and productivity were defined in Eqs. (1), (2), (3), and (4):

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

$$T = f(L, l, V, n, i, dt), \quad (2)$$

$$P_{PMH} = \frac{3600.V}{T_{net}}, \quad (3)$$

$$P_{SMH} = \frac{3600.V}{T}, \quad (4)$$

where $T_{net}$ and $T$ are, respectively, the productive time separated from the delay time and scheduled time, and $P_{PMH}$ and $P_{SMH}$ are, respectively, the productivity based on productive machine hours and scheduled machine hours.

The confidence level used for regression analysis was 95% ($\alpha$=0.05), and the assumed probability was P<0.05. Independent variables are significant at P<0.05, *i.e.*, a strong presumption against a neutral hypothesis. Statistica 8 (StatSoft Inc., Tulsa, OK, USA) software was used to process the experimental data.

# Results and Discussion

## Elemental time study and efficiency analysis

At site A, the average skidding distance was 251 m, the average distance of the outhaul of the main cable, hook, and inhaul, the load to the skidder was 13 m, and the average volume skidded per turn was 3.90 $m^3$. On site B, the average skidding distance was 277 m, the average distance of the outhaul of the main cable, hook, and inhaul, the load to the skidder was 15 m, and the volume of skidder per turn was 3.98 $m^3$. The extraction cycle time at site A with the winch was 970 s (±363 SD), while at site B the cable skidder extraction cycle time was 1359 s (±277 SD) (Table 3). Figure 3 shows the share of operations of the working cycle elements excluding and including delays of the cable skidder. The largest share occupies the operation travel loaded (34% and 29% respectively, excluding and including delays), followed by the travel unloaded (29% and 25% respectively, excluding and including delays), load inhaul (17% and 15% respectively), outhaul and hook (14% and 12% respectively). The breakdown by main groups of operations in delay-free cycle time shows the predominance of the movement of the skidder with the largest share of 63%, followed by the bunching of the load (34%) and unloading of the stem sections at landing (3%). Skidder's productive time was 86% of the scheduled time. The delays (14%) are due to organisational reasons (delays are due to waiting for the felling of trees in the cutting area) (4%), mechanical delays (4%), and those due to adverse weather conditions (rain, snow, thick fog) (6%).



**Figure 2.** The articulated 4WD TAF 690 PD cable skidder used in the test.

The regression analysis was done on the time-study data to develop prediction equations for estimating the skidder cycle time by excluding and including delays; in particular, the delay-free cycle time $T_{net}$ regression equation obtained with significant variables given in Eq. (1). In Eq. (1), the minimum duration of delay-free cycle time $T_{net}$ can be achieved in case of short skidding distances, bunching distances, and relatively lighter damage type *dt*=2 (code 1D, broken tree section prevailed) than the types of damage corresponded to code 1A - uprooted whole tree with stump (*dt*=1). In sites A and B, Eqs. (2) and Eq. (3), a reduction in delay-free cycle time can be expected by reducing the skidding and the winching distances, and in the first site, this will also be achieved by reducing the volume of payload (Figure 4). The regression equations (4), (5), and (6) for the studied cable skidder cycle time, including delays *T,* are also presented in Table 4. Generally, the cable skidder cycle time, including delays, also depends only on damage type *dt*, skidding distance *L* and winching distance *l,* and its minimum duration may be attained by minimising the skidding and bunching distances. Damage type *dt*=2, corresponding to code 1D (broken tree section prevailed), provides a greater cycle time

