forests

MDPI

Article

Productivity and Fuel Consumption in Skidding Roundwood on Flat Terrains by a Zetor Farm Tractor in Group Shelterwood Cutting of Mixed Oak Forests

Stelian Alexandru Borz * and Victor-Bogdan Mititelu

Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven 1, 500123 Brasov, Romania

* Correspondence: stelian.borz@unitbv.ro; Tel.: +40-742-042-455

Abstract: Productivity assessment studies are essential in forest operations, mainly because their results enable operational planning and rate setting, the development of equitable payment systems, the assessment of environmental performance, the assessment of improvements brought by technology development, and the optimization of larger forest-based systems. This study examines productive performance and fuel consumption in farm-tractor based skidding operations implemented in flat terrain oak harvesting by developing detailed statistics and predictive models on skidding performance. Two felling areas were selected to monitor the operations, and detailed statistics and predictive models were developed at two resolutions by an end-to-end assessment. Based on 56 observed work cycles, and for average values of the number of logs, payload volume, winching distance and extraction distance of 4.96, 1.81 m^3, 14.43 m, 177.3 m, respectively, the net efficiency and productivity rates of skidding operations were estimated at 0.125 h/m^3 and 8.03 m^3/h, respectively. At the resolution of piece-by-piece winching, winching time depended only on the winching distance. At the resolution of overall skidding operations, the skidding time depended on the number of logs in a payload and average winching and extraction distances. The same predictors were relevant in explaining the fuel consumption in skidding operations, which accounted for 3.72 L/h or 0.46 L/m^3, while there was a variation in fuel consumption induced by the type of operation. Both efficiency and productivity were found to be highly sensitive to the operational distances, as the main factors affecting them. Nevertheless, significant improvements in efficiency, productivity, and fuel consumption may be achieved when dealing with fewer logs per turn and higher volumes per piece, since the models indicated no effects brought in fuel and time consumption by the log size, and the technical limits of the used winched reached 8.5 tons.

Keywords: farm tractor; wood skidding; flat-terrain oak forests; efficiency; productivity; fuel consumption; observational study; detailed models; performance; capability; versatility

check for updates

Citation: Borz, S.A.; Mititelu, V.-B. Productivity and Fuel Consumption in Skidding Roundwood on Flat Terrains by a Zetor Farm Tractor in Group Shelterwood Cutting of Mixed Oak Forests. *Forests* **2022**, *13*, 1294. https://doi.org/10.3390/f13081294

Academic Editor: Raffaele Cavalli

Received: 27 July 2022
Accepted: 10 August 2022
Published: 15 August 2022

1. Introduction

The sustainability of human activities has been one of the central discourses in policy, practice and science. In forest operations, a complete evaluation of the degree to which a given process or operation meets the sustainability criteria is a challenging task. In this regard, sustainable forest operations were described to be framed around several key performance areas [1], namely the economics, ergonomics, environment, quality optimization of products, and people and society. Of these, economic and environmental challenges have become important lately given the rise in fuel prices, which not only affects the sustainability of operations but also energy security. On the other hand, the variability in forestry practices, experience of operators, machine types and models, and operational conditions often limits the applicability of existing studies, requiring the development of productivity and fuel consumption models able to reflect the regional operational reality [2]. Updated productivity models are essential to understand the differences brought by technology development [3], and models themselves are required for an effective planning, costing and control of forest operations [4], and for planning and optimizing larger systems [5].

Ground-based harvesting systems stand for the dominant option in forest operations around the world [6], though their mechanization level is rather country- or region-specific [7] and may depend on factors which include the historical, economic, social and technology contexts, topography and forestry resources and practices. Recent studies have found that skidding by specialized tractors holds an important share in North America and Europe [8], and it is common to use farm tractors fitted for skidding operations in many European [8,9] and non-European countries [10]. Among the reasons for opting for farm tractors in skidding operations are the affordability and versatility of such machines, which make them popular among small entrepreneurs. Compared to skidders, however, farm tractors are described to share some limitations in capability, which are mainly related to the tractive power and the physical condition and geometry of the skidding roads [6].

There are several factors affecting the productive performance of farm tractors used in skidding operations. Besides a careful planning of extraction infrastructure, which helps leverage their capabilities, and fitting them with forestry-related equipment such as winches [6], operational variables in the form of winching [10,11] and skidding distance, load volume and weight, number of pieces per turn, and harvesting stock characteristics have been found to affect the time consumption, efficiency and productivity [10]. In addition, the used harvesting method and the engine power class may add to the variation in productivity and fuel consumption, the same way that advancement in technology and improvement may enhance the capabilities of machines from a given class [3]. As documented by [12], there is a wide variability in skidding practices around the world, while the relevance of operational variables in the developed models may depend largely on the existing operational conditions, operational configuration, technology used and its capabilities. Since winching is a sub-component operation of skidding [13], in complex operational setups such as in steep terrain harvesting, and depending on the relation between machine capabilities and weight of the payloads, its performance may be affected by the distance, slope, direction of winching and weight of the winched logs [14]. Once deployed in flat terrains and when a sufficient capability of the machine in relation to the operated payloads is available, the set of relevant predictors may be constrained to fewer variables such as the distance and number of winched logs. When a sufficient tractive capacity is available, the performance of on-road skidding, on the other hand, may depend solely on the extraction distance [13,15].

Accounting for fuel consumption is important in forest operations because it enables the assessment of environmental performance in terms of fuel use and emissions [16] and helps in establishing the operational costs. Similar to time consumption, relating fuel use to the operational variables is important to understand how it may be affected by changing operational conditions. Elemental and work cycle-based fuel consumption measurement is, however, challenging in terms of resources spent. That may be the reason for using prospective accounting techniques to characterize the general fuel use [17], to model the fuel use based on an overall accounting [16] or just to report general, average values [3].

The aim of this study was to evaluate the performance of a farm tractor in skidding roundwood from mixed-oak group shelterwood cuttings deployed in flat terrains. The objectives of the study were to estimate and model the time consumption, fuel consumption and productivity of the observed timber skidding operations.

2. Materials and Methods

2.1. Study Location and Equipment Description

Two forest compartments were selected for this study based on their shared characteristics such as the species proposed for extraction, silvicultural system, equipment and timber harvesting systems used (Figure 1, Table 1). The forest compartments are located in the low-hill (19M) and plain (83B) regions of the Southern Romania, in the forests managed by the National Forest Administration—RNP Romsilva, through the forest districts of Filiaşi and Craiova.

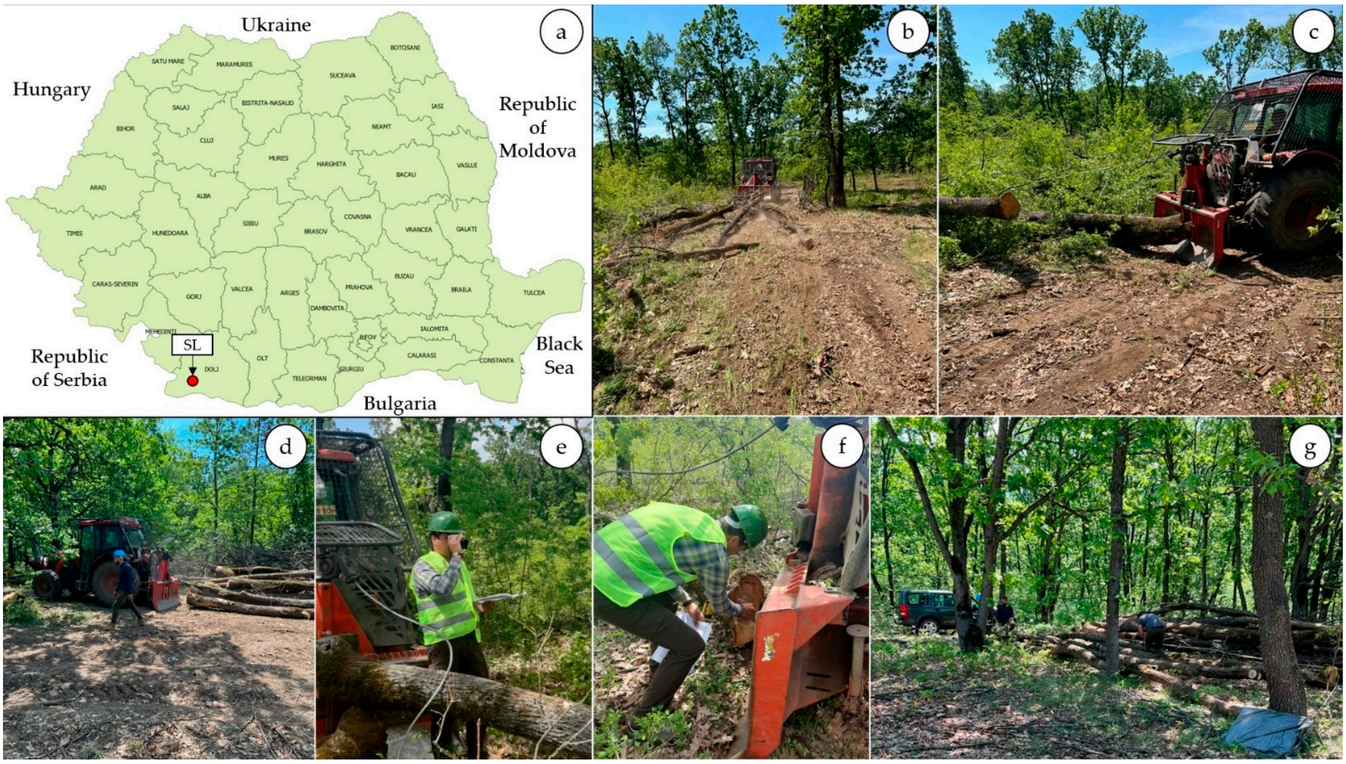

Figure 1. Study location and examples from operation and data collection activities: (**a**) location of the study area at the national level; (**b**) a snapshot taken during the loaded turn; (**c**) a snapshot taken during mechanical traction of logs; (**d**) wood piles at the roadside; (**e**) distance measurement during the winching operations; (**f**) piece-by-piece numbering by marking of the winched logs once they arrived at the rear part of the tractor; (**g**) log measurements taken at the roadside by marking segments, taking diameters by a caliper and lengths by a tape.

Table 1. Description of the study areas.

Parameter (Measurement Unit)	Forest Compartment		Source and Description
	19M	83B	
Location, topography and spatial extent			
County	Dolj	Dolj	-
Forest district	Filiaşi	Craiova	-
Coordinates	44°25.5634′ N–23°18.530′ E	44°14.351′ N–23°39.231′ E	Centers of the felling areas, based on GPS and GIS files
Altitude (m, a.s.l.)	240	165	Forest management plan
Area (ha)	9.53	17.72	Wood selling documents
Slope (°—%)	10–18	0–0	Wood selling documents
Aspect	Southeastern	-	Forest management plan
Topography	hill	plain	Forest management plan
Stock and silvicultural system			
Tree species	*Quercus frainetto* *Quercus cerris*	*Quercus frainetto* *Quercus cerris*	Wood selling documents
Age (years)	109	85	Wood selling documents, average value of trees proposed for extraction

Table 1. *Cont.*

Parameter (Measurement Unit)	Forest Compartment		Source and Description
	19M	83B	
Tree height (m)	13	15	Wood selling documents, average value of trees proposed for extraction
Diameter at the breast height (cm)	21	26	Wood selling documents, average value of trees proposed for extraction
Volume for extraction (m^3 over bark)	148.82	490.74	Wood selling documents, total value of trees proposed for extraction
No. of trees for extraction	578	1009	Wood selling documents, total value per compartment
Average tree size (m^3/tree)	0.257	0.486	Wood selling documents, average value of trees proposed for extraction
Silvicultural system	Group shelterwood	Group shelterwood	Wood selling documents
Harvesting system			
Felling and processing	Motor-manual	Motor-manual	Field observation
Extraction	Farm tractor equipped with a winch	Farm tractor equipped with a winch	Field observation
Landing operations	Farm tractor	Farm tractor	Field observation

Group shelterwood fellings were implemented in 2022 in both forest compartments, and the wood was dominantly extracted in the form of tree lengths by a Zetor Proxima HS farm tractor (Zetor, Brno—Líšeň, Czech Republic, Table 2) which was fitted for forest operations by a Krpan 8.5 EH single drum winch, cabin reinforcement, and by placing an additional weight on the front part. Farm tractors from the same class are frequently used to extract the wood in moderately sloped to flat forested terrain in Romania. Several brands such as Belarus, Valtra, UTB and Zetor are commonly used in harvesting operations implemented by RNP Romsilva, mainly due to low investments in equipment, low mass of the machines, and versatility in operations.

