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ORIGINAL PAPER

Could timber winching operations be cleaner? An evaluation of two options in terms of residual stand damage, soil disturbance and operational efficiency

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Abstract
Forests provide multiple services, products and values and finding ways to preserve their multifunctionality is important. However, all of the currently used harvesting systems produce some degree of environmental damage, potentially affecting the provision services on the long term. Skidding operations are common in many regions of the world. Skidding may suppose three operational steps: winching, strip-road skidding and landing operations. By using cables for winching, wounds are commonly inflicted to the residual trees, while the mechanical traction of logs may cause damage to the residual trees and soil. This study was designed to check if the use of pans during winching deployed in thinning operations of coniferous forests may help lowering the environmental impact in terms of damage to residual trees and soil, while accounting for operational efficiency of such operations. Four treatments were considered and framed around the winching direction (uphill, downhill) and the use of protective devices (use, nonuse) and detailed data was collected on the residual stand damage, soil damage and time consumption. The main finding was that uphill winching by the use of a pan performed the best in terms of lowering the environmental damage. It shown the smallest wounds by their average area per tree, the lowest number of wounds per tree, the lowest rate of wounding per hectare, as well as one of the lowest rates of soil damage. By excluding delays, working with a pan did not cause additional time consumption, supporting acceptable rates of operational efficiency. Further experiments would be needed to validate and extend the results of this study, as the forests and their type of management are heterogeneous systems in terms of terrain configuration and slope, soil, species, stand density, removal intensity, operational timing and operational conditions.

Keywords Thinning · Wounds · Skidder · Pan · Damage · Residual tree · Forest operations · Factors

Introduction

Forests provide a wide range of products and services, supporting several industries and the welfare of many people around the world (FAO and UNEP, 2020). Timber procurement has been one of the common activities of the mankind in its relation with forests, with the latter providing the raw materials for the human basic needs for life (Rowell 2005). Recent trends showing an increased timber consumption pattern, a significant demographic increment and economic development may raise questions about the ability of forests to sustain timber production while still preserving their environmental values. Delivering the wood in due time to the industries or to direct consumers is one of the main requirements and challenges of the today's forest supply chains, and it is commonly supported by the mechanization

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of operations (Oprea 2008). However, timber harvesting has brought environmental damage to the forests, of which the damage to the soil and to the residual trees may have consequences both at the local and global scale. For instance, damage to the residual trees is known to affect the growth patterns and the timber value at the final harvesting stage (Vasiliauskas 2001); in turn, less growth is likely to affect other forest ecosystem processes such those related to the forest ecosystems' ability to produce oxygen and to sink carbon. Therefore, it is of a first importance to find methods and solutions able to ensure more cleaner and sustainable timber procurement operations (Heiniman, 2007; Marchi et al. 2018).

From the category of ground-based timber extraction systems, skidders are commonly used in many geographical areas (Borz et al. 2015; Proto et al. 2018; Lundbäck et al. 2021; Spinelli et al. 2021). For instance, they are commonly used in many countries of the Eastern Europe, being an important component of harvesting systems such as those including mechanized or motor-manual felling (Moskalik et al. 2017). A particular category is that of winch skidders, which are machines designed to enable, in a first step, log extraction to the machine by dragging, which is done by the use of a winch (Oprea 2008). In most of the cases, timber extraction by winch skidders is done by implementing three successive steps, namely winching, strip-road skidding and landing operations (Borz et al. 2013, 2015). Among the benefits of using a winch in a first step is that of protecting the soil, by avoiding the equipment's traffic on extensive areas of the cut blocks (Oprea 2008; Marchi et al. 2018). By doing so, however, and depending on the skid road density, an extensive cable work may be required to drag the logs to the machine, which in turn may cause damage to the residual trees, seedling and soil (Oprea 2008). Reducing the distance on which the cable work is deployed may be done by increasing the skid road density, which in steep terrain is done by earth moving (Oprea 2008; Duţă et al. 2018). However, such technical measures may produce significant post-harvesting damage by sediment transport (Duţă et al. 2018), and in some cases they may not be accepted by the forest owners. As a consequence, there will always be a trade-off between damaging the soil by building a denser network of skid roads and damaging the trees by cable work, since the manual-mechanical control over the winched logs is difficult to maintain on long winching distances, particularly in steep terrain. One of the measures to keep the motion of the logs under a relative control during winching in steep terrain consists of winching them uphill (Oprea 2008). However, this would work under the assumption of winching the logs on the line of highest gradient, which does not hold true in all the situations found in practice, therefore some motion control loss will occur. Such events may increase the extent and severity of the damage to residual trees, in addition to that caused by the use of tensioned cables. Furthermore, dragging the logs in full contact with the soil, as well as rolling and uncontrolled sliding, may cause soil disturbance. To mitigate this last effect, the solutions are those of using cones, pans or similar protective devices, built from lightweight materials such as metal alloys or plastic polymers (Oprea 2008; https://woodlot.novascotia.ca/content/lesson-four-accessories-and-other-equipment-options). One just may assume that such devices will facilitate also the log motion by decreasing the friction between the log and the soil. Although experienced in the past, the solution is seldom used in the international practice if not used at all. At least in Romania, no evidence was found of using this technical option with the intended aim of protecting the soil. On the one hand, this could be because the contractors need to invest in additional equipment while nobody could guarantee that their operational efficiency will be preserved if not increased, which is fair if one thinks about the effect of productivity drops on costs. On the other hand, cable work has been repeatedly found to be particularly difficult in steep terrain (Kirk and Sullman 2001; Stampfer et al. 2010; Ottaviani et al. 2010; Magagnotti and Spinelli 2012; Spinelli et al. 2014); therefore, one reason of not using such devices could be related to the willingness of the contractors and their employees to work with additional weight. Last but not least, the supplementary knowledge which might be needed to operate with of such devices, as well as the missing examples in practice, could be among the limiting factors which contribute to keeping the business as usual.

Based on the above, this study was designed with the aim of evaluating the effects of using a pan during winching on the soil and residual tree damage, while accounting also for operational efficiency. In particular, it was assumed that (1) using a pan will help in lowering the soil disturbance by log dragging, (2) using a pan will produce less damage to the residual stand caused at least by log rolling, and (3) differences will occur as an effect of winching direction, and uphill winching using the device will perform the best in terms of soil and residual stand damage.

Materials and methods

Study location and site description

Study location was chosen based on a set of criteria. A first criterion was that of finding a company willing to support the study and its design, therefore to use a pan during the work, in a comparative test, and to allow direct observations on its workers during the operations. Once a company was found as willing to support the study, discussions were carried out to find and establish a field study location meeting the most difficult conditions in terms of terrain slope (up to the limit at which skidding operations are commonly done in Romania). Furthermore, a Norway spruce (*Picea abies* Lam.) dominated stand was chosen for the study, mainly due to the species susceptibility to mechanical damage (Vasiliuskas, 2001), and thinning operations were selected for study due to their typical operational feature of working in dense stands. Table 1 shows the main description of the site, vegetation and timber extraction parameters.

The study was carried out in the forest compartment 565A, which is located at approximately 46° 35′ 55″ N–26° 13′ 21″ E, 610 m a.s.l., and which is a part of the forest management unit III Camenca. The forests in the area of study are managed by the Comăneşti Forest District, being composed of various coniferous and broadleaved species. A number of 3937 trees were marked for extraction on the entire area of the forest compartment, which was planned for thinning operations by the personnel of the forest district. This resulted in an extraction intensity of ca. 281 trees ha^{-1} or ca. 56 m^3 ha^{-1}. The harvesting system planned for the compartment taken into study consisted of motor-manual felling, delimbing and topping and skidding using a winch skidder. Typically, winch skidders are used in Romania to carry on three types of operations, namely winching, strip-road skidding and landing operations (Oprea 2008; Borz 2014), an operational approach which was followed in this study; however, the focus of the study was only on the winching operations.