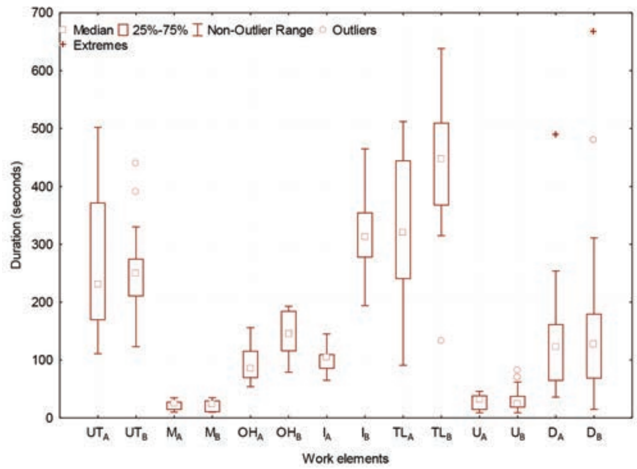


**Figure 3.** Summary statistics of work elemental time of TAF 690 PE cable skidder.



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

| Variables | Duration, s | | | Distance, m | | |
|---|---|---|---|---|---|---|
| | Mean value±SD | Min | Max | Mean value±SD | Min | Max |
| Travel unloaded (UT) | 261±105 | 111 | 502 | 264±103 | 60 | 450 |
| Site A | 252±134 | 111 | 502 | 251±131 | 60 | 450 |
| Site B | 269±66 | 111 | 440 | 277±63 | 75 | 405 |
| Manoeuvring (M) | 22±9 | 10 | 35 | | | |
| Site A | 23±8 | 10 | 35 | | | |
| Site B | 21±9 | 10 | 35 | | | |
| Outhaul and hook (OH) | 118±42 | 54 | 193 | 14±4 | 8 | 22 |
| Site A | 94±31 | 54 | 156 | 13±3 | 9 | 21 |
| Site B | 143±36 | 79 | 193 | 15±4 | 8 | 22 |
| Load inhaul (I) | 206±116 | 65 | 465 | 14±4 | 8 | 22 |
| Site A | 102±23 | 65 | 145 | 13±3 | 9 | 21 |
| Site B | 309±67 | 194 | 465 | 15±4 | 8 | 22 |
| Travel loaded (TL) | 381±138 | 91 | 638 | 264 | 60 | 450 |
| Site A | 318±139 | 91 | 512 | 251 | 60 | 450 |
| Site B | 443±108 | 133 | 638 | 277 | 75 | 405 |
| Unloading (U) | 29±17 | 9 | 83 | | | |
| Site A | 27±13 | 9 | 46 | | | |
| Site B | 32±20 | 9 | 83 | | | |
| Delays (D) | 147±125 | 15 | 668 | | | |
| Site A | 137±95 | 36 | 490 | | | |
| Site B | 158±149 | 9 | 668 | | | |
| Total cycle time | 1164±375 | 406 | 1804 | | | |
| Site A | 970±363 | 406 | 1548 | | | |
| Site B | 1359±277 | 633 | 1804 | | | |
| Delay-free cycle time | 1017±323 | 370 | 1587 | | | |
| Site A | 833±302 | 370 | 1294 | | | |
| Site B | 1201±225 | 559 | 1587 | | | |

SD, standard deviation; PMH, productive machine hour; SMH, scheduled machine hour.

**Table 4.** Summary of the work cycle time models.

| Equations | | *F* | $R^2$ | $R^2_{adj}$ | Std. error | P |
|---|---|---|---|---|---|---|
| $T_{net} = -3.49976 \cdot dt + 0.03892 \cdot L + 0.25665 \cdot l$, min | (1) | 179.65 | 0.95 | 0.95 | 1.23 | P<0.05 |
| $T_{net\_A} = 4.21 + 0.037 \cdot L + 0.85 \cdot V - 1.23 \cdot l$, min | (2) | 323.60 | 0.99 | 0.98 | 0.67 | P<0.05 |
| $T_{net\_B} = 0.042 \cdot L + 0.34 \cdot l$, min | (3) | 39.33 | 0.89 | 0.87 | 1.36 | P<0.05 |
| $T = -3.00 \cdot dt + 0.047 \cdot L + 0.28 \cdot l$, min | (4) | 68.80 | 0.89 | 0.87 | 2.23 | P<0.05 |
| $T_A = 0.045 \cdot L$, min | (5) | 35.91 | 0.97 | 0.87 | 1.17 | P<0.05 |
| $T_B = 0.07 \cdot L + 0.41 \cdot l$, min | (6) | 11.13 | 0.70 | 0.64 | 2.79 | P<0.05 |