Table 2. Description of the tractor and winch used in both forest compartments.

Component	Measurement Unit	Values	Description
Base machine	-	-	Zetor Proxima HS
Engine power	kW	86.4	Model: Zetor; Type: turbodiesel; Displacement: 4156 cc; Tier: IV; Number of cylinders: 4;
Mass	kg	4257	
Transmission	-	-	Mechanical, four-wheel drive, powershift
Winch	-	-	Krpan 8.5 EH
Type	-	-	Single drum
Recommended power	kW	>59	-
Average line speed	m/s	0.6	-
Tractive force	kN	85	-
Cable diameter	mm	13	-

The farm tractors observed in both sites were equipped with 86.4 kW engines, which provided the necessary power to work with the winches (Table 2). They were purchased in 2018 (18M) and 2019 (83B) and, at the time of field study, they had a number of 5000 (18M) and 5600 (83B) operating hours, respectively. The used winch model is a composite mechanism that integrates the winch itself, an upward protection grid and a blade-like frame which is used to hold and lift the logs from the ground during skidding. The nominal capacity for a line with a diameter of 13 mm is of 110 m. By the construction of the winch, several winching work cycles may be required to form a load for extraction, depending also on the log size and the availability of chokers.

In both felling areas, the trees were motor-manually felled and processed, and then the existing skid roads were used to extract the wood (dominantly as tree lengths—tree length harvesting method) to the roadside where it was piled. Wood piling was performed along the forest road, which required some movements of the tractor with the payloads to reach to the locations of individual piles. By implementing the group shelterwood fellings, the wood to be extracted was typically concentrated in the created forest gaps, which had areas of 0.1 to 0.3 hectares. Extraction by winching was performed always from the skid road, a fact that required additional maneuvers once arrived at the felling area. The condition of the soil in terms of moisture and bearing capacity was good during the extraction (Figure 1), the sky was mostly clear, and the average air temperature varied between 15 (compartment 19M) and 22 °C (compartment 83B). Although there was a moderate slope in forest compartment 19M, the skid roads were characterized by longitudinal slopes of up to 5° (9%).

2.2. Organization of Work and Field Data Collection

The organization of work was similar to that described in previous studies on the performance of skidding operations [12,14,15], and the observation was conducted by implementing an elemental time and motion study based on the general time consumption and productivity evaluation concepts described in [18,19]. Wood extraction (Figure 2) consisted of moving the tractor empty from the roadside to the felling area (hereafter empty turn, ET), making the necessary maneuvers to position the machine with the rear part towards the wood to be winched (hereafter maneuvering, MN), releasing the cable by a worker from the rear part of the machine to the pieces of wood to be winched (hereafter cable releasing, CR), hooking up the logs (hereafter log hook, LH), mechanical traction of the logs by the winch up to the rear part of the machine (hereafter mechanical traction, MT), forming and attaching the load for extraction, which contained the payload hookup and its lifting by the winch (hereafter payload attachment, PA), loaded turn of the tractor from the place in which the load was attached to the forest roadside (hereafter loaded turn, LT) and landing operations, which consisted of detaching the load (hereafter payload detachment, PD) and wood piling (hereafter WP).

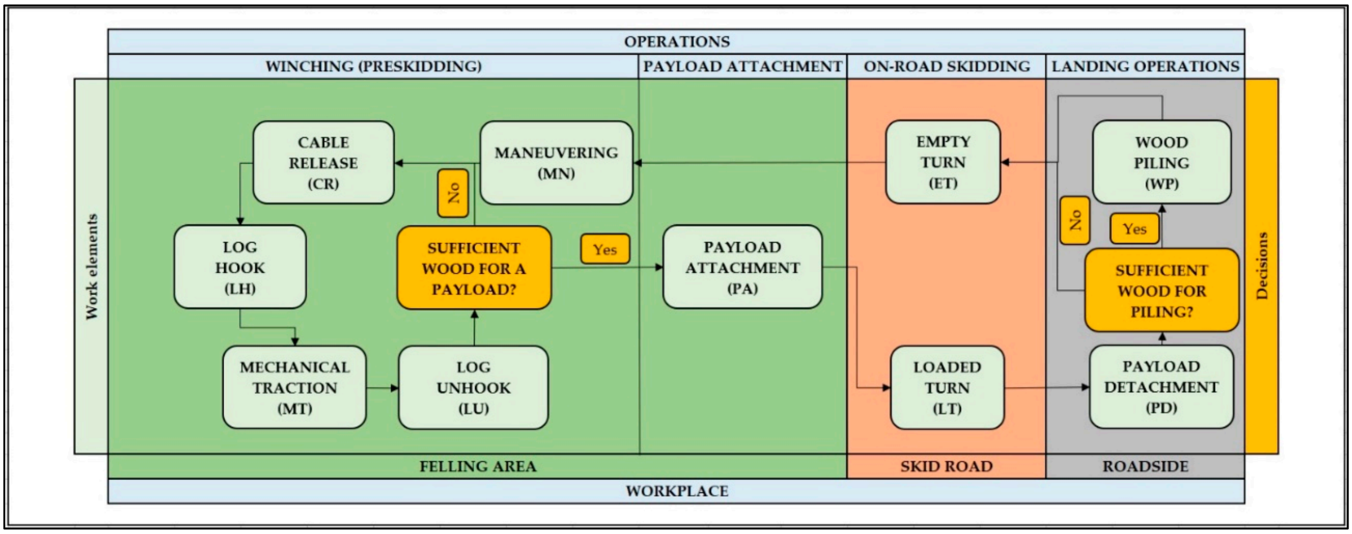

Figure 2. Process flow diagram describing the operations, work elements and workplaces as observed in this study.

Since, by construction, the winch enables the work with a single line, cable releasing, log hook, mechanical traction and log unhook were repeated for each of the winched logs until having winched a sufficient number of logs to form a load for extraction. Similarly, landing operations were composed always from payload detachment, and, when a sufficient number of logs were available, wood piling was performed. Figure 2 describes the concept of work organization in terms of operations, work elements, decisions affecting the occurrence of work elements within a work cycle, and workplaces in which each operation took place. Two types of delays were observed during the field study, namely delays caused by the study itself and delays caused by technical reasons. In the first category were included events related to placing and taking down the equipment used to monitor the operations and to perform the necessary measurements (mainly on the log biometrics and fuel consumption). In the second category were included the delays caused by various technical reasons such as removing obstacles, reattaching a log to a payload, etc. Conceptually, the study was designed in a hierarchic organization, where the first node was that of general skidding operations (hereafter SOP); they were divided in winching (hereafter WIN), on-road skidding (hereafter ORS) and landing operations (hereafter LOP), each of which was then decomposed in repetitive work elements at two hierarchical levels. Table 3 describes the operations, workplaces, work objects, and the breakpoints selected to delimitate them following the concept shown in Figure 2.

Table 3. Description of operations, work and time elements.

Operations and Work Elements	Abbreviation	Description
Skidding (Operations)	SOP	Description: extracting and piling the wood at the roadside; Breakpoints: begins when the tractor leaves the forest road and ends when the payload was detached or the tractor has finished wood piling at the roadside; Component operations: Landing operations, On-road skidding, Winching, Payload forming; Workplaces: roadside, skid-road; felling area; Work object: payload.
Landing operations (Operation)	LOP	Description: transporting the wood along the piles, payload detachment and wood piling. Occurrence: cyclic, observed in most skidding cycles; Breakpoints: begins when the tractor entered the forest road and ends when it finished piling or when a payload was detached and the tractor begun an empty turn; Work elements: payload detachment and piling; Workplace: roadside; Work object: payload.
Load detachment (Work element)	LD	Description: the worker detaches a payload once the tractor arrived at the roadside; Occurrence: cyclic, observed in all cycles of landing operations; Breakpoints: begins when the tractor ended the empty turn and ends when the load was detached and the tractor engages either in piling or in a new empty turn; Workplace: skid road; Work object: payload.
Wood piling (Work element)	WP	Description: the tractor makes maneuvers to pile the wood; Occurrence: cyclic, observed in most of the cycles of landing operations; Breakpoints: begins when a payload was detached and ends when the tractor starts a new empty turn; Workplace: skid road; Work object: payload.
On-road skidding (Operation)	ORS	Description: moving empty on the skid road from the roadside to felling area and loaded back; Occurrence: cyclic, observed in all skidding cycles; Breakpoints: see the description of component work elements; Work elements: empty turn and loaded turn; Workplace: skid road; Work object: payload.
Empty turn (Work element)	ET	Description: moving empty on the skid road from the roadside to felling area; Occurrence: cyclic, observed in all on-road skidding cycles; Breakpoints: begins when a payload was left at the roadside or after piling and ends when the tractor reaches the felling area and starts to make positioning maneuvers; Workplace: skid road; Work object: payload.
Loaded turn (Work element)	LT	Description: moving loaded on the skid road from the felling area to roadside; Occurrence: cyclic, observed in all on-road skidding cycles; Breakpoints: begins when a payload was attached at the felling area and ends once the tractor has reached the roadside and starts to work at landing; Workplace: skid road; Work object: payload.

Table 3. *Cont.*

Operations and Work Elements	Abbreviation	Description
Winching (Operation)	WIN	Description: maneuvering the tractor to place it with the winch towards the logs to be extracted, releasing the cable, attaching the log, mechanical traction and detaching the log; Occurrence: cyclic, observed in all skidding work cycles; Breakpoints: begins when the tractor reached to the felling area and starts maneuvering to place the winch towards the logs and ends once the tractor was ready to attach a payload; Work elements: maneuvering, cable releasing, log hooking, mechanical traction, log unhooking; Workplace: felling area; Work object: payload.
Maneuvering (Work element)	MN	Description: maneuvering the tractor to place it with the winch towards the logs to be extracted; Occurrence: cyclic, observed in all of the winching work cycles; Breakpoints: begins when the tractor reached to the felling area and starts maneuvering to place the winch towards the logs and ends when the cable starts to be released; Workplace: felling area; Work object: payload.
Cable release (Work element)	CR	Description: the tractor driver unlocks the winch and a worker pulls the cable to a log; Occurrence: cyclic, observed in all of the winching work cycles; Breakpoints: begins when the worker grabs the cable and ends when the worker reaches to the log; Workplace: felling area; Work object: log.
Log hook (Work element)	LH	Description: the worker uses the cable to hookup a log; Occurrence: observed in all of the winching work cycles; Breakpoints: begins when the worker starts to hookup the log and ends when the log is attached to the cable; Workplace: felling area; Work object: log.
Mechanical traction (Work element)	MT	Description: the tractor driver operates the winch to move the log at the tractor while the worker tracks the log until the back of the tractor and releases it from obstacles when the case; Occurrence: observed in all of the winching work cycles; Breakpoints: begins when the tractor driver starts to operate the winch and ends once the log reached at the tractor; Workplace: felling area; Work object: log.
Log unhook (Work element)	LU	Description: the worker detaches the log at the back of the tractor; Occurrence: observed in all of the winching work cycles; Breakpoints: begins when the log reached the tractor and ends once the cable is free; Workplace: felling area; Work object: log.
Payload attachment (Operation)	PA	Description: the worker attaches several logs to the cable to form a payload for loaded turn once enough logs are available at the back of the tractor; Occurrence: observed in all of the skidding work cycles; Breakpoints: begins when the worker grabs the cable and ends when the payload is attached and suspended at one end; Workplace: felling area; Work object: payload.