Pre-operational data collection

Several steps were taken to collect the field data prior to harvesting operations. One of them referred to the identification of a suitable area for the field tests. The aim was to get as much as possible homogeneous conditions in terms of slope, standing stock and removal intensity, as well as to account for the possibility to delimit the four test plots while accounting for the use and nonuse of the protection device and for the winching direction (downhill and uphill). However, this step was constrained by the geometry and location of the existing skidding road. A suitable area was identified and it was delimited in the field by preliminary measurements and tree marking by paint; then, it was divided in four plots sharing at one edge the skidding road. Once all the plots' boundaries were established and marked by paint, a GPSmap® 62stcGPS (Garmin Ltd., https://buy.garmin.com/ro-RO/RO/p/89557) unit was used to delimitate the four plots by field measurements and to collect the data needed for the location of the skidding road. Figure 1 shows the location and shapes of the delimited plots, as well as the location of the skidding road.

A full pen-and-paper tree inventory was carried out in each test plot prior to the harvesting operations. Each tree was given an identification number which was painted at a visible place on two sides, then the diameter at the breast height (DBH, cm) was measured to the nearest 2 cm, and tree species was visually evaluated and noted. In addition, descriptive codes were given to differentiate between

Table 1 Site, vegetation and harvesting system description

Category	Parameter	Measurement unit	Average value
Site	Altitudinal range	m a.s.l	600–1050
	Aspect	–	Northwestern
	Average slope	°	25
	Total area	ha	14.0
	Area taken into study[a]	ha	0.841
Vegetation	Flora	–	*Asperula-Oxalis*
	Dominant species	–	Norway spruce and Silver fir
	Stand density	–	0.9
	Average DBH[b]	cm	26.6
	Average tree height	m	18
	Average tree volume	m^3	0.20
	Volume for extraction	m^3	788
	Extraction intensity	m^3 ha^{-1}	56.29
Extraction	Silvicultural system	–	Thinning
	Harvesting method	–	Tree length
	Harvesting system	–	Chainsaw + cable skidder
	Extraction direction	–	Downhill

[a]Area taken into study refers to a portion of the total area of the forest compartment which was delimitated for the purpose of this study; [b]refers to the area taken into study and it was computed based on the inventory done during the study. The figure on area taken into study is based on office calculation using GPS data collected in the field and the open source QGis software

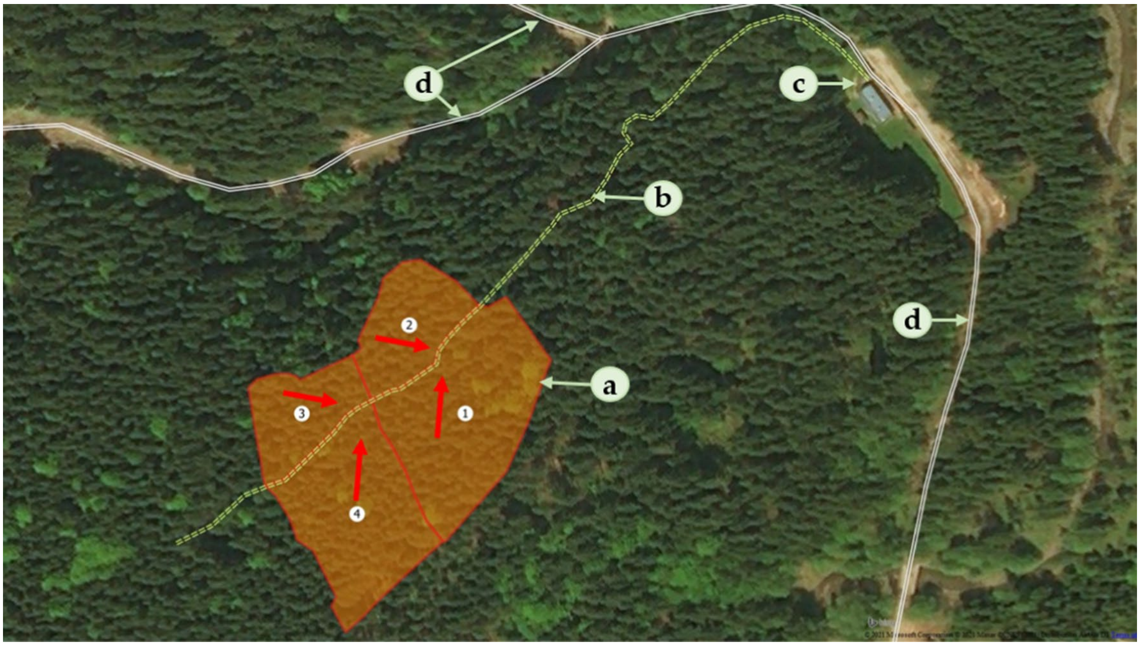

Fig. 1 Study area showing the four delimited test plots, the skidding road used for extraction, location of the landing and the main forest road network in the area. Legend: **a**: area of study, delimited from the forest compartment, where 1 is the test plot 1 (TP1), 2—test plot 2 (TP2), 3—test plot 3 (TP3) and 4—test plot 4 (TP4); **b**: skidding road used for extraction, **c**:location of the landing; **d**: forest roads. Red arrows indicate the dominant winching direction as observed in the field. Figure was developed by the use of open source QGis software in conjunction with GPS collected data and freely available imagery provided by Bing® (Bing® aerial)

the individuals proposed for extraction and residual trees, which was based on the visible tree-marks made by the forest district's personnel. Location of each tree was estimated mainly relative to the skidding road. For that, the perpendicular distance from the tree to the skidding road was measured for each tree. Measurements were done from the road toward the trees using a combination of instruments. Distances higher than 20 m were measured by the use of a Nikon Forestry Pro ® (Nikon Romania, https://www.nikon.ro/ro_RO/) laser rangefinder, while distances less than 20 m were measured by a graded tape.

Each tree was carefully inspected so as to identify previous wounds, if any. A similar procedure was used to inspect the condition of the soil, by a visual evaluation to check if there were damaged areas in the test plots. No previous damage to the trees or disturbed soil portions were identified in this phase of the study. Actually, the soil was a Distric Cambisol showing uniform conditions at the surface and on several areas herbaceous vegetation was present. This soil type accounts for an important share in the Romanian mountains as well as in other regions, being typical for those forests made of coniferous species. The average slope of each test plot was estimated in the office phase of the study based on measurements taken in the field by the use of the laser rangefinder. All the inventory data was noted in a field book designed for this purpose, and the GPS collected data was saved in the used unit, concluding this way the end of the first field study phase.

Data collected during the operations

Data collected during the winching operations was that referring to the parameters needed to estimate the operational efficiency for comparison purposes and it was provided by the implementation of a time study. A number of 36 work cycles were observed in TP1 and TP2, where the pan was used, and a number of 25 work cycles were observed in TP3 and TP4, where the extraction was done without a pan. During the collection of time study data, a number of 42 trees were extracted in TP1 and TP2, and the same number of trees (42) were extracted in TP3 and TP4 (some work cycles included 2 or 3 trees winched together), respectively. The time study concept was adapted to the guidelines developed for forest operations (Acuna et al. 2012; Björheden et al. 1995; Cataldo et al. 2020), by assuming the concepts and a division of a work cycle in the elements given in Eq. (1). To enable the comparison of data, all the delays were excluded from the study at the field data collection stage; therefore, the work cycle time given in Eq. (1) stands for the delay-free work cycle time. Measurements were taken by the use of the continuous chronometry method, and the data were noted on a field book along with the identification number of the trees extracted in each work cycle. For each work cycle, the winching distance (hereafter wd) was measured using the same instruments described in "Soil impact" section.

$$\text{Cycle Time} = \text{Release} + \text{Attach} + \text{Winch} + \text{Adjust} + \text{Detach} \quad (1)$$

where:

(1) *Cycle Time* is the time of a work cycle framed around one (dominant procedure) to three stems extracted at once by including a single cable release from the skidder to the felling place and a single mechanical traction of the load from the stump to the skidder. The delay-free work cycle time was calculated in the office phase of the field study, by summing up the elemental time consumptions;
(2) *Release* is a work element consisting of the worker movement with the cable (and the pan when the case) from the rear part of the skidder to the place at which the stems were attached to the cable. It started when the worker has grabbed the cable and it ended when the worker reached the location where the stems were attached;
(3) *Attach* is a work element consisting of the worker attaching the stems directly to the cable or by using the pan. It started when the worker reached the location where the stems were attached to the cable and it ended when the stems were attached to the cable;
(4) *Winch* is a work element consisting of mechanical (cable-based) traction of the stems after attaching them to the cable;
(5) *Adjust* is a work element consisting of the worker adjusting the pan during winching and it was specific to the operations taken in TP1 and TP2 even though it occurred only in ca. 36% of the observed work cycles. It consisted of the measures taken by the worker to replace/readjust the pan over the end of the stem at which the cable was attached. It is worth to mention that irrespective of the case, one of the worker's tasks was to follow the stems during mechanical traction so as to intervene when they were blocked by various obstacles. In addition, the worker was required to follow the stems so as to detach them in the rear part of the skidder;
(6) *Detach* is a work element consisting of the worker detaching the stems (and the pan) at the rear part of the skidder, supposing that the cable will then be used for a new winching work cycle. For most of the observed work cycles (60 out of 61) this work element was done.

Figure 2 shows the pan used in this study by a snapshot taken during the operations; it was a pan made by Northern Tool company (Portable Winch Skidding Cone, 2021), model PCA-1290, which features a length of 62 cm, an aperture of ca. 51 cm, a thickness of the material of 8 mm, a mass of ca. 5 kg and a cable hole. As the producer claims, this device could be used to prevent the dragged logs from being obstructed or damaged by roots, stumps or residual

Fig. 2 A snapshot during the winching operations showing the pan used and the layout of the trees marked before the operations

trees, being made by high-performance polymer plastic. In addition, it could contribute to getting cleaner logs due to the fact that one of their ends is protected; therefore, dirt is prevented to attach to the winched logs. Extraction operations were carried out in April 2020 in conditions of a good weather, clear sky and no serious concerns in terms of excessive soil moisture. As a fact, the soil was characterized by a good operational condition during the operations, and the operations were surveyed in 3 days.

Post-operational data collection

Data collected after the operations aimed mainly at quantifying the extent of damage to the residual trees and soil. Damage to the residual trees is commonly examined in terms of wounds' size and severity (Vasiliauskas 2001), and there are several factors known to affect their variation. Therefore, a careful examination of the test plots was taken to:

1. Identify all the wounded trees and their identification numbers (Fig. 2);
2. Count the number of wounds per tree, hereafter NWT;
3. Measure the maximum height and width of each wound to be able to calculate the area of each wound, hereafter WA. The maximum height and width of each wound was measured by a graded tape to the nearest centimeter and the calculation of the WA assumed a rectangular shape of the wound;
4. Measure the distance of each wound from the soil, hereafter WH. Measurement was done by the use of a graded tape to the nearest centimeter;
5. Evaluate the wound severity in two classes: bark removed only (B) and cambium affected (C).

Soil disturbance is often a complicated problem to assess. There are several accounting methods, disturbance classification systems, all of them with strengths and weaknesses (Borz 2014). Their main aim is to evaluate the extent and severity of the impact and may start from simple visual ones and end to the most-advanced sensing-based quantifications (Talbot and Astrup 2021). In this study, a simple method, based on systematic sampling, was used to account for soil disturbance, having in mind that only the displacement of the organic layer was in question as a distinctive feature between the operational alternatives. Figure 3 shows the main layout and equipment used in the field.

Soil damage was evaluated by placing a rope in a layout of parallel straight lines so as to keep their equidistance at ca. 10 m and their orientation as much as possible parallel to the width of the test area. By doing so, the main winching directions were intersected by the ropes. The rope was prepared in advance so as to have consecutive parts of 1 m in length each, painted alternatively in red and yellow (Fig. 3). Evaluation of the soil impact considered two categories, namely disturbed (organic layer or part of it was displaced as a consequence of the winching operations, hereafter D) and undisturbed (non-touched soil, soil covered by vegetation as well as touched soil without removal of organic layer or parts of it, hereafter U). Evaluation was done by a visual examination aimed at quantifying the absolute length on which the two categories occurred along the rope. When a category was found, following the examination, the

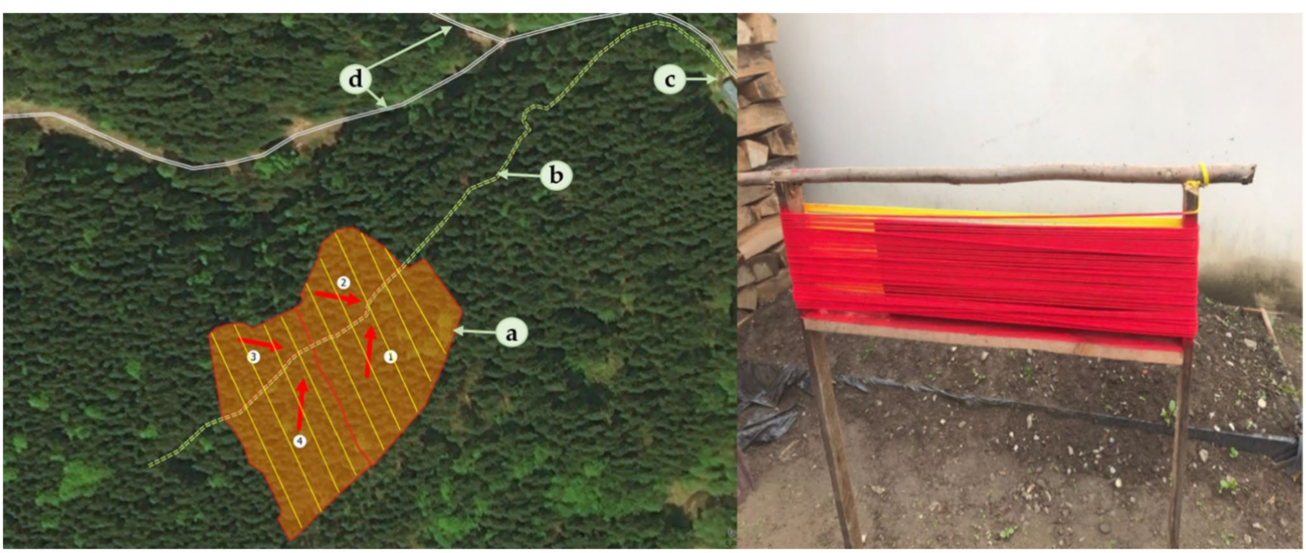

Fig. 3 The concept used to systematically evaluate the soil impact. Left: meaning of 1, 2, 3 and 4 is TP1, TP2, TP3 and TP4; **a**: boundary of the plots; **b**: skidding road; **c**: location of the landing; **d**: forest roads; red arrows indicate the main winching direction and yellow lines indicate the approximate setup of the rope in the field to collect the data; Right: preparation of the rope for field sampling

length (length of disturbed soil, hereafter LD or length of undisturbed soil, hereafter LU) on which it occurred was accounted and rounded to the nearest 10 cm. As indicated in Fig. 3, a number of 5 repetitions were done in TP1 and TP2 and a number of 4 repetitions were done in TP3 and TP4, respectively. Once a repetition was done, wooden sticks were placed along it to serve as a reference for placing the rope on the next location.