reduction including delays than the types of damage corresponding to code 1A - uprooted whole tree with stump (*dt*=1). The mean travel speed of the skidder is 2.90 km·h$^{-1}$ (Table 5). The mean speeds with and without load are 2.49 km·h$^{-1}$ and 3.62 km·h$^{-1}$, respectively. For comparison, Orlovsky *et al.* (2020) pointed to higher mean travel speed monitoring four LKT 81T wheel cable skidders (3.97 km·h$^{-1}$) working on average 5.9 m$^3$ with a slop inclination of 35%. Spinelli and Magagnotti (2012) reported empty and loaded travel velocities of 96 kW agricultural tractors of 8.1 and 7.3 km h$^{-1}$ skidding on flat terrain (12%) and moving meanly 2.4 m$^3$ for each cycle. The mean travel speeds of the skidder in site A and site B are close in value. However, when the skidder is loaded, the speed in site B is lower compared to site A; the opposite is observed at the speed of the unloaded skidder, where it is higher in site B; this trend is not due to the average slope of the skid track equal to 4.72° (8.26%), but is probably due to the different conformation of the roads in the two sites; in fact, site B has a more significant number of hairpin bends that can affect the speed of the unloaded skidder. Theoretically, the movement time of the cable skidder could be reduced by increasing the travel velocity loaded and unloaded. Unfortunately, the terrain conditions practically do not afford a significant increase in travel velocity. The mean speed of a cycle load during winching was 0.09 m·s$^{-1}$. Due to more obstacles, the winching speed is more than twice lower in site B, where the damages are of code 1A.

## Productivity models and cost analysis

Delay-free skidder productivity was defined by the regression Eqs. (7), (8), and (9), shown in Table 6. From the equations, to enhance the delay-free productivity of the studied machine, skidding distance $L$ and winching distance $l$ should be reduced, whereas the load volume $V$ should be increased. In the general model described by Eq. (7), the damage type should be from code 1D (*dt*=2) to improve the delay-free skidder productivity.

The skidder productivity, including delays, is expressed by equations (10), (11), and (12), also shown in Table 6. From Eqs. (10), (11), and (12), to increase skidder productivity, including delays, the skidding distance should be reduced, whereas the load volume per cycle $V$ should be increased. In the general model (10), the lighter damages from type 1D make better skidder productivity, including delays. The delay-free skidder productivity in Site B (damage corresponded to code 1A - uprooted whole tree with stump) is 65% from that in Site A (damages from type 1D). The mean productivity obtained at a mean skidding distance of 264 m, a mean winching distance of 14 m, a mean load volume of 3.94 m$^3$, and a mean 2.2 logs per cycle (turn) is 15.73 m$^3$·PMH$^{-1}$ and 13.80 m$^3$·SMH$^{-1}$, respectively. For LKT 81T cable skidders and LKT 81 ILT cable skidders with knuckle-boom operated primarily in beech, beech-fir, and beech-oak stands, Orlovský *et al.* (2020) registered at mean skidding distance of 300 m and 316 m respectively, mean load volume of 5.45 m$^3$ and 8.01 m$^3$ and gross production rate of 3.91 m$^3$·SMH$^{-1}$ and 4.21 m$^3$·SMH$^{-1}$, respectively. Stoilov and Krumov (2016) monitored a modification of the same machine (LKT81T), equipped without a knuckle-boom loader, reporting an efficiency of 6.27 m$^3$ PMH$^{-1}$ at a skidding distance of 1290 m and a load volume of 5.65 m$^3$. The results obtained regarding average net productivity with the skidder in salvage logging by Bodaghi *et al.* (2018) showed a value almost lower compared to 14.73 m$^3$ h$^{-1}$ observed in this study. This notable difference was probably mainly due to the different stand characteristics. Comparing the results with those reported by Borz *et al.* (2015) for TAF 690 PE, the net and gross production rates were around three times lower 4.41 m$^3$·h$^{-1}$ and 3.12 m$^3$·h$^{-1}$, respectively. Therefore, the productivity of the cable skidder in salvage cutting in a beech stand with a removal intensity of 10% is close and higher than that of similar type skidders in ordinary logging activities.