Field data collection was implemented to account for the time and fuel consumption, production and operational variables, and it covered a number of 56 skidding work cycles, of which 22 were observed in compartment 19M and the rest in compartment 83B. Data were collected over 5 operational days, 2 (13 and 14 of April, 2022) in compartment 19M and 3 (10, 11 and 12 of May, 2022) in compartment 83B. The observed workers were well-experienced in skidding operations. To control the observer's effect on the performance of workers, they were informed in advance about the goals of the study and were asked to work as usual, which is a common strategy to familiarize the subjects with the study outcomes [19]. Following this step, all the workers agreed verbally to participate in the study.

Time consumption was documented at elemental level by the technique of cumulative timing [18]. To this end, the work elements described in Figure 2 and Table 3 were taken into study. To support the collection of time consumption and other relevant data, in each site, a Hero 10 (GOPRO Inc., San Mateo, CA, USA) video camera was placed on the cabin's frame with the field of view oriented towards the rear part of the machine. The camera was powered by a mobile external power source and set to continuously collect video files of ca. 20 min in length each. At the end of each day of observation, the video files were downloaded, stored, and organized in a personal computer.

A Garmin GPSmap 62 stc Global Positioning System unit (Garmin International Inc., Olathe, KS, USA) was placed on the cabin of the tractor and set to sample locations at one second. The resulting data, in the form of .gpx files, were downloaded and stored in the personal computer, with the aim of documenting the extraction distances for the empty (hereafter ETD) and loaded (LTD) turns. Winching distance (hereafter WD) was assimilated to the straight distance between the winch and the end of the log at which the cable was attached. It was measured by a Nikon Forestry Pro LASER rangefinder (Nikon Inc., Melville, NY, USA) to the nearest decimeter (Figure 1e). Distances shorter than 10 m were measured by a forestry tape at the same resolution.

Once arrived at the rear part of the tractor, each log was numbered by marking with forestry chalk (Figure 1f); then, at the landing, the numbers were used for the identification and measurement of the diameters and lengths (hereafter LL) as input variables to estimate the individual log (hereafter LV), payload (hereafter PV) and production (hereafter P) volume. These variables were based on measurements of the logs' diameters starting from one end at an interval of 1 m up to reaching the second end. When the second end was not located at a 1 m multiple, the length between the last 1 m segment and the second log end was accounted. To mark and measure the log segments, a tape, chalk and a forest caliper were used, and the volume estimations were based on Huber's formula, which was applied to all the segments identified in a log. The volume of a log was calculated as the sum of volumes of individual segments in the office phase of the study.

Fuel consumption was documented at two resolutions using the refilling to full method, which supposes the measurement of fuel consumed for a given time frame or event based on the amount of fuel used to refill to full the tank following that period of time or event. There are several examples of this method's application, as described in [3,19,20]. A number of 12 work cycles were systematically chosen to make fuel consumption measurements for empty turn, winching (including payload attachment), loaded turn (including payload detachment) and landing operations consisting of wood piling, with the aim of characterizing the fuel consumption distribution between different engine running regimes and operations. Fuel consumption was measured at the skidding work cycle level for all the work cycles observed in the field. To measure the fuel consumption, graded hard-polymer recipients were used, and readings were conducted at the nearest 5 centiliters. Specifically, each time a fuel consumption measurement was taken, the engine of the tractor was shut down following the completion of a relevant work element or operation. Then, measurements were taken after checking that the machine was located on leveled ground. A pen-and-paper approach was taken to record data on winching distance, log biometrics and fuel consumption, as well as to document other events and characteristics observed in the field.

2.3. Data Processing

2.3.1. Time Consumption, Efficiency and Productivity Data

Time consumption data were obtained by processing the video files in the office phase of the study. Video-based analysis has the strength of observing the events in detail and the weakness of spending important time resources on data processing [21]. Its choice was based on accuracy reasons and possibility to track-back eventual data-related issues. The real sequence of events was observed by playing the field-collected video files, and a Microsoft Excel ® (Microsoft, Redmond, WA, USA, 2013 version) worksheet was set up to store the initial and final times of a given work element based on the concepts described in Figure 2 and Table 3. Elemental time consumption was calculated in seconds as the difference between the final and initial times of a given observation, and codes (Table 3) were attributed to each of the observed events. Delays induced by the study and technical reasons were counted separately. Efficiency and productivity estimates were based on the time consumption and production data. Production data were calculated based on the log biometrics in the form of individual log volume, payload volume and total production and included in the database where relevant. Equations (A1)–(A22) (Appendix A) describe the time consumption, efficiency and productivity concepts and metrics used in this study.

Data on logs' biometrics were used to estimate the volumes of individual logs, payloads (Equation (A7)) and production (Equation (A8)); then, they were manually filled in the database. Based on a cyclic approach, two data processing resolutions were taken in account, namely at the individual log for winching operations (Equation (A6)) and at the skidding work cycle (Equations (A2)–(A5)). Data on the empty (ETD) and loaded turn (LTD) distances were extracted by analyzing the .gpx files in the Garmin Base Camp ® (Garmin International Inc., Olathe, KS, USA) software. The software enables a scaled data mapping and detailed analysis of the GPS locations in terms of events characterizing the movement, which is useful in various applications that require GPS tracking and analysis [3,22,23]. Segments of locations characterizing movement by changes in speed collected by GPS unit were used to differentiate between the main work elements and to account for ETD and LTD on a cyclic basis. Based on ETD and LTD, the average extraction distance (hereafter AED) was calculated for each skidding work cycle. ETD, LTD and AED were estimated to the closest meter. Based on the log-wise winching distances (Equation (A6)), the average winching distance (hereafter AWD) was calculated to characterize the winching operations at the level described in Equation (A3). Accordingly, the number of logs and payload volumes were accounted at this resolution of data processing.

Data on operational variables such as the winching, empty and loaded turn distances, as well as the data on individual, payload and production volumes were organized in the Microsoft Excel database to allow the estimation of descriptive statistics, efficiency and productivity, and to model the relationships between time consumption and productivity metrics as functions on operational variables.

2.3.2. Fuel Consumption Data

Following a manual transfer into the database, fuel consumption data were processed at two resolutions. A first level of resolution was that of the overall skidding operations (Equation (A2)) and was applied based on recordings of the 56 observed work cycles. The second level of resolution was based on 12 observations; data were processed for winching operations (Equation (A3)), which included payload attachment, for the empty and loaded turn, with the latter including payload detachment, and for landing operations, respectively, consisting of wood piling. At both levels of resolution, hourly fuel consumption (hereafter HFC, L/h) was computed based on the engine working time; unit fuel consumption (hereafter UFC, L/m^3) was estimated at both resolutions as well. Cycle-wise fuel consumption data were then prepared for developing models explaining the variation in fuel consumption as a function of relevant operational variables at both resolutions.

2.4. Data Analysis

2.4.1. Statistical Design

The statistical design used in this study was adapted to the workflow described in [19] and included most of the steps required in observational modeling studies. The step of checking for outliers in the data was skipped due to the techniques used to measure the values of relevant variables, as well as due to the fact that there was a high certainty on accuracy of collected and processed data. For all the metrics and resolutions taken into account, the variables were checked for normality by the means of a Shapiro–Wilk test. The test was applied to all presumptive independent and dependent variables with the main aim of choosing the most appropriate descriptive statistics for data reporting and of validating the developed models. Then, a correlation analysis was implemented to tackle multicollinearity problems and to improve the reliability of the models by avoiding their overfitting. For this, a target threshold of the correlation coefficient (R) ± 0.50 was selected [15], and a pairwise comparison of independent variables was done to keep in further analyses only those best suited to the modeling scope.

Models explaining the variation in time and fuel consumption as a function of operational variables were developed by the means of least square ordinary linear regression, which, depending on the number of available predictor variables, was implemented either as a simple or multiple linear regression. The strategy used to build the multiple predictor-based models was that of using the stepwise backward regression technique. According to the technique [24], in a first step, a maximal model is built (i.e., including all the relevant predictors); then, the overall and predictors' significances in the model are checked against an a priori chosen confidence threshold. Depending on the outcomes, further iterations may be required by reducing the number of predictors until the two parameters become statistically significant; the order of predictor variable exclusion is typically given by the maximum p-values found in the predictor list at a given iteration [19]. For all the above-described statistical steps, a confidence threshold of α = 0.05 was selected, meaning that p-values equal to or exceeding 0.05 indicated normality of data, while p-values less than or equal to 0.05 indicated both that a model was globally significant or a given predictor variable was significant in the architecture of a model. The predictive power of the models was evaluated by the means of the coefficient of determination (R^2), which is a simple metric explaining how much of the variability in a predicted variable is explained by one or a set of independent variables [19,24].

2.4.2. Prediction of Efficiency and Productivity

Descriptive statistics characterizing the log and payload volume, as well as the models developed by regression, were further used to graphically describe the relation between efficiency and productivity, respectively, and the variation in operational distances, which were assumed to be the most important and logical predictors of performance. The first level of analysis was that of a log-based winching work cycle. The mean and standard deviation values of log volumes were used to predict efficiency and productivity based on the outcomes of the corresponding time consumption model applied to the range of winching distance data. For that, the estimates of efficiency and productivity were computed in three scenarios related to the mean log volume (mean value − standard deviation, mean value, and mean value + standard deviation), based on the time estimations produced by the time consumption models over the range of winching distance data. As outcomes, three curves describing the expected efficiency and three curves describing the expected productivity were plotted against the winching distance. The same prediction procedure was repeated for the winching, on-road skidding and overall skidding operations by adaptations of the time consumption predictive models and using the mean payload volume for computations instead of log volumes. In all cases, the standard deviation was used to account for uncertainty in log and payload volume data.

2.4.3. Software Used

For data processing, simple computations, artwork development and advanced statistical analysis, Microsoft Excel ® (Microsoft, Redmond, WA, USA, 2013 version) software fitted with Real Statistics (https://www.real-statistics.com/ accessed on 9 August 2022) add-in was used. Microsoft Excel enables the computation of descriptive statistics, correlation and linear regression analysis. Real Statistics enables advanced statistical analysis, which includes performing tests for normality of data. Shapiro–Wilk tests were carried out by means of Real Statistics and the remaining analyses, computations, and development of artwork were performed in Microsoft Excel.

3. Results

3.1. Time Consumption

3.1.1. Log-Based Winching

Table 4 shows the descriptive statistics of operational and time consumption variables for log-based (piece-by-piece) winching. Log length varied between ca. 1 m, which was an effect of extracting some very short logs in few cases, and 15 m. Winching distance varied widely between 1 and 32.5 m, averaging 14 m, and the log volume averaged 0.37 m^3. Dominant in the structure of a work cycle were the cable releasing (T_{CRL}, 31.11%) and mechanical traction (T_{MTL}, 36.30%) time (Table 4, Figure 3), and a work cycle averaged approximately 1.15 min. The variation in cable releasing, mechanical traction and log-based winching time was related to the winching distance, as shown in Figure 3a–c.

Table 4. Descriptive statistics of operational and time consumption variables for log-based winching.

Category and Variable	Descriptive Statistics					
	Minimum Value	Maximum Value	Mean Value ± Standard Deviation	Median Value	Number of Observations	Sum
Operational						
Log length (LL, m)	1.45	14.50	10.14 ± 2.26	10.50	278	-
Log volume (LV, m^3) [a]	0.03	0.93	0.37 ± 0.17	0.37	278	101.52
Winching distance (WD, m)	1.00	32.50	14.13 ± 6.25	13.50	278	-
Time consumption						
Cable releasing time (T_{CRL}, seconds)	1.00	55.00	21.85 ± 9.73	21.00	278	6073.00
Log hook time (T_{LHL}, seconds)	3.00	65.00	13.59 ± 8.90	11.00	278	3778.00
Mechanical traction time (T_{MTL}, seconds)	6.00	81.00	25.49 ± 14.06	22.00	278	7087.00
Log unhook time (T_{LHL}, seconds)	3.00	24.00	9.30 ± 4.74	8.00	278	2585.00
Log-based winching cycle time (T_{WINL}, seconds)	14.00	159.00	70.23 ± 26.52	66.00	278	19,523.00

Note: [a]—variable that passed the normality check.