Data processing

As most of the data were collected in paper format, a first data processing step was that of building an electronic database to summarize the field-collected data. Since many of the field-collected data required further computation, the software used to build the database was Microsoft Excel® (Office 2013, Microsoft, Redmond, WA, USA). Data collected via GPS was transferred as GPX files into a personal computer, then the QGis open source software (QGis, version 2.14.0, https://www.qgis.org/en/site/) was used for mapping purposes, to calculate the areas of the test plots and to produce part of the artwork used in this study. Damage to residual stand was evaluated by the means of several indicators. Besides the area of the test plots (hereafter A) and the average terrain slope within them (hereafter S), several other indicators were either counted or computed. The number of trees per hectare (hereafter TPH) was computed as the ratio of the number of initial trees (inventoried trees, hereafter IT) to the area of each test plot (Eq. 2). For each test plot, the number of removed trees (hereafter RT) was counted from the data collected prior to the operations and checked against the situation from the field, then the number of residual trees (hereafter FT) was calculated as the difference between IT and number of removed trees. The number of damaged trees (hereafter DT) was accounted from the data collected after the operations, along with the data on their diameter at the breast height (DBHD). Based on the above, Eqs. (3) and (4) were used to account for the extent of damage as the share of damaged trees to the residual trees (hereafter SDT) and as the ratio of the damaged trees to the area of the test plot (hereafter SDH).

$$\mathrm{TPH}i = \mathrm{IT}i/\mathrm{A}i \tag{2}$$

$$\mathrm{SDT}i = \mathrm{DT}i/\mathrm{FT}i \times 100 \tag{3}$$

$$\mathrm{SDH}i = \mathrm{DT}i/\mathrm{A}i \tag{4}$$

where: i stands for the identification number of the test plot ($i = 1$–4).

The number of wounds per tree (hereafter NWT) was calculated as the ratio of the number of wounds (NW) to the number of damaged trees (DT) in each plot. Wound area (WA) was calculated as the average figure for each test plot, by considering the total wounded area and the number of wounds. The same procedure was applied to get the average height of the wound above the soil. Share of damaged trees in relation to their species (SSD) was evaluated by counting them on the two species for each test plot. The same procedure was applied to account for wound severity (WS).

To enhance comparisons in terms of tree location and test plot, the data were further ordered so as to account for the number of the damaged trees (DT) in relation to their distance to the skidding road. Also, to enhance the comparisons in terms of wounding severity, the data characterizing the size of the wounds was organized on severity categories (B—bark removal, C—cambium affected, and overall—O, respectively, which grouped the frequency on all the severity categories) by considering the test plot to which it belonged. A similar data processing procedure was used to organize the lengths (LD, LU) and the shares (%D, %U) of disturbed soil on test plots and at the study site level. Time study data were included in the database at the elemental level, then the cycle time was calculated according to Eq. (1). Elemental and work cycle time consumption data was then organized for the two technical options: with and without using a pan.

Data analysis

Descriptive statistics were computed for most of the parameters characterizing the damage to the residual trees (DBHD, NWT, WA, WH) at the test plot and site levels. The same levels of analysis were considered for describing the relative frequencies of damage by considering the species (SSD) and the wound severity (WS). The number of damaged trees (DT) was used as an absolute figure to check if there was a pattern in relation to the distance from the skidding road. For this task, a graphical approach was taken to plot the wounded trees in relation to their distance to the skidding road, and then the share of the damaged trees was calculated and plotted on distance categories, from 0 to 45 m, using a category size of 5 m. This methodological step considered the relative values calculated as the ratio of the damaged number of trees found in a category to the total number of damaged trees found in the test site, followed by a breakdown of the data on tests plots, which was also given in relative figures. Nonparametric statistical tests assuming independent samples (Mann–Whitney, U) were used to compare the data on the number of damaged trees (DT) and wounded area (WA), assuming a confidence set at 95% ($p < 0.05$). The choice of this test was based on the type of data to be compared, which was both discrete (i.e., DT) and continuous (i.e., WA), the type of comparison (the design was unbalanced with no chances to control this issue a priori or a posteriori) and the predictable failure of the data to follow a normal distribution, which was assumed based on the descriptive statistics computed for all the datasets. Comparison was done pairwise, so as to check the eventual statistical differences between the data coming from each test plot against that coming from each other test plot. As such, six tests were carried out for the DT data and six tests were carried out for the WA data. A similar procedure was used to compare the data on soil impact using as inputs the LD and LU variables at the test plot level, which was complemented by a description of the data in terms of absolute and relative frequency.

As mentioned before, the data describing both the local conditions (area, slope and number of trees per hectare), pre- and post-operational conditions (number of initial trees, number of removed trees, number of residual trees, number of damaged trees) as well as the data characterizing the location, extent and severity of the damage (7 variables) was very wide in terms of number of variables. In addition, there were four operational options to be compared so as to find the best one in terms of reducing the damage to residual stand. For that reason, a data dimensionality reduction was necessary in order to see the main trend. The main statistical approaches for dimensionality reduction are the principal component analysis (PCA) and the correspondence analysis (CA). The latter was chosen as a technique to infer potential dependencies among the data and to associate the operational options to the variables described above, based on the fact that some of the data were categorical and nominal. As a guidance for running the correspondence analysis and interpreting the data, the worked example given in Bendixen (2003) and explanations of Correspondence Analysis Basic Concepts (2021) were used.

Analysis of the time study data was based on the development of the main descriptive statistics such as the mean and standard deviation values. A rough comparison between the treatments (with and without the use of a pan) was done based on the relative figures without the implementation of any kind of statistical tests. This data analysis step was based on graphical representations of the data. Since the average winching distance was found to be different in the four testing plots, further analyses were run to check and compare the differences in terms of time consumption per meter and the speed, as more relevant descriptors for comparison. These metrics were computed for *Release* and *Winch* work elements, as described in Eq. (1), by considering the data grouped in two treatments: with and without using a pan. Statistical analysis and most of the artwork and tables given in this study were done by using the Microsoft Excel® software (Office 2013, Microsoft, Redmond, WA, USA). Comparison tests and the correspondence analysis were implemented by using the RealStatistics ® add-in (Real Statistics Using Excel 2022).

Results

Damage to residual stand

Table 2 shows the main descriptive statistics characterizing pre- and post-harvesting conditions in terms of damage to residual trees, along with the terrain and stand conditions. The average slope was found to be rather similar in TP1 and TP2, as well as in TP3 and TP4. Also, TPH was similar in TP3 and TP4, but different in TP1 and TP2. As these were factors imposed by the local conditions, keeping them under control was difficult. A total number of 666 trees in the area were taken into study, of which 84 were removed and 582 remained. As a number of 62 residual trees were found to be damaged, the global share of the damage by considering the residual trees (SDT) was of ca. 11%. However, there were differences in terms of SDT among the test plots (Table 2). Surprisingly, the highest SDT was found in TP2, for which the expectation was to have the lowest tree damage. However, this figure could be attributed to the lowest number of residual trees in this test plot rather than to the environmental performance of operations. This can be seen if one considers the damage as the ratio of damaged trees per hectare (SDH), for which the results of the TP3 and TP4 have shown the worst situation.

The benefits of using a pan may be judged by analyzing the rest of the indicators characterizing the residual tree damage. For instance, both the number of wounds and the average wound size per damaged tree were the lowest in the case of TP2, which was characterized by uphill winching. However, the highest number of wounds per tree was found in TP1, which may be the effect of favoring the tree uncontrolled sliding and rolling, including by the use of the pan. In terms of average wound size, however, the highest figures were found in TP3 and TP4, where the operations were done without a pan. Wound severity was similar in TP1 and TP2 but somehow different in TP3 and TP4. However, the uphill winching without a pan caused less damage in terms of severity. On average, the wounds were located in between ca. 15 and 50 cm above the soil, but there was a difference caused by the direction of winching and probably the slope of the test plots. For downhill winching the wounds were found to be located at an average height of ca. 15–18 cm above the soil, while for uphill winching they were located at ca. 34–44 cm above the soil.