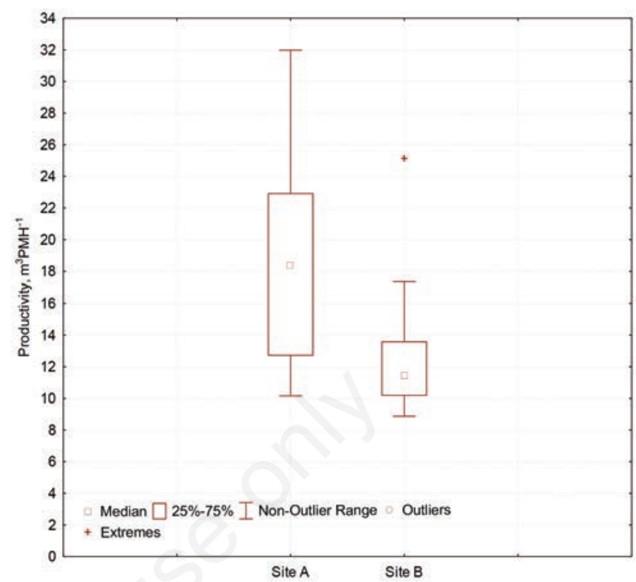


**Figure 4.** Summary statistics of the skidding productivity for the two sites. PMH, productive machine hour.



**Table 5.** Payload, productivity, and speed metrics.

| Variables | Mean value±SD | Min | Max |
|---|---|---|---|
| Load volume, m$^3$ | 3.94±0.40 | 2.60 | 4.84 |
| Site A | 3.90±0.60 | 2.60 | 4.84 |
| Site B | 3.98±1.00 | 2.70 | 4.80 |
| Pieces number | 2.20±0.40 | 2.00 | 3.00 |
| Site A | 2.10±0.31 | 2.00 | 3.00 |
| Site B | 2.30±0.47 | 2.00 | 3.00 |
| Productivity, m$^3$·PMH$^{-1}$ | 15.73±6.43 | 8.87 | 31.98 |
| Site A | 19.11±7.08 | 10.16 | 31.98 |
| Site B | 12.36±3.24 | 8.87 | 25.12 |
| Productivity, m$^3$·SMH$^{-1}$ | 13.80±5.71 | 7.35 | 27.91 |
| Site A | 16.57±6.38 | 9.00 | 27.91 |
| Site B | 11.04±3.13 | 7.35 | 22.18 |
| Number of cycles per SMH | 3.58±5.57 | 2.00 | 8.87 |
| Site A | 4.39±6.39 | 2.33 | 8.87 |
| Site B | 2.78±3.19 | 2.00 | 5.69 |
| Mean travel speed, km·h$^{-1}$ | 2.90±0.42 | 2.04 | 3.74 |
| Site A | 2.92±0.50 | 2.04 | 3.74 |
| Site B | 2.87±0.34 | 2.11 | 3.63 |
| Travel speed loaded, km·h$^{-1}$ | 2.49±0.42 | 1.69 | 3.49 |
| Site A | 2.71±0.41 | 2.08 | 3.49 |
| Site B | 2.27±0.29 | 1.69 | 2.97 |
| Travel speed unloaded, km·h$^{-1}$ | 3.62±0.83 | 1.95 | 5.33 |
| Site A | 3.24±0.79 | 1.95 | 5.33 |
| Site B | 4.01±0.68 | 2.20 | 4.95 |
| Winching speed, m·s$^{-1}$ | 0.09±0.04 | 0.03 | 0.19 |
| Site A | 0.13±0.2 | 0.10 | 0.19 |
| Site B | 0.05±0.1 | 0.03 | 0.07 |
| Road inclination, deg | 4.72±2.95 | 0.00 | 9.00 |
| Site A | 2.13±1.70 | 0.00 | 5.00 |
| Site B | 7.30±1.02 | 5.00 | 9.00 |

SD, standard deviation; PMH, productive machine hour; SMH, scheduled machine hour.

**Table 6.** Summary of the productivity models.

| Equations | | $F$ | $R^2$ | $R^2_{adj}$ | Std. error | P |
|---|---|---|---|---|---|---|
| $PPMH = 13.34 + 4.93 \cdot dt - 0.051 \cdot L + 2.58 \cdot V$ $m^3 \cdot h^{-1}$ | (7) | 87.20 | 0.91 | 0.90 | 2.06 | P<0.05 |
| $PPMH_{\_A} = 24.91 - 0.052 \cdot L + 0.99 \cdot V$, $m^3 \cdot h^{-1}$ | (8) | 40.90 | 0.89 | 0.87 | 2.52 | P<0.05 |
| $PPMH_{\_B} = 13.33 - 0.036 \cdot L + 3.10\ V - 0.24 \cdot l$, $m^3 \cdot h^{-1}$ | (9) | 26.56 | 0.85 | 0.82 | 1.39 | P<0.05 |
| $PSMH = 11.24 + 3.97 \cdot dt - 0.046 \cdot L + 2.74 \cdot \mathrm{V}$, $m^3 \cdot h^{-1}$ | (10) | 64.07 | 0.88 | 0.87 | 2.10 | P<0.05 |
| $PSMH_{\_A} = 26.23 - 0.048 \cdot L + 2.63 \cdot V$, $m^3 \cdot h^{-1}$ | (11) | 37.01 | 0.89 | 0.86 | 2.37 | P<0.05 |
| $PSMH_{\_B} = 8.19 - 0.033 \cdot L + 3.04 \cdot V - 0.20 \cdot \mathrm{l}$, $m^3 \cdot h^{-1}$ | (12) | 19.83 | 0.81 | 0.76 | 1.52 | P<0.05 |