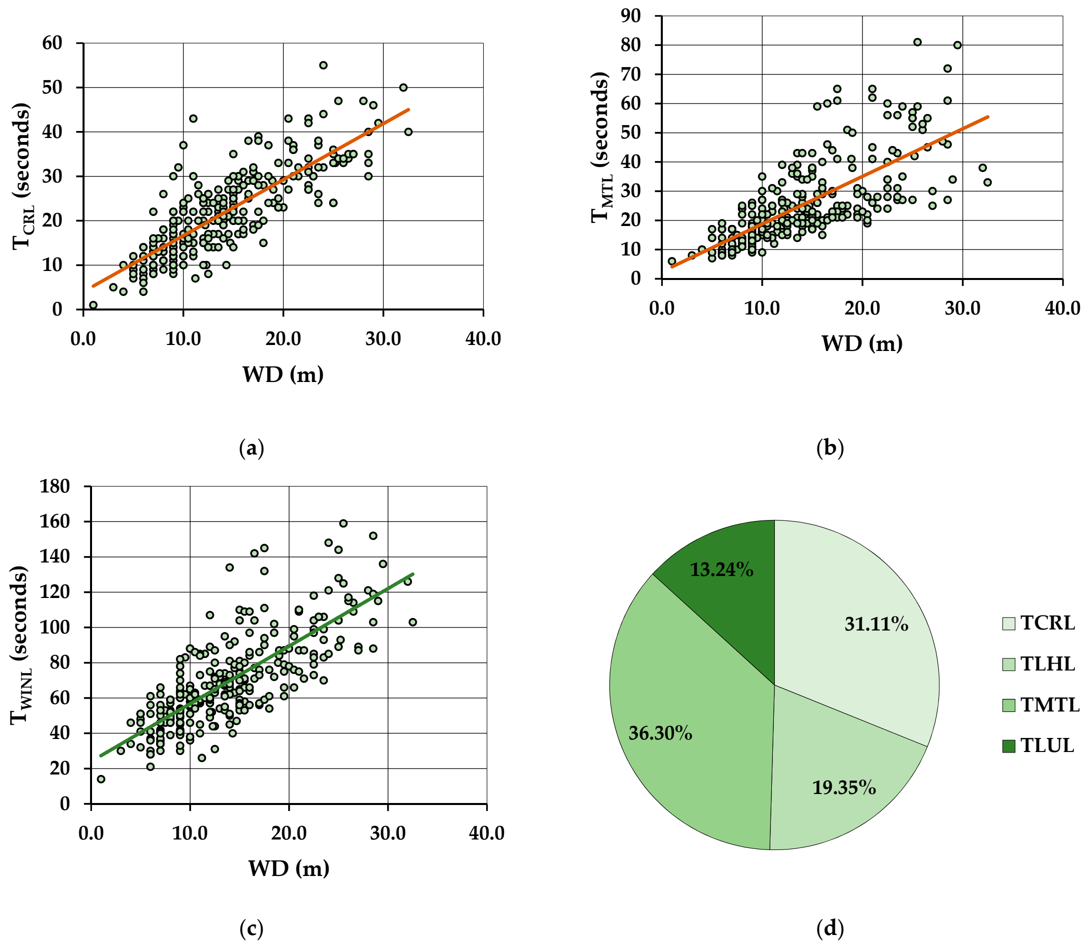

Figure 3. Time consumption estimates: (**a**) variation in log-based cable releasing time (T_{CRL}) as a function of winching distance (WD); (**b**) variation in log-based mechanical winching time (T_{MTL}) as a function of WD; (**c**) variation in log-based winching time (T_{WINL}) as a function of WD; (**d**) share of elemental time consumption in log-based winching.

The variability in time consumption data increased proportionally with the winching distance, suggesting the contribution of other unaccounted factors to the time consumption. Since, by the results of the correlation analysis, the log length (LL) variable was excluded due to a high correlation with log volume (LV), attempts were made to model by stepwise regression the time consumption for mechanical traction (T_{MTL}) and for the log-based winching work cycles (T_{WINL}) as a function of logs' volume (LV) and winching distance (WD), respectively. For cable releasing (T_{CRL}), only the winching distance was considered as a predictor. Table 5 includes the final simple linear models of the three time consumption categories along with their main statistics. As shown, log volume (LV) was not significant in explaining the variation in mechanical traction (T_{MTL}) and log-based winching work cycle (T_{WINL}) time (p = 0.24, data not included), respectively.

Table 5. Predictive models of time consumption for log-based winching.

Model	*N*	R^2	Predictor	α	*p*-Value
T_{CRL} (seconds) = 1.26 × WD (m) + 4.01	278	0.66	WD	0.05	<0.001
T_{MTL} (seconds) = 1.63 × WD (m) + 2.47	278	0.53	WD	0.05	<0.001
T_{WINL} (seconds) = 3.27 × WD (m) + 24.07	278	0.59	WD	0.05	<0.001

In the developed models, the variation in winching distance explained the variation in time consumption in proportions of 53% to 66% (Table 5). In addition, cable releasing model seemed to output lower time consumption values in relation to winching distance as opposed to the model developed for mechanical traction. This was due to the constrains in line speed as specified in Table 2, which were verified by the developed model, which, for an average winching distance of 14 m, would support a line speed of ca. 0.55 m/s. For the same condition in terms of winching distance, cable releasing, on the other hand, would support a speed of ca. 0.65 m/s, meaning a higher speed in cable releasing as opposed to mechanical traction.

3.1.2. Skidding Operations

The relevant descriptive statistics of operational and time consumption variables of skidding operations are shown in Table 6. The number of logs per turn varied between two and eight and averaged five pieces. Similar to log volume variable (Table 4), payload volume (PV) was the only variable passing the normality test. It ranged from 0.61 to 2.76 m^3, averaging 1.81 m^3. Distances for empty (ETD) and loaded (LTD) turns, as well as the average extraction distance (AED), were in range of ca. 300 m, averaging ca. 160, 194 and 177 m, respectively. The average winching distance (AWD) was close in value to the log-based winching distance (WD, Table 4).

In terms of time consumption (Table 6), the total observed time (T_{OBS}) accounted for close to 26 h, of which delay free time specific to skidding operations (T_{SOP}) accounted for ca. 13 h. Accordingly, half of the observed time was spent in delays caused by the study itself (ca. 10 h) and technical reasons (ca. 3.5 h). The high amount of time spent as study delays was directly related to the need to carry on measurements on the fuel consumption and log biometrics. A delay free skidding work cycle, which included all the operations described in Figure 2, averaged ca. 14 min. In terms of time consumption, those dominant in a skidding work cycle were the winching operations, which averaged close to 6.5 min, followed by on-road skidding (ca. 4.5 min) and landing operations (ca. 1.6 min).

To complement the data presented in Table 6, Figure 4 describes the time consumption estimates specific to skidding operations. Figure 4a–e plot the dependence relations between the time variables taken into study and the relevant distances, while Figure 4f–h give an overview on the time shares. As shown, there were significant dependence relations between the time consumption categories and the relevant operational distances.

Table 6. Descriptive statistics of operational and time consumption variables for skidding operations.

Category and Variable	Descriptive Statistics					
	Minimum Value	Maximum Value	Mean Value ± Standard Deviation	Median Value	Number of Observations	Sum
Operational						
Number of logs per payload (NL)	2.00	8.00	4.96 ± 1.37	5.00	56	278.00
Payload volume (PV, m^3) [a]	0.61	2.76	1.81 ± 0.36	1.81	56	101.52
Average winching distance (AWD, m)	8.00	26.00	14.43 ± 4.22	13.15	56	-
Empty turn distance (ETD, m)	69.00	359.00	160.34 ± 53.47	153.50	56	8979
Loaded turn distance (LTD, m)	123.00	429.00	194.27 ± 60.22	180.50	56	10,879
Average extraction distance (AED, m)	103.00	394.00	177.30 ± 53.66	165.25	56	9929
Time consumption						
Empty turn time (T_{ET}, seconds)	62.00	199.00	105.82 ± 34.13	98.00	56	5926.00
Maneuvering time (T_{MN}, seconds)	5.00	85.00	31.96 ± 17.29	30.00	56	1790.00
Winching time (T_{WIN}, seconds)	204.00	792.00	380.59 ± 131.68	352.00	56	21,313.00
Payload attachment time (T_{PA}, seconds)	22.00	142.00	58.70 ± 27.14	51.5	56	3287.00
Loaded turn time (T_{LT}, seconds)	80.00	399.00	168.09 ± 78.88	144.00	56	9413.00
Payload detachment time (T_{LD}, seconds)	3.00	32.00	13.64 ± 6.82	12.00	56	764.00
Wood piling time (T_{WP}, seconds)	18.00	205.00	92.85 ± 45.43	75.00	52	4828.00
On-road skidding time (T_{ORS}, seconds)	144.00	559.00	273.91 ± 107.29	241.50	56	15,339.00
Landing operations time (T_{LOP}, seconds)	3.00	218.00	99.86 ± 50.90	89.00	56	5592.00
Skidding cycle time (T_{SOP}, seconds)	520.00	1524.00	813.05 ± 247.08	723.50	56	45,531.00
Study delays (T_{SD}, seconds)	-	-	-	-	-	36,106.00
Technical delays (T_{TD}, seconds)	-	-	-	-	-	11,688.00
Total observed time (T_{OBS}, seconds)	-	-	-	-	-	93,325.00

Note: [a]—variable which passed the normality check.

The maximal model of skidding time consumption (T_{SOP}) included the number of logs (NL), payload volume (PV), average winching distance (AWD) and average extraction distance (AED) variables. Following the stepwise backward regression procedures, the payload volume (PV) variable was excluded based on significance reasons. The final model is shown in Table 7 along with the models developed for on-road skidding (T_{ORS}), empty turn (T_{ET}), loaded turn (T_{LT}) and winching (T_{WIN}). Non-significance of the payload volume (PV) variable was preserved also in the case of on-road skidding (T_{ORS}) and loaded turn (T_{LT}) models, while the T_{ET} model was developed using only the empty turn distance (ETD) variable. In the skidding operations model (T_{SOP}), the highest contribution to time consumption was brought by the number of winched logs (NL) and the average extraction distance (AED), results that are consistent with the data on time consumption shown in Table 6. Number of logs (NL) became a significant variable also for the model developed for winching operations where, for average values of NL, AWD and AED, it contributed the most to the time consumption. Variation in time consumption for on-road skidding (T_{ORS}), empty turn (T_{ET}), and loaded turn (T_{LT}) was best explained by the relevant operational distances: AED, ETD and LTD, respectively. Although describing a less time-consuming work element, the model developed for empty turn had the lowest predictive power (R^2 = 0.47). The rest of the models had a predictive capacity of 64 to 67%, while the model developed for the global skidding operations was characterized by a predictive capacity of 75%.