Figure 4 shows the statistics of damaged trees in terms of their location relative to the skidding road. For comparison purposes, the main statistics describing the winching distance were included as well. More injured trees were observed closer to the skid road. However, their

Table 2 Descriptive statistics characterizing the damage to residual trees

Test Plot (treatment)	Area (ha)	Slope (°)	TPH	IT	RT	FT	DT	DBHD (cm)	SDT (%)	SDH	NWT	WA	WH	SSD	WS
TP1 (downhill, protected)	0.31	21	771	223	25	198	15	30.93 (±8.58)	7.58	47.17	1.60 (±0.74)	773.6 (±707.1)	17.73 (±16.45)	40S60F	60B40C
TP2 (uphill, protected)	0.13	23	565	73	17	56	11	26.91 (±5.01)	19.64	82.09	1.18 (±0.40)	377.2 (±328.8)	36.73 (±42.12)	82S18F	64B37C
TP3 (uphill, unprotected)	0.11	27	966	115	14	101	11	26.00 (±6.93)	10.89	92.44	1.36 (±0.50)	913.4 (±1154.3)	43.64 (±55.52)	45S55F	91B09C
TP4 (downhill, unprotected)	0.27	26	944	255	28	227	25	30.04 (±7.24)	11.89	92.59	1.44 (±0.77)	873.4 (±789.6)	15.32 (±21.86)	60S40F	68B32C
OVERALL	0.84	24	792	666	84	582	62	–	10.65	73.72	1.40	734.4	28.36	57S43F	71B29C

TPH trees per hectare, *IT* number of initial trees, *RT* number of removed trees, *FT* number of residual trees, *DT* number of damaged trees, *DBHD* diameter at the breast height of the damaged trees, *SDT* share of damage by residual trees, *SDH* number of damaged trees per hectare, *NWT* number of wounds per tree, *WA* wounded area, *WH* wound height above the soil, *SSD* share of damage on species, *WS* wound severity

distribution as a function of the distance to the skidding road was heterogeneous at the test plot level. The distribution of wound size on severity categories is shown in Fig. 5, in a comparison approach. At overall level (O), the lowest damage was found in TP2 (uphill winching using a pan), with an average figure of the wound size of 377 cm^2. Next in line was the downhill winching using a pan (TP1), with an average wound size of 774 cm^2. Uphill and downhill winching without a pan produced the highest damage to the residual trees in terms of wound area (TP3 = 913 cm^2, TP4 = 873 cm^2).

As a general rule, wound severity class was associated with the wound area. Therefore, the higher the wound size the higher the severity class. However, the use of a pan has led to less wound sizes included in higher severity classes compared to the situations in which it has not been used. For instance, in the case of downhill winching, those wounds for which the cambium was found to be affected were characterized by an average area of approximately 1.4 times higher when not using a pan. The results of the statistical comparison tests run on the number of wounded trees having as a factor the operational option (TP1-TP4) revealed no significant differences; however, the results of the same statistical comparison test run on the area of the wounds as a variable revealed significant one-tail differences when comparing the TP2 and TP4 ($p_{onetail} = 0.031$, $p_{twotail} = 0.061$) and were close to do so also when comparing TP1 against TP2 ($p_{onetail} = 0.054$, $p_{twotail} = 0.109$), showing that the wound size was somehow different in TP2 (uphill winching using a pan).

The main results of the correspondence analysis are given in Fig. 6. The correspondence analysis considered 27 degrees of freedom (3 × 9) coming from the test plots (TP1, TP2, TP3 and TP4, 4–1 = 3 degrees of freedom) and the variables taken into study (10–1 = 9 degrees of freedom). At a confidence level of 5%, the critical value of the χ^2 test is 16.151, while the χ^2 test itself has an output value of 136.17, therefore indicating a significant dependency between the TPs and the variables. Contribution of the first two factors to the total inertia was of 79.24 and 14.27%, respectively; therefore, they were kept for further analysis since their cumulated contribution was of ca. 94%, preserving most of the information coming from the original data in just two dimensions.

If one considers the TP1-TP4 variables, for which the computed inertias were, in order, of ca. 0.21, 0.60, 0.09 and 0.10, then it is obvious that the contribution of TP2 (uphill winching with protective device), had a high significance than that expected by a random distribution. Figure 6 shows some of this information, placing TP2 well outside the group of TP1, TP3 and TP4, as separated by the first factor. In what concerns the second factor, TP3 was found to be placed at a higher distance compared to the group formed by TP1, TP2 and TP4. In what concerns

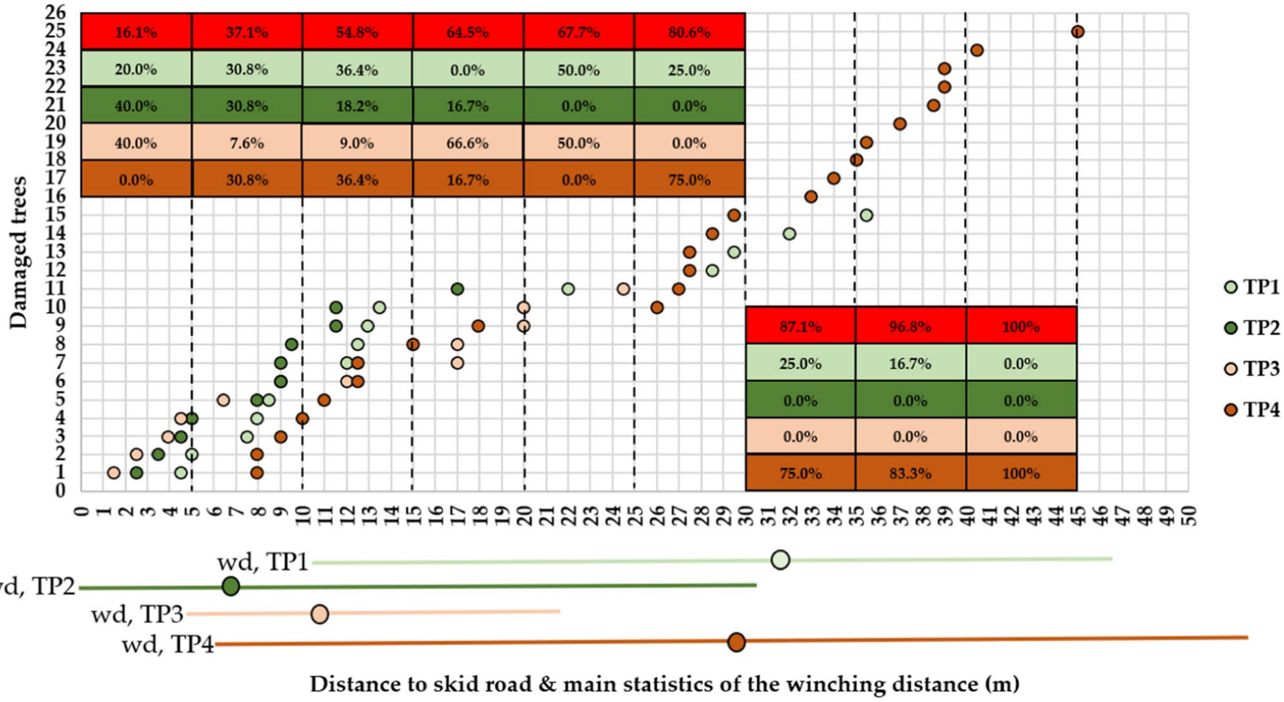

Fig. 4 Absolute and relative distribution of damaged trees in relation to their distance to the skidding road. Legend: TP1–TP4 stand for the test plots 1–4, figures given in red boxes stand for the global shares in relation to the distance to the skidding road, figures given in light and dark green and brown boxes stand for the shares of damaged trees in each test plot for a given category of distance to the skidding road. Winching distance (wd) of each test plot (TP1–TP4) is given for comparison in terms of minimum (left end of the lines), maximum (right end of the lines) and average value (circle on the line).