**Table 7.** Characteristics of costs of the studied skidder.

| Costs in € | Costs per PMH | Costs per $m^3$ | % of total | Costs per $m^3$ Site A, Code 1D | Costs per $m^3$ Site B, Code 1A |
|---|---|---|---|---|---|
| Fixed costs | 13.60 | 0.86 | 25.75 | 0.71 | 1.10 |
| Variable costs | 18.68 | 1.19 | 35.56 | 0.98 | 1.52 |
| Labour costs | 15.64 | 0.99 | 29.60 | 0.82 | 1.27 |
| Net costs (excluding profit) | 47.92 | 3.05 | 90.91 | 2.51 | 3.89 |
| Gross costs (including 10% profit) | 52.72 | 3.36 | 100 | 2.76 | 4.27 |

PMH, productive machine hour.

Cost calculations were based on the assumption that companies worked all year round except for adverse weather conditions (heavy rain, deep snow, thick fog) when cutting areas are not normally accessible by wheel skidder. The hourly fixed, operating (variable) costs of the studied skidder, and the labour cost of an operator, are shown in Table 7. For downhill skidding semi-suspended stem sections of the TAF 690 PE cable skidder, the gross costs were calculated at €52.72 per productive machine hour (PMH). In the structure of the gross costs, the fixed costs (25.75%) were slightly lower than the labour (29.60%) and variable costs (35.56%). Therefore, for the productive time of the machine, the mean extraction costs were estimated at €3.36 per $m^3$. Thus, when the skidder was productive, the extraction costs were at €2.76 $m^{-3}$ and €4.27 $m^{-3}$, respectively, for the stand, Site A, and Site B. The differences in the costs for site A, characterised by code 1D *versus* more severe code 1A (Site B), led to 55% lower extraction costs. The increase of wheel skidder's productive time would lead to decreased extraction costs. These costs are lower compared to the effective cost consumptions for the Timberjack 450C cable skidder and higher than those of SAME 140 Virtus operated in salvage hardwood logging in Iran and Italy, were calculated as €70.11·$h^{-1}$ and €53.00·$h^{-1}$, respectively (Bodaghi *et al.,* 2018).

## Conclusions

Forest disturbances have caused considerable damage to European forests in recent decades, particularly in the Northern Hemisphere. Moreover, in the near future, global climate warming is expected to increase the extent of biotic and abiotic disturbances. For these reasons, post-disturbance salvage logging will become more predominant to recover economic value from timber in disturbed forests. For this purpose, this study aimed to determine the productivity and costs of a TAF 690 PE skidder in a European beech-high forest damaged by wet snow disturbance. The importance of this study and the results are mainly related to enlarging existing knowledge on the productivity and costs of salvage logging operations. The results revealed that operational costs of salvage tree extraction are higher than traditional stand cutting but necessary to recover the future economic value of the forest. In fact, salvage logging benefits can exceed the economic limit in these forests that should be managed to guarantee ecological and productive aspects.

## References


Ackerman P., Belbo H., Eliasson L., de Jong A., Lazdiņš A., Lyons J. 2014. The COST model for calculation of forest operations costs. Int. J. Forest Engine. 25:75-81.

Bodaghi A.I., Nikooy M., Naghdi R., Venanzi R., Latterini F., Tavankar F., Picchio R. 2018. Ground-based extraction on salvage logging in two high forests: a productivity and cost analysis. Forests 9:729:1-18.

Borz S.A., Ignea G., Popa B., Dinulică F. 2013: Time consumption and productivity of skidding Silver fir (Abies alba Mill.) round wood in reduced accessibility conditions: a case study in windthrow salvage logging from Romanian Carpathians. Ann. Forest Res. 56:363-75.

Borz S.A., Ignea G., Popa B. 2014. Assessing timber skidding efficiency in a group shelterwood system applied to a fir-beech stand. Afr. J. Agric. Res. 9:160-7.

Borz S.A., Ignea G., Popa B., Spârchez G., Iordache E. 2015. 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. Forest Engine. J. Theory Appl. Forest. Engine. 36:137-46.

Cadei A., Mologni O., Marchi L., Sforza F., Röser D., Cavalli R., Grigolato S. 2021. Energy efficiency of a hybrid cable yarding system: A case study in the North-Eastern Italian Alps under real working conditions. J. Agric. Engine. 52:3.