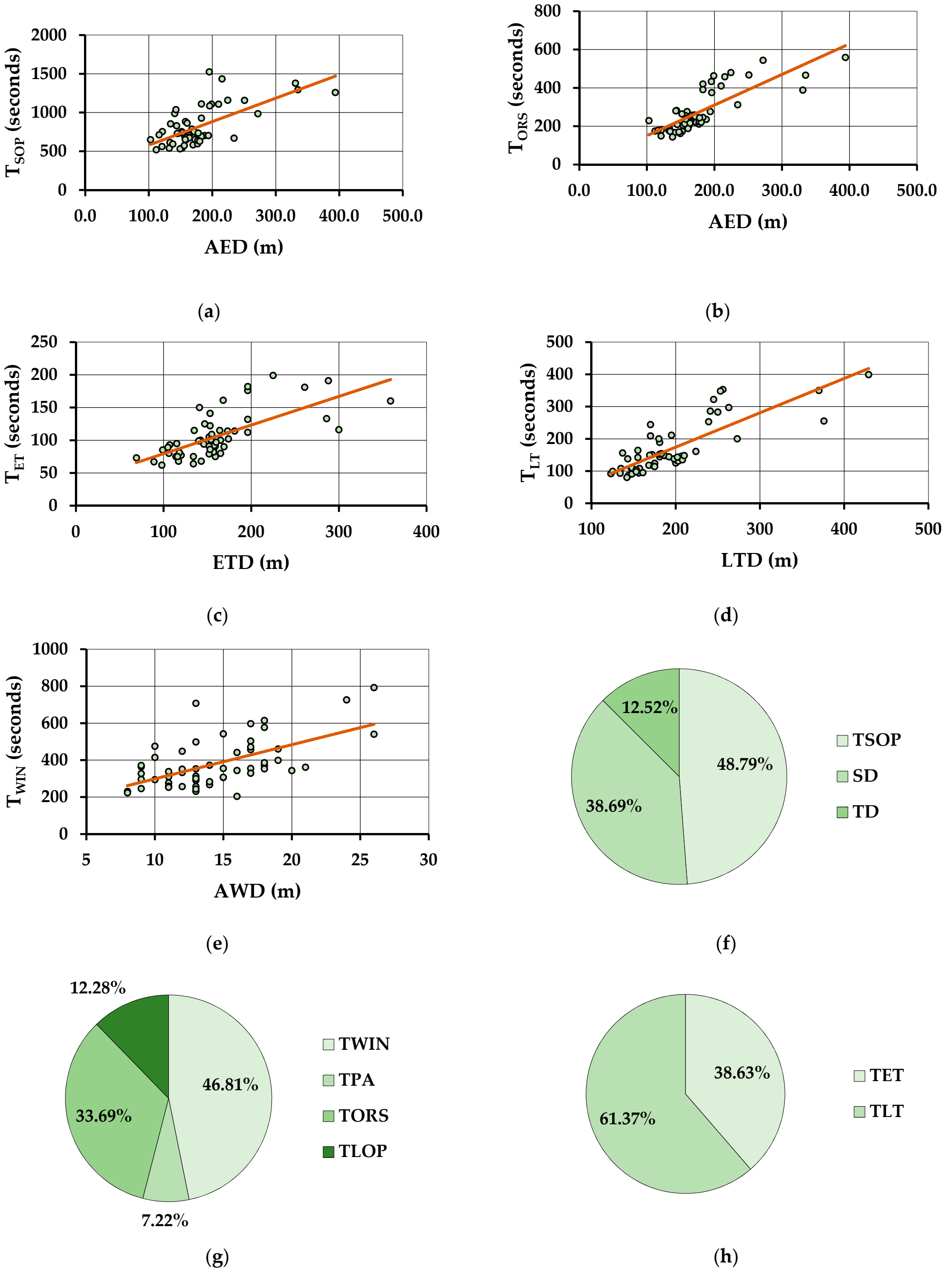

Figure 4. Time consumption estimates: (**a**) variation in time consumption of skidding operations (T_{SOP}) as a function of average extraction distance (AED); (**b**) variation in time consumption of on-road skidding (T_{ORS}) as a function of AED; (**c**) variation in empty turn time (T_{ET}) as a function of empty turn distance (ETD); (**d**) variation in loaded turn time (T_{LT}) as a function of loaded turn distance (LTD); (**e**) variation in winching time (T_{WIN}) as a function of average winching distance (AWD); (**f**) share of delay-free time (T_{SOP}) in the total observed time; (**g**) share of operational time (T_{WIN}, T_{PA}, T_{ORS}, T_{LOP}) in the delay-free time (T_{SOP}); (**h**) share of empty (T_{ET}) and loaded turn (T_{LT}) time in the on-road skidding time (T_{ORS}).

Table 7. Predictive models of time consumption for skidding operations.

Model	*N*	R^2	Global Sig.	Predictor	α	*p*-Value
T_{SOP} (seconds) = 90.09 × NL + 15.81 × AWD (m) + 2.24 × AED (m) − 259.20	56	0.75	<0.001	NL	0.05	<0.001
				AWD	0.05	<0.001
				AED	0.05	<0.001
T_{ORS} (seconds) = 1.60 × AED (m) − 9.20	56	0.64	<0.001	AED	0.05	<0.001
T_{ET} (seconds) = 0.44 × ETD (m) + 35.60	56	0.47	<0.001	ETD	0.05	<0.001
T_{LT} (seconds) = 1.06 × LTD (m) − 38.77	56	0.66	<0.001	LTD	0.05	<0.001
T_{WIN} (seconds) = 54.35 × NL + 17.20 × AWD (m) – 137.40	56	0.67	<0.001	NL	0.05	<0.001
				AWD	0.05	<0.001

Based on the data on time consumption and distance travelled, the speed of empty turn was estimated at 5.58 km/h and the speed of loaded turn at 4.51 km/h, meaning that the speed of on-road skidding was of approximately 5 km/h.

3.2. Fuel Consumption

The descriptive statistics on fuel consumption are given in Table 8. In what regards the statistics of operational variables developed by considering the 12-detailed measurement work cycles, except the number of logs (NL), all the variables were found to be normally distributed. The same was found for the fuel consumption for the empty turn (FC_{ET}) and for the fuel consumption for winching and payload attachment (FC_{WIN}). The mean values of operational variables were close to those developed for all the skidding work cycles, as shown in Table 6. In these conditions, fuel consumption for the empty turn (FC_{ET}) averaged 0.27 L (ETD = 185.58 m), fuel consumption for winching including payload attachment (FC_{WIN}) averaged 0.28 L (NL = 6.58, PV = 1.76 m^3, AWD = 13.92), fuel consumption for loaded turn including payload detachment (FC_{LT}) accounted for 0.42 L (PV = 1.76, ETD = 180.00 m) and fuel consumption for landing operations—wood piling (FC_{LOP}) accounted for 0.18 L. Globally (56 work cycles), and by accounting for the mean values of NL, PV, AWD and AED given in Table 6, the average fuel consumption in skidding operations was of 0.84 L (Table 8). Taking as a reference the mean values of operational variables estimated based on the 12 work cycles, the greatest share of fuel consumption was in the loaded turn and payload detachment (FC_{LT} = 39.0%), followed by winching and payload attachment (FC_{WIN} = 25.8%), empty turn (FC_{ET} = 25.4%) and landing operations (FC_{LOP} = 9.8%).

Accordingly, there were differences in the operational steps in terms of hourly and unit fuel consumption. The highest hourly fuel consumption was that of loaded turn and payload detachment (HFC_{LT} = 7.44 L/h), followed by empty turn (HFC_{ET} = 7.07 L/h), landing operations consisting of wood piling (HFC_{LOP} = 4.50 L/h), and winching and payload attachment (HFC_{WIN} = 2.04 L/h). For the same operational steps, the unit fuel consumptions were of 0.24, 0.16, 0.15 and 0.06 L/m^3, respectively. Based on the data sampled at the skidding operations level (56 work cycles), the hourly fuel consumption (HFC_{SOP}) was estimated at 3.72 L/h and the unit fuel consumption at 0.46 L/m^3.

Figure 5 shows the variation in fuel consumption for the operational steps taken into study as a function of operational variables. At the chosen confidence threshold, only two models were found to be relevant based on their global- and predictor-level significance (Table 9). The model explaining the fuel consumption in skidding operations (FC_{SOP}) was built based on the measurement taken for all the work cycles. Significant contributors to the fuel consumption variation were the number of logs (NL), average winching distance (AWD), and the average extraction distance (AED). Of these, the number of logs (NL) and the average extraction distance (AED) were the most significant, whereas the average winching distance (AWD) was close to fail the significance test at the chosen confidence threshold (α = 0.05, p = 0.049, Table 9). No significant models could be developed to explain the variation in fuel consumption for winching (FC_{WIN}) and loaded turn (FC_{LT}). However, the empty turn distance (ETD) explained the variation in fuel consumption during empty turn (FC_{ET}) in a proportion of 60%. The common variation of NL, AWD and AED predictors explained the variation in FC_{SOP} in a proportion of 54% (Table 9).

Table 8. Descriptive statistics of operational and fuel consumption variables for skidding operations.

Category and Variable	Descriptive Statistics					
	Minimum Value	Maximum Value	Mean Value ± Standard Deviation	Median Value	Number of Observations	Sum
Operational						
Number of logs (NL)	4.00	8.00	6.58 ± 1.51	7.00	12	79.00
Payload volume (PV, m^3) [a]	1.23	2.23	1.76 ± 0.33	1.74	12	21.123
Average winching distance (AWD, m) [a]	8.00	21.00	13.92 ± 4.08	14.00	12	-
Empty turn distance (ETD, m) [a]	89.00	288.00	185.58 ± 53.44	177.00	12	2227.00
Loaded turn distance (LTD, m) [a]	123.00	256.00	180.00 ± 44.83	170.00	12	2160.00
Average extraction distance (AED, m) [a]	112.00	272.00	182.79 ± 45.14	175.50	12	2193.50
Fuel consumption						
Fuel consumption for empty turn (FC_{ET}, L) [a]	0.05	0.65	0.27 ± 0.18	0.23	12	3.25
Fuel consumption for winching and payload attachment (FC_{WIN}, L) [a]	0.10	0.45	0.28 ± 0.10	0.28	12	3.30
Fuel consumption for loaded turn and payload detachment (FC_{LT}, L)	0.20	1.00	0.42 ± 0.25	0.33	12	5.00
Fuel consumption for landing operations (FC_{LOP}, L)	0.10	0.40	0.18 ± 0.11	0.15	7	1.25
Fuel consumption for skidding operations (FC_{SOP}, L)	0.40	1.90	0.84 ± 0.36	0.73	56	47.10
Fuel consumption metrics						
Hourly fuel consumption for empty turn (HFC_{ET}, L/h)	-	-	7.07	-	12	3.25
Hourly fuel consumption for winching and payload attachment (HFC_{WIN}, L/h)	-	-	2.04	-	12	3.30
Hourly fuel consumption for loaded turn and payload detachment (HFC_{LT}, L/h)	-	-	7.44	-	12	5.00
Hourly fuel consumption for landing operations (HFC_{LOP}, L/h)	-	-	4.50	-	7	1.25
Hourly fuel consumption for skidding operations (HFC_{SOP}, L/h)	-	-	3.72	-	56	47.10
Unit fuel consumption for empty turn (UFC_{ET}, L/m^3)	-	-	0.15	-	12	3.25
Unit fuel consumption for winching and payload attachment (HFC_{WIN}, L/m^3)	-	-	0.16	-	12	3.30
Unit fuel consumption for loaded turn (HFC_{LT}, L/m^3)	-	-	0.24	-	12	-
Unit fuel consumption for landing operations (HFC_{LOP}, L/m^3)	-	-	0.06	-	7	-
Unit fuel consumption for skidding operations (HFC_{SOP}, L/m^3)	-	-	0.46	-	56	-

Note: [a]—variables that passed the normality check.