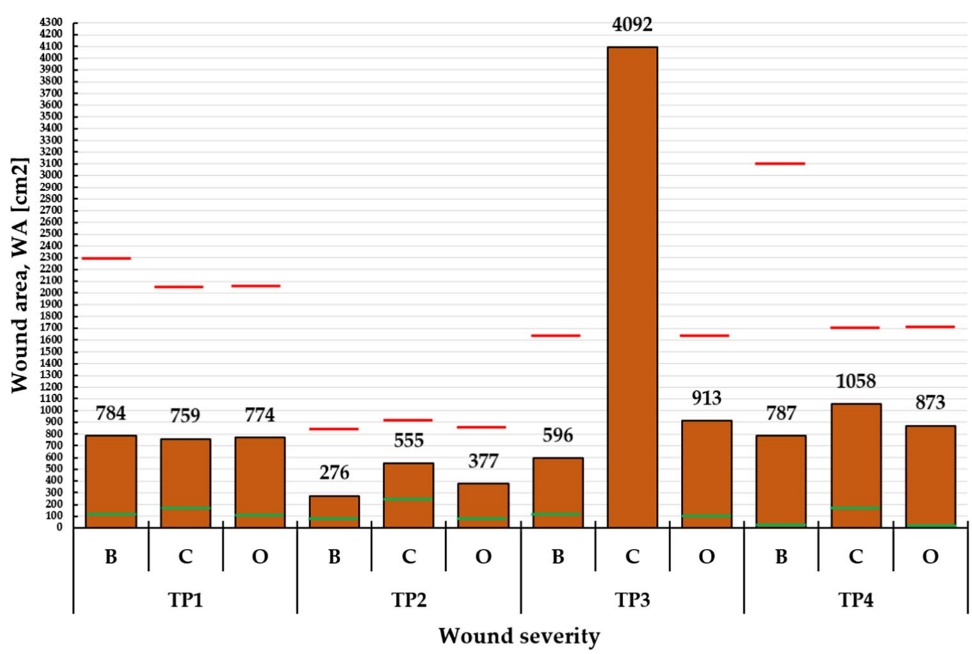

Fig. 5 Distribution of wound sizes on severity classes. Legend: B: bark removal, C: cambium affected, O—overall, columns indicate the average value, green lines indicate the minimum value and red lines indicate the maximum value; TP1–TP4 stand for test plots 1–4. In TP3, only one tree was found in C class, showing the highest wound size (4092 cm^2).

the column profiles (variables), the highest inertias were found for WH (1.52), WA (1.44), SDH (1.31) and SDT (0.93). Wound area (WH) seems to be set apart from the rest of the variables by the first factor, while the wound height above the soil was set apart from the rest of the variables by the second factor. As such, the main finding of the correspondence analysis was that TP2 was distinct from the rest of test plots, accounting for most of

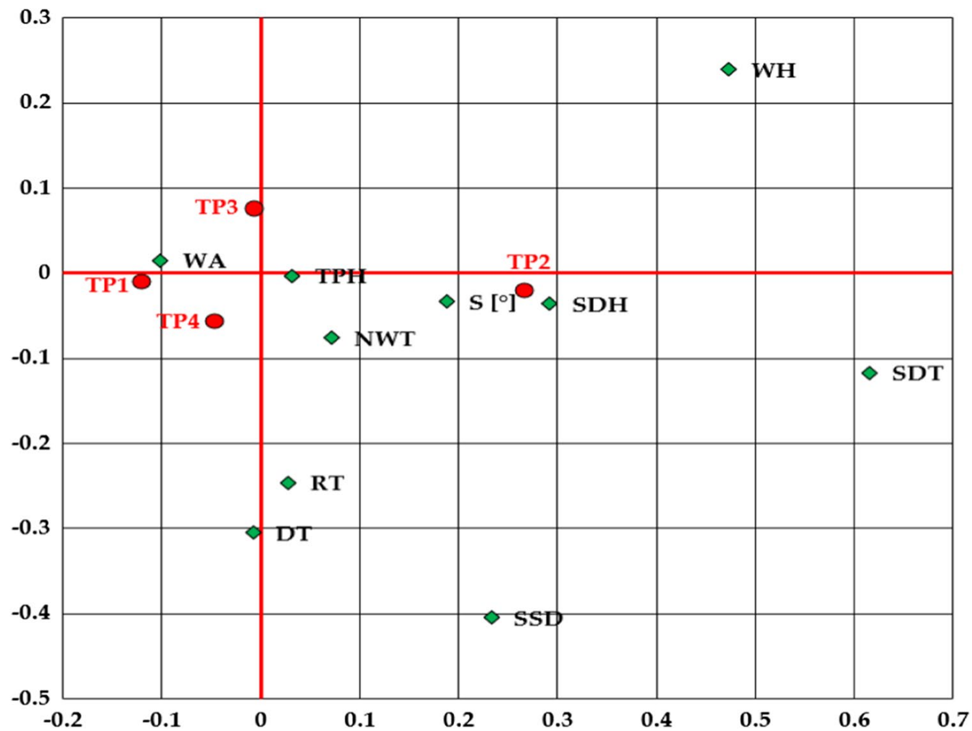

Fig. 6 Results of the correspondence analysis given as a combined plot against two main factors (red lines). Legend: the red vertical line stands for the first factor and the red horizontal line stands for the second factor; TP1–TP4 stand for test plots 1–4; TPH—trees per hectare, RT—number of removed trees, DT—number of damaged trees, SDT—share of damage by residual trees, SDH—number of damaged trees per hectare, NWT—number of wounds per tree, WA—wounded area, WH—wound height above the soil, SSD—share of damage on species, S(°)average slope of the test plot

the inertia of the first factor which captured most of the variation (ca. 80%).

Soil impact

The situation of TP3 showing the highest damage to the residual trees was preserved also when analyzing the soil disturbance. Figure 7 shows the main statistics related to the evaluation of the soil disturbance. The total length covered by the rope layout was of ca. 544 m, resulting in a sample rate of ca. 0.07 m/m^2. However, the total covered length was different in the TPs due to their area and shape.

TP1 and TP2 have shown ones of the lowest soil disturbance rates, which were of 22.3 and 23.3%, respectively. While the expectation was that of having less damage to the soil in TP2, one has to consider also the fact that in TP1 were removed considerably less trees per hectare (78) compared to TP2 (127), a fact which may have affected the

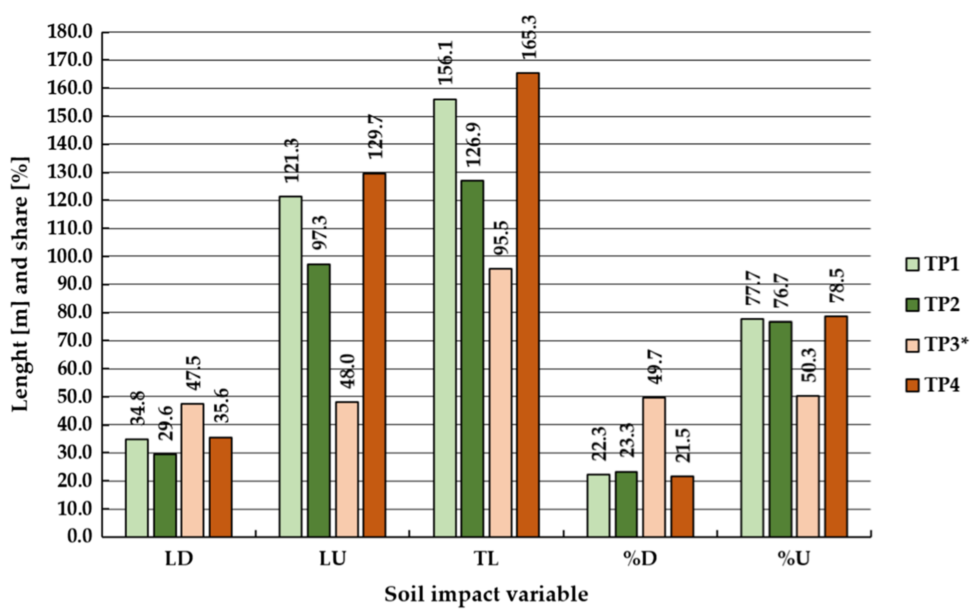

Fig. 7 Summary statistics characterizing soil disturbance Legend: TP1–TP4 stand for test plots 1–4, LD—length on which soil disturbance was observed, LU—length on which the soil was found to be undisturbed, TL—total length, %D: share of disturbed soil, %U: share of undisturbed soil. *denotes significant differences in terms of soil disturbance when compared to each other test plot

results. However, soil disturbance in these two test plots was considerably lower if compared, for instance, against that of TP3, which was found to have close to 50% of the soil disturbed. Having a soil disturbed on ca. 22% in TP4 (downhill winching, unprotected), which was comparable, for instance, with that from TP1 (downhill winching, protected), may also be a consequence of a lower number of trees extracted per hectare if compared to TP2 and TP3. From this point of view, it should be noted that TP2 was characterized by the highest number of trees extracted per hectare (127) and still, the results in terms of soil disturbance were among the best. As such, the results of the statistical comparison tests have revealed significant differences in those instances in which a compared pair has included TP3. No statistically significant differences were found when comparing to each other TP1, TP2 and TP4 (Fig. 7).