Cadei A., Mologni O., Röser D., Cavalli R., Grigolato S. 2020. Forwarder productivity in salvage logging operations in difficult terrain. Forests 11:341.

Carbaugh E., Hensle A. 2005. Farm tractor harvesting systems; college of natural resources. Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, p. 7.

Cataldo M.F., Proto A.R., Macrì G, Zimbalatti G. 2020. Evaluation of different wood harvesting systems in typical Mediterranean small-scale forests: a Southern Italian case study. Ann. Silvicult. Res. 45:1-11.

Georgiev D., Stoilov S. 2007. Wheel cable skidder productivity in selection sylvicultural system. pp 70-74 in Proc. International Symposium 'Sustainable forestry - problems and challenges', 24-26.10.2007, Ohrid, FYR of Macedonia.

Kramer K., Brang P., Bachofen H., Bugmann H., Wohlgemuth T. 2014. Site factors are more important than salvage logging for tree regeneration after wind disturbance in Central European forests. For. Ecol. Manag. 331:116–28.

Kärhä K., Anttonen T., Poikela A, Palander T., Laurén A., Peltola H., Nuutinen Y. 2018. Evaluation of salvage logging productivity and costs in windthrown norway spruce-dominated forests. Forests 9:280.

Magagnotti N., Picchi G., Spinelli R. 2013. A versatile machine system for salvaging small-scale forest windthrow. Biosyst. Eng. 115:381-8.

Olsen E.D., Hossain M.M., Miller M.E. 1998. Statistical comparison of methods used in harvesting work studies. College of Forestry, Forest Research Laboratory, Oregon State University Corvallis, OR, USA.

Orlovský L., Messingerová V., Danihelová Z. 2020. Analysis of the time efficiency of skidding technology based on the skidders. Central Eur. Forest. J. 66:177-87.

Proto A.R., Skoupy A., Macri G., Zimbalatti G. 2016. Time consumption and productivity of a medium size mobile tower yarder in downhill and uphill configurations: a case study in Czech Republic. J. Agric. Engine. 47:216-21.

Proto A.R., Macrì G., Visser R., Russo D, Zimbalatti G. 2018. Comparison of timber extraction productivity between winch and grapple skidding: a case study in Southern Italian Forests. Forests 61:3-12.

Schelhaas M.J., Nabuurs G.J., Schuck A. 2003. Natural disturbances in the European forests in the 19th and 20th centuries. Glob. Chang. Biol. 9:1620-33.

Schmiegelow F.K., Stepnisky D.P., Stambaugh C.A., Koivula M. 2006. Reconciling salvage logging of boreal forests with a natural-disturbance management model. Conserv. Biol. J. Soc. Conserv. Biol. 20:971-83.

Spinelli R., Magagnotti N. 2012. Wood extraction with farm tractor and sulky: estimating productivity; cost and energy consumption. Small-Scale Forest. 11:73-85.

Spinelli R., Magagnotti N. 2011. The effects of introducing modern technology on the financial, labour and energy performance of forest operations in the Italian Alps. Forest Policy Econ. 13:520-4.

Stoilov S., Proto A.R., Angelov G., Papandrea S.F., Borz S.A. 2021. Evaluation of salvage logging productivity and costs in the sensitive forests of Bulgaria. Forests 12:309.

Stoilov S. 2021. Logging equipment in Bulgaria - current state and future prospective. Forest. Ideas 61:19-28.

Stoilov S., Krumov T. 2016. Study of wheel cable skidder productivity in West Balkan Mountains. Manage. Sustain. Develop. 61:103-7. [In Bulgarian].

Stokes B.J., Ashmore C., Rawlins C.L., Sirois D.L. 1989. Glossary of terms used in timber harvesting and forest engineering. Gen. Tech. Rep. SO - 73. U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, LA, USA, 33 p.

Thorn S., Bässler C., Svoboda M., Müller J. 2017. Effects of natural disturbances and salvage logging on biodiversity - Lessons from the Bohemian Forest. Forest Ecol. Manage. 388:113-9.

Wang J., Long C., McNeel J., Baumgras J. 2004. Productivity and cost of manual felling and cable skidding in central Appalachian hardwood forests. Forest Prod. J. 54:45-51.

Zhu Y., Liu S., Yan W., Deng D., Zhou G., Zhao M., Xie M. 2022. Impact of ice-storms and subsequent salvage logging on the productivity of Cunninghamia lanceolata (Chinese Fir) forests. Forests 13:296.