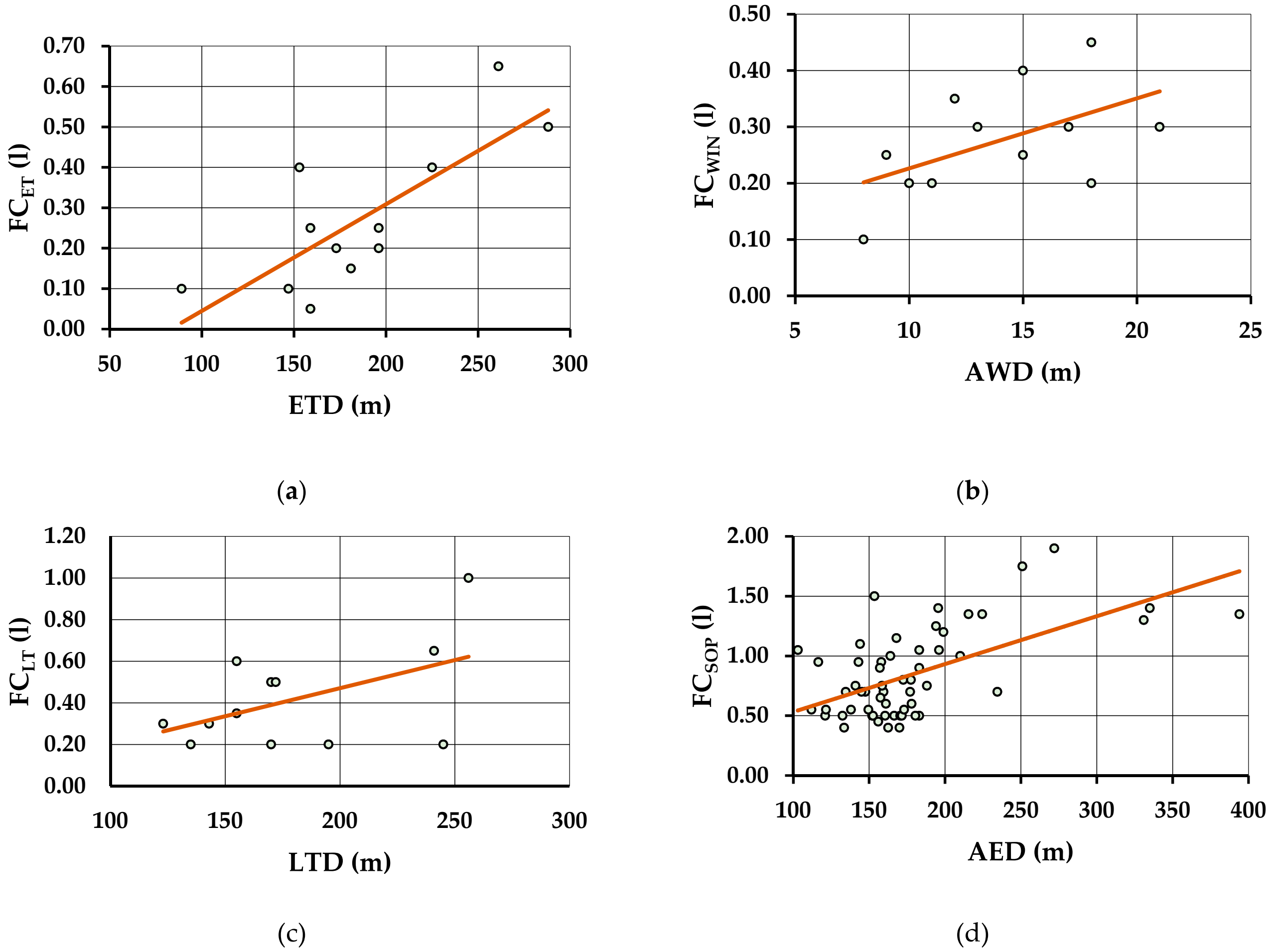

Figure 5. Fuel consumption estimates: (**a**) variation in fuel consumption for empty turn (FC_{ET}) as a function of empty turn distance (ETD); (**b**) variation in fuel consumption for winching and payload attachment (FC_{WIN}) as a function of average winching distance (AWD); (**c**) variation in fuel consumption for loaded turn and payload detachment (FC_{LT}) as a function of loaded turn distance (LTD); (**d**) variation in fuel consumption for skidding operations (FC_{SOP}) as a function of average extraction distance (AED).

Table 9. Predictive models of fuel consumption for skidding operations.

Model	*N*	R^2	Global Sig.	Predictor	α	*p*-Value
FC_{SOP} (l) = 0.105 × NL + 0.017 × AWD (m) + 0.003 × AED (m) − 0.478	56	0.54	<0.001	NL	0.05	<0.001
				AWD	0.05	0.049
				AED	0.05	<0.001
FC_{ET} (l) = 0.003 × ETD (m) − 0.219	12	0.60	0.003	ETD	0.05	0.003

Taking into consideration the minimum, maximum and mean values of NL, AWD and AED, as shown in Table 6, the cycle-wise fuel consumption in skidding operations (FC_{SOP}) estimated by the model from Table 9 may account for 0.177 (NL = 2, AWD = 8 m, AED = 103 m, minimum conditions), 0.820 (NL = 4.96, AWD = 14.43 m, AED = 177.30 m, average conditions) and 1.986 L (NL = 8, AWD = 26 m, AED = 394 m, maximum conditions), respectively.

3.3. Efficiency and Productivity

Efficiency and productivity estimates are shown in Table 10 as average figures along with the baseline variables used to compute them. The figures are based on the productive machine hours (PMH). Among the most efficient and productive operations was the payload attachment, with a net efficiency of 0.009 h/m^3 and a net productivity of 111.194 m^3/h. At the level of studied operations (winching, payload attachment, on-road skidding and landing operations), this outcome was related with the lowest time consumption, as shown in Table 10. Landing operations were next in line, with a net efficiency of 0.015 h/m^3 and a net productivity of 65.370 m^3/h. Globally, skidding operations observed in the two study sites were characterized by a net efficiency of 0.125 h/m^3 and a net productivity of 8.027 m^3/h; technical delays substantially affected the skidding efficiency and productivity estimates. Accordingly, there was an increase of 0.032 h/m^3 and a reduction of 1.640 m^3/h in efficiency and productivity, respectively. These reductions in productive performance were related to a time of 3.246 h spent to solve technical issues.

Table 10. Estimates of Net and Gross Efficiency and Productivity.

Category, Performance Metric (Measurement Unit)	Production (m^3)	Net Time (h)	Gross Time (h)	Values
EN_{SOP} (h/m^3)	101.52	12.648	-	0.125
EN_{WIN} (h/m^3)	101.52	5.920	-	0.058
EN_{ORS} (h/m^3)	101.52	4.261	-	0.042
EN_{PA} (h/m^3)	101.52	0.913	-	0.009
EN_{LOP} (h/m^3)	101.52	1.553	-	0.015
EG_{SOP} (h/m^3)	101.52	-	15.894	0.157
PN_{SOP} (m^3/h)	101.52	12.648	-	8.027
PN_{WIN} (m^3/h)	101.52	5.920	-	17.149
PN_{ORS} (m^3/h)	101.52	4.261	-	23.825
PN_{PA} (m^3/h)	101.52	0.913	-	111.194
PN_{LOP} (m^3/h)	101.52	1.553	-	65.370
PG_{SOP} (m^3/h)	101.52	-	15.894	6.387

Productivity and efficiency of log-based winching were affected by the variation in winching distance, as shown in Figure 6. The effect of including the maneuvering time in the estimation of efficiency and productivity for winching operations can be seen in the shape of respective functions from Figure 6b,c. For mean values of winching distance (WD) and average winching distances (AWD) of 14 m, the difference in productivity of log-based winching (which does not include the maneuvering time) compared to that of overall winching operations (which includes the maneuvering time) was of ca. 2 m^3/h. Comparing the same data analysis resolutions, the difference in efficiency was of 0.024 h/m^3.

For on-road skidding (empty and loaded turns), the average extraction distance (AED) affected to a large extent the productivity and efficiency functions, indicating a productivity almost 4 times higher for distances of approximately 100 m as opposed to extraction distances of approximately 400 m (Figure 6e). Accordingly, in net figures, ca. 4.5-fold more time was required to be spent on a unit of production for an extraction distance of 400 m than that of 100 m (Figure 6f).

At the level of overall skidding operations, the effect of winching and landing operations time has reduced the contrasts in productivity and efficiency. Still, for the median values in terms of number of winched logs (NL = 5) and average winching distance (AWD = 13.15 m), the net productivity of overall skidding operations was two times higher at an extraction distance of 100 m as opposed to an extraction distance of 400 m. Accordingly, the time spent per unit of production was higher by 0.1 h for a distance of 400 m, as opposed to a distance of 100 m.

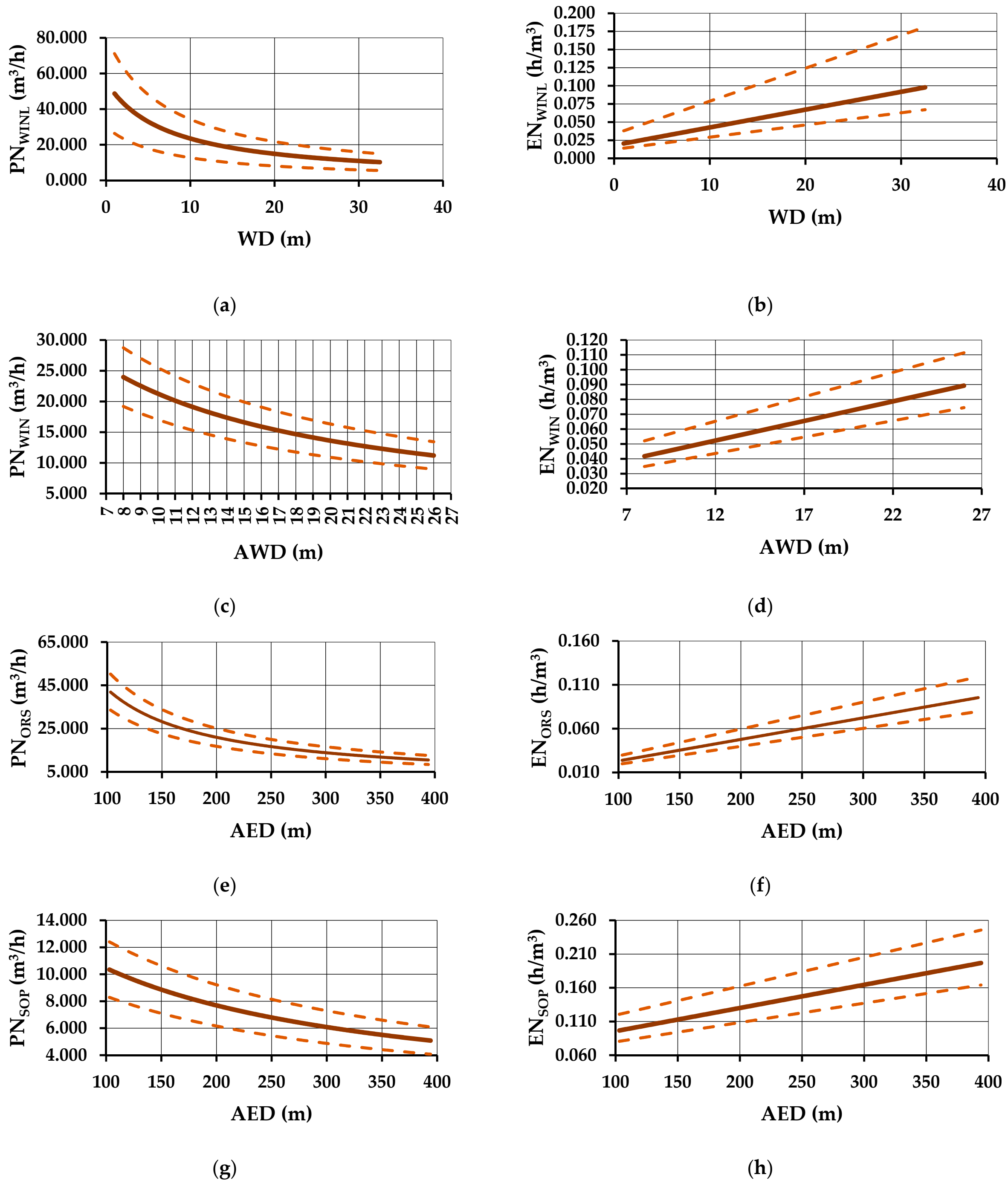

Figure 6. Efficiency and productivity models developed by taking as a reference the mean and standard deviation values of log (LV) and payload (PV) volumes and the ranges of operational distances: (**a**) variation in net productivity of log-based winching; (**b**) variation in net efficiency of log-based winching; (**c**) variation in net productivity of winching; (**d**) variation in net efficiency of winching; (**e**) variation in net productivity of on-road skidding; (**f**) variation in net efficiency of on-road skidding; (**g**) variation in net productivity of skidding operations; (**h**) variation in net efficiency of skidding operations. Note: light brown dashed lines stand for productivity and efficiency computed by using mean $\pm$ standard deviations of the log (**a**,**b**) and payload volume (**c**–**h**), dark brown continuous lines stand for productivity and efficiency computed by using mean values of the log (**a**,**b**) and payload volume (**c**–**h**); models from (**c**–**f**) were built using the median value of the number of logs (NL = 5), and models from (**g**,**h**) were built by using the median values of NL (5) and average winching distance (AWD = 13.15 m).