Time consumption

After the exclusion of delays, the total observed time accounted for 17,209 s (ca. 4.8 h), out of which ca. 2.1 h were characteristic to the observation of operations done with the pan. Delays were caused mainly by interruptions of personal, mechanical and organizational nature; therefore, they were excluded to support data comparison. Table 3 shows the main descriptive statistics (mean and standard deviation values) of time consumption on work elements along with the main operational variables such as the average slope and winching distance. Taken together, the operational conditions from TP1 to TP2, on the one hand, and from TP3 to TP4, on the other hand, were rather similar. The average winching distance (wd) was of ca. 21 and 23 m for the two groups of test plots. The slope was higher by ca. 5° in the second group, but it stands for the slope of the test plots and not to that on the winching direction.

The same number of trees was extracted in each test plot group (42 in each). However, the number of work cycles observed in TP1 and TP2 was considerably higher compared to TP3 and TP4. The reason for grouping the first two and the last two test plots was mainly that related to the main treatment (protected vs. unprotected), for which a difference was foreseen at least due to the need to place the pan on the cable. However, the number of work cycles observed in each TP, which in some cases was low, was also considered for this grouping to make the analysis more balanced. As shown in Table 3, the *Adjust* work element was specific and found only in the case of TP1 and TP2 (36% of the work cycles), averaging 22 s. Work cycle time was considerably lower when the operations were carried out by the means of a pan. As the average winching distance was similar in the two groups of test plots (Table 3, protected vs. unprotected), among the factors that could have been produced considerably lower work cycle times in the first group could be the density of the stand in these plots (less trees per hectare before operation, Table 2) and the general slope in the test plot groups (Table 3). It is worth to note that the average winching distances were similar in T1 and T4 and in TP2 and TP3, respectively (Fig. 4), being a reflection of these plot sizes. Cable releasing took, in average, considerably less time when the pan was used, which may come as a surprise, but this figure is also related to the distance covered by the worker and to the factors mentioned above. Stem attaching to the cable took ca. 2 times more when the pan was used, which reflects the need to pass the cable through the device's front hole. Stem detaching, on the other hand, yielded about the same average time consumption irrespective of the case.

Figure 8 shows a breakdown of the time consumption on work elements in terms of relative figures. In both treatments, cable releasing accounted for about the same share (ca. 30%). However, considerable differences were found for stem attaching, mechanical traction (*Winch*) and stem detaching at the rear of the skidder (*Detach*), with the highest differences being those found in the case of *Winch* work element. For a better comparison, two additional indicators were computed, accounting for the *Release* and *Winch* work elements, namely the average time spent by the worker (*Release*) or by the stem (*Winch*) to move one meter (s/m) and the speed at which the *Release* and *Winch* work elements were done (m/s). These were computed as ratios by considering the total amount of time and the cumulated winching distance on a given treatment and work element.

The first indicator yielded values of 3.07 and 5.00 s/m for the *Release* work element in the case of first (TP1 and TP2, protected) and second (TP3 and TP4, unprotected) group of test plots, indicating therefore a higher amount of time spent when working without a pan. The same figures were of 4.09 and 10.2 s/m in the case of *Winch* work element. As such, the operational speeds for *Release* and *Winch* work elements,

Table 3 Descriptive statistics of time consumption

Option	Operational variables		*N*	Time consumption (s)					
	S (°)	WD (m)		Release	Attach	Winch	Adjust	Detach	Cycle Time
Protected	22.0	21.0 ± 16.0	36	64.7 ± 41.0	23.6 ± 28.3	86.1 ± 52.5	22.0 ± 16.6	24.1 ± 23.7	206.6 ± 114.2
Unprotected	26.5	23.4 ± 14.5	25	117.1 ± 113.0	12.9 ± 24.6	234.8 ± 188.6	–	25.7 ± 26.2	390.7 ± 244.3
Overall	24.2	22.0 ± 15.3	61	86.2 ± 82.2	19.3 ± 27.1	147.0 ± 145.8	22.0 ± 16.6	24.8 ± 24.6	282.1 ± 199.5

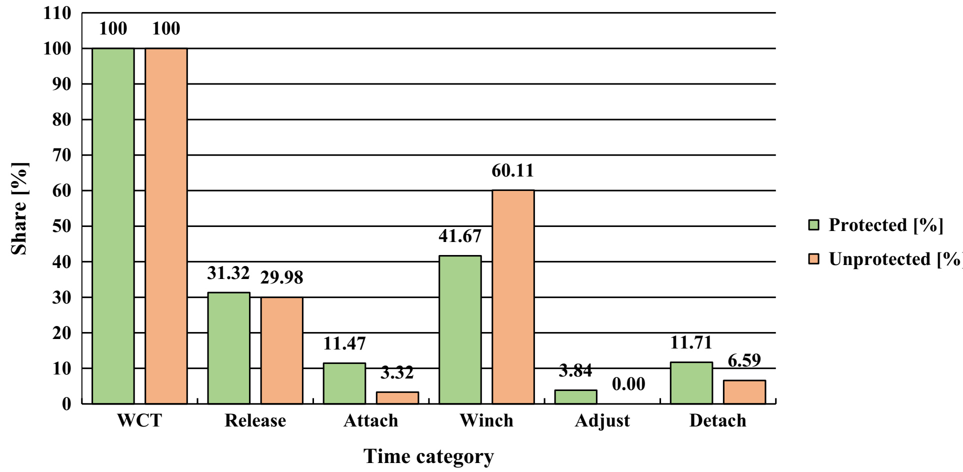

Fig. 8 Share of time consumption on work elements and main treatments. Legend: protected refers to the data collected in TP1 and TP2, unprotected refers to the data collected in TP3 and TP4

for the first and second group of test plots were of 0.33, 0.20 (*Release*, protected and unprotected) and of 0.24 and 0.10 (*Winch*, protected and unprotected), reinforcing our statement that the available space generated by the tree density in the test plots and the general slope, could have been affected the performance of these work elements.

Discussion

In last decades, several studies have been carried out to evaluate possible systems or techniques able to reduce stand damage and soil disturbance. This interest was aimed at improving the sustainability of forest management by favoring new methods and technologies which are capable of finding a balance between the use of forest resources and negative impact on the environment. Several studies on logging impact reported that skidding operations may cause increased levels of damage (Nikooy et al. 2010) and different authors have highlighted that a number of factors affect the susceptibility to and effect of mechanical injury.

Studies on improving the quality of winching operations are, indeed, very few. Coupled with the high diversity in forest conditions and practices, this fact limits our ability of understanding, designing and implementing the right solutions to the right forest conditions and operational setups. In this regard, Picchio et al. (2012) studied the possibility of improving the winching techniques with the aim of decreasing stand damage in the forests of central Italy, while in recent years, the forest engineering community has also studied the impact of forest operations in relation to the soil and the stand conditions (Picchio et al. 2020). In this study, the residual tree damage frequency was lower compared to those reported for mechanized operations based on whole tree system (WTS), which are usual in North America (30–50%), as in Bettinger and Kellogg (1993), and similar with the frequencies of logging operations based on the cut-to-length system (CTL), which are still common in Mediterranean Europe (10–20%) as in Vasiliauskas (2001). Cudzik et al. (2017) reported less damage on remaining trees and soil following CTL (cut-to-length) as compared to TL (tree length) during a late thinning operation implemented in Polish forestry. In a Turkish study, Eroğlu et al. (2016) found that the ground-based extraction systems had the greatest impact on soil permeability and bulk density compared to skyline and chute systems.