Both log (LV) and payload (PV) volumes were variables that were found to be normally distributed. Accordingly, the standard deviations of these variables could reflect and were used to describe the uncertainty in efficiency and productivity estimates. The trends shown in Figure 6 indicate higher and lower uncertainties in productivity and efficiency, respectively, for lower ranges of operational distances. In the case of on-road skidding and overall skidding operations, the number of logs (NL) and the winching distance (AWD) were kept at their median values. Lower winching distances, for instance, would contribute to increases in the productivity of skidding operations. For instance, log-based winching may output a productivity between 30 and 70 m^3/h when the logs are to be attached to the cable right from the back of the farm tractor (Figure 6a). Going up to an average winching distance of 8 m, and including the maneuvering time, the winching operation may output a productivity anywhere between ca. 19 and 29 m^3/h (Figure 6c). For median values of 5 and 13.15 m in the number of logs (NL) and average winching distance (AWD), respectively, the productivity of skidding operations was modeled at 10.345 ± 2.058 m^3/h for an average extraction distance (AED) of 103 m and at 5.084 ± 1.011 m^3/h for an average extraction distance (AED) of 394 m.

4. Discussion

In general, the results of this work confirm previous findings in terms of time consumption and productivity in skidding operations by farm tractors. However, they bring novelty in terms of approach and variables used, models developed and inferences made on the variability in time consumption, efficiency and productivity. There is a set of options tested so far in terms of operational layout, configuration of machines used, and operational conditions. The performance of piece-by-piece winching may depend on several operational variables such as the volume of the log, winching distance, slope on the winching path, and winching direction [10,14], while winching itself can be significantly improved in terms of productivity whenever chokers may be used to increase the payload per work cycle [6]. However, the effects brought by these variables are context-dependent, and some of them may become irrelevant, as indicated by this study. For instance, the volume of the winched stems was too low to output a weight able to create a sensible variation in the time consumption. This was also found in the Greek flat land skidding conditions by farm tractors [25] and was due to the capacity of the used winch, which was much higher than that required to deal with the weight of the extracted stems. Although the productivity of piece-by-piece winching was found to be the highest among the studied operational steps, there are limits in capability brought by the line speed and the speed at which the manual workers can move the cable from the tractor to the wood pieces to be attached. The average speed in mechanical traction accounted for 0.55 m/s, and it was consistent with the average speed of the winch, while the speed of cable releasing was significantly higher, accounting for 0.65 m/s; therefore, cable releasing time required less time as a function of the winching distance. However, the outcome on the cable releasing speed may be valid only in flat terrain as the presence of slope could affect it depending on the winching direction. For instance, in sloped terrain, the study of [26] found speeds of 0.43 to 0.53 m/s for both, cable releasing and mechanical traction, while another study of [27] reported considerably higher speeds, which were in the range of 0.5–1.3 m/s. In addition, the direction of cable releasing was found to add to the time consumption models when it was done uphill [14].

In flat land skidding, the operational distances may become the most relevant predictors of time consumption assuming that the mechanical capacity of the winch and of the tractor itself in much higher than that required to move the logs from stump to the landing. In this study, operational distances were relevant for winching and on-road skidding. For a skidding work cycle, the number of extracted logs, average winching and average extraction distances were the significant predictors explaining the time consumption. These results are in line with those of [25] but disagree with those of studies conducted in sloped terrain [28,29] where the slope and payload volume became relevant. It is a fact that winching is an operation that takes an important amount of time, particularly in low ranges of extraction distances, as it was found in this research. Since forming a load required two to eight stems (median value of five stems), it was unsurprising to find that these cable releasing and mechanical traction repetitions in a winching work cycle affected the time consumption proportionally. Since the average winching distance was used, and the stems and payloads were too small to affect the traction capacity, the number of logs became a significant variable in explaining the skidding cycle time along with the average winching and extractions distances. Then, the time spent in winching operations accounted for close to half of the operational time of a skidding work cycle; therefore, the effect brought by the number of logs was higher in the model.

Productivity depends largely on the variation in average payload size and the time needed to move the wood form the felling area to the landing; payload size depends on the type of felling, tree size and the used harvested method [6]; while the time needed to move and pile the wood at the landing depends on variation in many predictor variables such as the winching and skidding distances, slope, direction of winching and skidding, etc. The variation in net productivity found by this study was assumed to depend on the average payload size as input, and on the number of logs, average winching and extraction distances, as explanatory variables. For a mean payload of 1.8 m^3, a median number of logs of five, and winching and extraction distances of 14 and 177 m, respectively, the net productivity was estimated at ca. 8 m^3/h, but it varied widely, for instance, as a function of extraction distance from approximately 5 m^3/h (for an extraction distance of 394 m) to approximately 10 m^3/h (for an extraction distance of 103 m). These results complement the existing knowledge on the time consumption and productivity in skidding by farm tractors. For instance, the study of [28] has reported a mean skidding distance of 665 m, a payload volume of ca. 1.5 m^3 and a number of 1.17 logs skidded per turn in sloped terrain by an 80.5 kW farm tractor. For these conditions, they found a mean productivity of 2.6 m^3/h. The slope of the skidding roads, and particularly the skidding direction in relation to the slope, may affect the productivity. As an example, the productivity of uphill skidding by farm tractors directly from the stump was found to be reduced by 25% as an effect of increasing the slope by 10% [30], while for downhill skidding, using the same operational pattern, the study of [31] reported a mean productivity of 4.75 m^3/h for an extraction distance of 385 m, a payload volume of 1.80 m^3 (close to that of this study), and a number of 2.6 logs per turn. As of this study, a similar productivity would be probably reached at 430 m, which probably indicates the effects that the number of logs per turn and winching distance may have on the performance of farm tractors in skidding.

Fuel consumption evaluations are, indeed, rare in studies assessing the performance of skidding operations, and fuel consumption variation models were not identified by the authors of this study for farm tractor skidding. The attempt to develop fuel consumption models for all important operational steps of skidding was partly successful in this study. Hence, only for the overall skidding operations and for the empty turn were developed suitable models, although the pattern in data indicated relations between operational distances and fuel consumption for all the operational steps involving movement. For instance, the average winching distance just failed (p = 0.079) to become significant in explaining the fuel consumption in winching operations. The fuel consumption for a skidding work cycle was found to be dependent on the same variables as in the case of time consumption, namely the number of winched logs and average winching and extraction distances. The high number of winched logs, reflecting the repeated work elements to form a payload, was found to contribute to a large extent in the model; by the developed model, one can estimate how variation in the number of piece-by-piece winched logs, average winching and extraction distances may affect the fuel consumption. The same apply to the figures estimated for the main operational steps in terms of hourly, unit and share in fuel consumption, which may be used to differentiate between machine running regimes.

Since detailed models explaining the fuel consumption in skidding operations were difficult to find, the results of this study are compared only in terms of hourly and unit fuel consumption. For an end-to-end delivery of wood (from felled stems to piled wood), the hourly fuel consumption was found to be of 3.72 L/h, while the unit fuel consumption was found to be of 0.46 L/m^3. These results agree with the size class of the farm tractor taken into study, as well as with the state of technological development. In comparison, for skidding operations, the study of [32] has found hourly fuel consumptions in the range of 6.7 to 7.0 L/h, respectively, and unit fuel consumptions in the range of 0.50 to 0.54 and L/ m^3, respectively. Their study considered an average extraction distance of 200 m, which was close to that of this study; however, the machine was a specialized older skidder with an engine output of 75 kW.

The increasing pressure on the fossil fuel resources, energy security and environmental concerns stand for important reasons to account for the fuel consumption and environmental performance in product or service-oriented systems. Data on fuel consumption are important to run energy analyses and to account for the environmental performance of forest operations [16,20,33–37]. The same way, accounting for fuel consumption variation due to changes in operational conditions is important to scale the outputs of future studies, particularly in a changing technological environment that favors the introduction of significantly improved machines in operations that have different fuel and lubricant consumption characteristics [38]. From this point of view, the developed fuel consumption model may help in understanding the variations brought by contrasting operational conditions, but it is restricted to flat terrains. As an example, by the model developed by this study, for a number of logs set at eight, an average winching distance of 14 and an average extraction distance of 100 m, the fuel consumption estimate would be of 1.378 L. For the same conditions but for a number of logs set at two, the fuel consumption would be almost half, accounting for 0.748 L.

Understanding the limitations of the models developed in this study is important. First of all, the models apply to flat terrains and to a given amount of variation in log biometrics and operational distances. Accordingly, for similar conditions in terms of number of logs, payload volume and extraction distances, the presence of sloped terrains has the potential to significantly affect the mathematical shape of the time consumption, efficiency and productivity models. This is because an important share of the work is performed manually, while the slope is a conditioning factor of human performance in winching operations [39]. It is likely that the time needed to winch the logs would depend more on their locations and availability in the felling area than on their size. This is due the capacity of the winch taken into study. Accordingly, winching operations would become more productive, as the volume per log will increase with some differences probably brought by the log size in the log hooking work element. For fewer but larger logs, the productivity increment will propagate also in on-road skidding and in the overall skidding operations by two mechanisms, namely an increased size of the payload and a lower number of winching repetitions until forming a payload. To what extent the fuel consumption in winching will vary, however, needs additional checks for larger log sizes. In addition, the figures and models on fuel consumption were built based on observations taken in a relatively warm weather; therefore, for contrasting conditions such as those from winter, they need to be updated by a correction factor. The same conditions in the form of snow layer's presence may also affect the time consumption and productivity of operations. For conditions similar to those of this study in terms of number of logs and their size, it is likely that the productivity and efficiency trends would be similar for distances out of that used to build the time consumption models.

Flat terrains are operable by several ground-based timber extraction systems, which may include the use of specialized skidders and forwarders [6]. Most of such machines are rather heavy and, excepting winch skidders, require access to the felled trees, and therefore would cause a more pronounced impact on the forest soils. In addition, specialized forestry machines come at higher purchasing and owning costs, which may result in high operational costs, particularly when extracting small-sized wood at low extraction intensities. These may be among the reasons for using farm tractors in local practice as versatile machines for timber extraction.

5. Conclusions

Based on the results of this study, it is evident that the characteristics of the operational environment such as the slope and size of the logs affect the significance of the variables explaining the time and fuel consumption in skidding operations by farm tractors. For log and payload volumes that are not challenging for the winch and tractor's tractive capacities, the only explaining variables were those characterizing the operational distances and the number of repetitions required to winch logs and to form a payload. The models explaining the variation in time and fuel consumption for the overall skidding operations included the same set of predictor variables that, in the absence of slope, indicate a link between the variability in time and fuel consumption. Similar to other studies, the productivity of most of the studied skidding operations varied widely as a function of operational distances. Therefore, the developed models may be useful for production planning, organization, cost setting and environmental accounting. For similar operational conditions, improving the productivity while lowering the fuel consumption and CO^2 emissions per unit of production may rest in changing the methods of work in winching operation by the use of chockers whenever possible. This would increase the number of pieces and volume inputs per winching cycle and would reflect positively on the productivity and unit fuel use. Arguably, specialized skidders could be an alternative solution to similar conditions. However, the final skidding costs would be affected by the cost of machine purchasing and owning as compared to the farm tractor studied herein.

Author Contributions: Conceptualization, S.A.B.; data curation, S.A.B. and V.-B.M.; formal analysis, V.-B.M.; funding acquisition, S.A.B.; investigation, V.-B.M.; methodology, S.A.B. and V.-B.M.; project administration, S.A.B.; resources, S.A.B. and V.-B.M.; software, S.A.B.; supervision, S.A.B.; validation, S.A.B.; visualization, S.A.B.; writing—original draft, S.A.B. and V.-B.M.; writing—review and editing, S.A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding and the APC was funded by the Transilvania University of Brasov.

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

Data Availability Statement: Data supporting this study may be provided upon a reasonable request to the first author of the study.

Acknowledgments: The authors would like to thank to the management of the Forest Directorate of Dolj and to the management of the National Forest Administration—RNP Romsilva. The analytical part of this work was funded by the project "*Studiu privind stabilirea consumurilor de combustibili și a normelor de timp și producție în activitatea de colectare a lemnului ca urmare a modernizării parcului de utilaje al unităților regiei*", financed by the National Forest Administration—RNP Romsilva. Part of the data supporting this study was used in the master thesis of the second author.