Soil damage mainly depends on the method of extraction and the machines used, their weight and number of passes, and several studies added to the knowledge the importance of texture on soil compactability (Slesak et al. 2017; Picchio et al. 2020). The results of this study indicate that the number of passes (cycles) and the volume of trees extracted were important variables that affected the damage to the soil. In similar cases, a proper skid trail network and a well-developed forest road can limit soil damage. Lacking such conditions, a solution can be the use of protective devices as proved in this research by the lower levels of soil damage rates found in test sites where such a device was used. Unfortunately, the use of skidding pans is not widespread and only few studies such as those conducted by Britto et al. (2017; 2019; 2022) in southern Brazil tested them. As opposed to the device tested in this study, Picchio et al. (2012) studied winching techniques designed to decrease stand damage by applying a snatch block, and they found a reduction by one-quarter in the frequency of wounded trees. In this study, the tree damage decreased with distance from the skidding road, which reinforces the mechanism of spatial distribution of damage in relation to the extraction infrastructure as reported by several studies such as those of Nichols et al. (1994) and Spinelli et al. (2010). For instance, more than half of the damaged trees were found at a distance of less or equal to 15 m from the skidding road and close to 16% of the damaged trees were found in the first 5 m from the skidding road. Therefore, a careful planning of the extraction roads holds important as reported in previous studies (Gullison and Hardner 1993). In addition, the results of this study are comparable to the findings of Marchi et al. (2014) who carried out tests with a forestry-fitted farm tractor and of Allman et al. (2015) using different skidders. In detail, the results showed that residual trees can be affected by mechanical damage during harvesting operation and the severity of damage is influenced by the logging system and harvesting intensity, which was in agreement with findings of Picchio et al. (2020). In addition, Siren et al. (2015) considered also stand density and basal area. In this study, the location of wounds was correlated to the direction of winching and to the slope, confirming the results reported by Behjou (2012; 2014) where steeper slopes contributed to more damage. In particular, the findings in terms of frequency and the typology of damage to the remaining stand indicated that the use of a pan reduced by approximately 1.4 times the cambium injury. Tavankar et al. (2017) showed that the share of wounded trees was directly related to slope steepness, and there is a dominance of large wounds on steeper slopes (Britto et al. 2019). In addition, the influence of terrain steepness as found in this study agrees with several studies which suggested that ground-based harvesting operations should be planned whenever possible on slopes less than 20% (Majnounian et al. 2013; Jourgholami et al. 2014; Solgi et al. 2015; Proto et al. 2016; Jankovský et al. 2019; Labelle et al. 2022). However, when terrain steepness is higher and there are no other options available for extraction, winching should be done in an uphill direction which, according to this study, may cause less damage to the trees and soil, particularly when using a pan. Accordingly, the use of a pan enabled a reduction of wound sizes compared to unprotected test plots, confirming previous findings of Britto et al. (2017; 2019; 2022) who tested a similar device in different conditions compared to those of this study. In their study, the authors highlighted higher rates of damaged basal area in stands where the logs were extracted by conventional methods. It is important to keep in mind that trees with damage will produce lower quality timber and are vulnerable to fungi and rot development. For this reason, the use of a protective device might guarantee better results in terms of tree damage and, most likely, a lower harvesting impact. In addition, it could contribute to a better value recovery at the final harvest since the amount of tree damage and soil disturbance is less. However, a critical precondition for the successful implementation of sustainable wood harvesting systems is the investment in human factors to build professional skills which sometimes are disregarded in harvesting operations (Britto et al. 2019; 2022). In terms of productive performance, the use of a pan did not cause any substantial increase in time consumption thanks to the short winching distances and stand density. Also, the use of protective devices might help to better avoid the obstacles and stem blocking during traction (Britto et al. 2022). However, the delays were excluded from analysis in this study, and the observed operations accounted for rather a limited period of time. To what extent such delays could be caused by fatigue, and if they are cyclic or non-cyclic in nature, remains to be evaluated. For such evaluations long-term studies able to capture the occurrence pattern in delays (Spinelli and Visser 2008) should be implemented. Altogether, a system perspective over the performance of operations must be able to make informed decision on the usefulness of this method of doing work. The approach of this study was fourfold and integrated the requirements of preserving a similar productivity with a lower damage to the residual stand. The hypotheses of the study were tested in the sense that, as a general rule, using a pan helped in lowering the soil and tree damage while not significantly affecting the productive performance of operations. In addition to the method (protected vs. unprotected) uphill winching direction was proved to be the best option.

Still, in relation to using protective devices for winching, some issues need to be addressed by further studies, at least in temperate forests. First of all, the utility of such devices could be evaluated in many other forest conditions and operational setups. It is likely that in less dense forests, the benefits brought by such devices would be higher. This is because the stand density in study was high, therefore some effects of this operational condition could have been reflected in the evaluated performance metrics. Then, the removal rate could be another important factor to be considered since it was particularly low in this study; although it was not under the control of the authors but rather under the control of regulated silvicultural practices in Romania, low removals negatively affect productivity, increase costs and cause increased impact to the residual stand.

The number of extracted stems per cycle, as well as the payload, could be another factor which would deserve further studies. This is because a higher number of stems to be extracted in the same cycle may need additional attaching work which may reflect negatively on cycle time and damage to the soil and residual trees since their ends are under less control. In contrast, larger stems extracted individually may result in increased productivity and less damage. In relation to the direction of winching, further studies should assess also the contribution of this method to the fuel consumption and ergonomics since moving the logs by cables in the uphill direction may require more fuel. On the contrary, this winching direction could be more favorable from an ergonomics point of view since the manual cable (and device) movement is done toward a downhill direction, benefiting from mechanical traction in the uphill direction. Further studies should also be focused on finding design solutions for such devices so as to continuously decrease their mass and to enhance their strength.

Based on the findings of this study, it seems that the option of using a pan for downhill winching could be a good fit for moderate slopes to help gravity-assisted sliding. This may be supported by lower share of residual damaged trees and a lower number of damaged trees per hectare, as specific to TP1. In addition, soil damage was comparable for downhill winching irrespective of using or not the pan.

Conclusions

Preserving the environmental values of the forests is important to ensure the sustainability of other product flows. This study demonstrates that the use of protective devices during winching operations significantly reduces the impact to the residual stand and to the soil. The results confirm the existing knowledge that preference should be given to uphill at the expense of downhill winching, particularly in steep terrain, which is known to provide a better control over the extracted logs. On the other hand, the data clearly indicate that the use of protective devices helps lowering the damage to the trees and to the soil irrespective of the winching direction. As the material science has significantly progressed, there are various lightweight alloy- or polymer-based materials available on the market at affordable prices which could be used to design and built customized solutions of protective devices so as to meet various operational needs. The device used in this study was purchased at a cost of ca. 300 euro and, by accounting that in the harvested area the extraction was of 788 m^3, this would mean an additional cost of ca. 0.4 euro/m^3; this cost would have been increasingly lowered as the same device would have been used in other harvesting sites. Given the complexity of this study, which was limited in terms of operational conditions and extraction type, further studies should be setup to check if the option studied herein could help lowering the environmental impact in other conditions. Also, further studies could test other applications of the tool taken into study.

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Data availability Data are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval Ethical review and approval were waived for this study, due to the fact that the company accepting our study was under the partial management of B.C.C. who informed the workers about the study and obtained their free will to participate.

Informed consent Informed consent was obtained from all subjects involved in the study.

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