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

Appendix A

Equations used to characterize the time, fuel consumption, efficiency and productivity metrics.

$$T_{OBS} = T_{SOP} + T_{SD} + T_{TD} \text{ (seconds)} \quad (A1)$$

$$T_{SOP} = T_{WIN} + T_{PA} + T_{ORS} + T_{LOP} \text{ (seconds)} \quad (A2)$$

$$T_{WIN} = T_{MN} + T_{CR} + T_{LH} + T_{MT} + T_{LU} \text{ (seconds)} \quad (A3)$$

$$T_{ORS} = T_{ET} + T_{LD} \text{ (seconds)} \quad (A4)$$

$$T_{LOP} = T_{PD} + T_{WP} \text{ (seconds)} \quad (A5)$$

$$T_{WINL} = T_{CRL} + T_{LHL} + T_{MTL} + T_{LUL} \text{ (seconds)} \quad (A6)$$

$$PV = \sum_{1}^{n} LV_i \left(m^3\right) \quad (A7)$$

$$P = \sum_{1}^{n} PV_i \left(m^3\right) \quad (A8)$$

$$EN_{WINL} = T_{WINL}/P \ (h/m^3) \quad (A9)$$

$$EN_{SOP} = T_{SOP}/P \ (h/m^3) \quad (A10)$$

$$EN_{WIN} = T_{WIN}/P \ (h/m^3) \quad (A11)$$

$$EN_{ORS} = T_{ORS}/P \ (h/m^3) \quad (A12)$$

$$EN_{PA} = T_{PA}/P \ (h/m^3) \quad (A13)$$

$$EN_{LOP} = T_{LOP}/P \ (h/m^3) \quad (A14)$$

$$EG_{SOP} = (T_{SOP} + T_{TD})/P \ (h/m^3) \quad (A15)$$

$$PN_{WINL} = P/T_{WINL} \ (m^3/h) \quad (A16)$$

$$PN_{SOP} = P/T_{SOP} \ (m^3/h) \quad (A17)$$

$$PN_{WIN} = P/T_{WIN} \ (m^3/h) \quad (A18)$$

$$PN_{ORS} = P/T_{ORS} \ (m^3/h) \quad (A19)$$

$$PN_{PA} = P/T_{PA} \ (m^3/h) \quad (A20)$$

$$PN_{LOP} = P/T_{LOP} \ (m^3/h) \quad (A21)$$

$$PG_{SOP} = P/(T_{SOP} + T_{TD}) \ (m^3/h) \quad (A22)$$

where:

T_{OBS} is the total observed time, T_{SOP}—time consumed during the overall skidding operations, T_{SD}—delay time caused by the study, T_{TD}—delay time caused by technical reasons, T_{WIN}—time consumed during winching operations, T_{PA}—time consumed during payload attachment. T_{ORS}—time consumed during on-road skidding, T_{LOP}—time consumed during landing operations, T_{MN}—time consumed during all maneuvers for positioning, T_{CR}—time consumed during all cable releasing events, T_{LH}—time consumed during all cable hook events, T_{MT}—time consumed during all mechanical traction events, T_{LU}—time consumed during all log unhooking events, T_{ET}—time consumed during all empty turn events, T_{LT}—time consumed during all loaded turn events, T_{PD}—time consumed during all payload detachment events, T_{WP}—time consumed during all wood piling events, T_{WINL}—time consumed during a log-based winching event, T_{CRL}—time consumed during a log-based cable releasing event, T_{LHL}—time consumed during a log-based hook event, T_{MTL}—time consumed during a log-based mechanical traction event, T_{LUL}—time consumed during a log-based unhooking event, PV—volume of a payload as the sum of volumes of individual logs (i = 1 to n, LV), P—production as the sum of volumes of individual payloads (i = 1 to n), EN_{WINL}—net efficiency of piece-by-piece (log-based) winching, EN_{SOP}—net efficiency of overall skidding operations, EN_{WIN}—net efficiency of winching operations, EN_{ORS}—net efficiency of on-road skidding operations, EN_{PA}—net efficiency of payload attachment, EN_{LOP}—net efficiency of landing operations, EG_{SOP}—gross efficiency of overall skidding operations, PN_{WINL}—net productivity of piece-by-piece (log-based) winching, PN_{SOP}—net productivity of overall skidding operations, PN_{WIN}—net productivity of winching operations, PN_{ORS}—net productivity of on-road skidding operations, PN_{PA}—net productivity of payload attachment, PN_{LOP}—net productivity of landing operations, PG_{SOP}—gross productivity of overall skidding operations.

References

1. Marchi, E.; Chung, W.; Visser, R.; Abbas, D.; Nordfjell, T.; Mederski, P.S.; McEwan, A.; Brink, M.; Laschi, A. Sustainable forest operations (SFO): A new paradigm in a changing world and climate. *Sci. Total Environ.* **2018**, *634*, 1385–1397. [CrossRef] [PubMed]
2. Hiesl, P.; Benjamin, J.G. Applicability of international harvesting equipment productivity studies in Maine, U.S.A.: A literature review. *Forests* **2013**, *4*, 898–921. [CrossRef]

3. Borz, S.A.; Marcu, M.V.; Cataldo, M.F. Evaluation of an HSM 208F 14tone HVT-R2 forwarder prototype under conditions of steep-terrain low-access forests. *Croat. J. For. Eng.* **2021**, *42*, 185–200. [CrossRef]
4. Lindroos, O.; Cavalli, R. Cable yarding productivity models: A systematic review over the period 2000–2011. *Int. J. For. Eng.* **2016**, *27*, 79–94. [CrossRef]
5. Heinimann, H.R. A computer model to differentiate skidder and cable-yarder based road network concepts on steep slopes. *J. For. Res.* **1998**, *3*, 1–9. [CrossRef]
6. Oprea, I. *Tehnologia Exploatării Lemnului*; Transilvania University Press: Braşov, Romania, 2008; pp. 11–80. ISBN 978-973-598-301-7.
7. Lundbäck, M.; Häggström, C.; Nordfjell, T. Worldwide trends in methods for harvesting and extracting industrial roundwood. *Int. J. For. Eng.* **2021**, *32*, 202–215. [CrossRef]
8. Spinelli, R.; Magagnotti, N.; Visser, R.; O'Neal, B. A survey of skidder fleet of Central, Eastern and Southern Europe. *Eur. J. For. Res.* **2021**, *140*, 901–911. [CrossRef]
9. Moskalik, T.; Borz, S.A.; Dvorák, J.; Ferencik, M.; Glushkov, S.; Muiste, P.; Lazdinš, A.; Styranivsky, O. Timber harvesting methods in Eastern European countries: A review. *Croat. J. For. Eng.* **2017**, *38*, 231–241.
10. Ghaffaryian, M.R. An overview on work productivity evaluation of farm tractors in skidding operations. *Silva Balc.* **2022**, *23*, 21–36. [CrossRef]
11. Bîrda, M. Evaluation of winch performance in roundwood harvesting. *Bull. Transilv. Univ. Bras. Ser. II For. Wood Ind. Agric. Food Eng.* **2013**, *6*, 1–8.
12. Borz, S.A. A Review of the Romanian and International Practices in Skidding Operations. In Proceedings of the XIV World Forestry Congress, Durban, South Africa, 7–11 September 2015; p. 11.
13. Borz, S.A.; Ignea, G.; Popa, B.; Sparchez, G.; Iordache, E. Estimating time consumption and productivity of roundwood skidding in group shelterwood system—A case study in a broadleaved mixed stand located in reduced accessibility conditions. *Croat. J. For. Eng.* **2015**, *36*, 137–146.
14. Borz, S.A.; Ignea, G.; Popa, B. Modelling and comparing timber winching performance in windthrow and uniform selective cuttings for two Romanian skidders. *J. For. Res.* **2014**, *19*, 473–482. [CrossRef]
15. Borz, S.A.; Dinulica, F.; Birda, M.; Ignea, G.; Ciobanu, V.D.; Popa, B. Time consumption and productivity of skidding Silver fir (Abies alba Mill.) round wood in reduced accessibility conditions: A case study in windthorw salvage logging from Romanian Carpathians. *Ann. For. Res.* **2013**, *56*, 363–375.
16. Vusić, D.; Šušnjar, M.; Marchi, E.; Spina, R.; Zečić, Ž.; Picchio, R. Skidding operations in thinning and shelterwood cut of mixed stands—Work productivity, energy inputs and emissions. *Ecol. Eng.* **2013**, *61*, 216–223. [CrossRef]
17. Holzleitner, F.; Stampfer, K.; Visser, R. Utilization rates and cost factors in timber harvesting based on long-term machine data. *Croat. J. For. Eng.* **2011**, *32*, 501–508.
18. Björheden, R.; Apel, K.; Shiba, M.; Thompson, M.A. *IUFRO Forest Work Study Nomenclature*; Swedish University of Agricultural Science: Grapenberg, Sweden, 1995; p. 16.
19. Acuna, M.; Bigot, M.; Guerra, S.; Hartsough, B.; Kanzian, C.; Kärhä, K.; Lindroos, O.; Magagnotti, N.; Roux, S.; Spinelli, R.; et al. *Good Practice Guidelines for Biomass Production Studies*; CNR IVALSA Sesto Fiorentino (National Research Council of Italy—Trees and Timber Institute): Sesto Fiorentino, Italy, 2012; pp. 1–51. ISBN 978-88-901660-4-4.
20. Ignea, G.; Ghaffaryian, M.R.; Borz, S.A. Impact of operational factors on fossil energy inputs in motor-manual tree felling and processing: Results of two case studies. *Ann. For. Res.* **2017**, *60*, 161–172. [CrossRef]
21. Muşat, E.C.; Apăfăian, A.I.; Ignea, G.; Ciobanu, V.D.; Iordache, E.; Derczeni, R.A.; Spârchez, G.; Vasilescu, M.M.; Borz, S.A. Time expenditure in computer aided time studies implemented for highly mechanized forest equipment. *Ann. For. Res.* **2016**, *59*, 129–144. [CrossRef]
22. Borz, S.A.; Cheţa, M.; Bîrda, M.; Proto, A.R. Classifying operational events in cable yarding by a machine learning application to GNSS-collected data: A case study on gravity-assisted downhill yarding. *Bull. Transilv. Univ. Bras. Ser. II For. Wood Ind. Agric. Food Eng.* **2022**, *15*, 13–32. [CrossRef]
23. Cataldo, M.F.; Marcu, M.V.; Iordache, E.; Zimbalatti, G.; Proto, A.R.; Borz, S.A. Performance of forwarding operations in biomass recovery from apple orchards. *Small-Scale For.* **2022**. [CrossRef]
24. Zar, J.H. *Biostatistical Analysis*, 5th ed.; Pearson Prentice Hall: Hoboken, NJ, USA, 2010; p. 944.
25. Gallis, C.; Spyroglou, G. Productivity linear regressions of tree-length harvesting system in natural coastal Aleppo pine (*Pinus halepensis* L.) forests in the Chalkidiki area of Greece. *Croat. J. For. Eng.* **2012**, *33*, 115–123.
26. Yoshida, M.; Sakai, H. Winch harvesting on flat and steep terrain areas and improvements of its methodology. *Croat. J. For. Eng.* **2015**, *36*, 55–61.
27. Sowa, J.M.; Szewczyk, G. Time consumption of skidding in mature stands performed by winches powered by farm tractor. *Croat. J. For. Eng.* **2013**, *34*, 255–264.
28. Gilanipoor, N.; Najafi, A.; Heshmat Alvaezin, S.M. Productivity and cost of farm tractor skidding. *J. For. Sci.* **2012**, *58*, 21–26. [CrossRef]
29. Proto, A.R.; Macri, G.; Visser, R.; Russo, D.; Zimbalatti, G. Comparison of timber extraction productivity between winch and grapple skidding: A case study in Southern Italian Forests. *Forests* **2018**, *9*, 61. [CrossRef]
30. Gülci, S.; Büyüksakalli, H.; Taş, I.; Akay, A.E. Productivity analysis of timber skidding operation with farm tractor. *Eur. J. For. Eng.* **2018**, *4*, 26–32. [CrossRef]

31. Özturk, T.; Varsak, M.G.; Bilici, E. Evaluating productivity and cycle time of skidding method with farm tractors in Bigadic Forest Enterprise Directorate in Turkey. *Eur. J. For. Eng.* **2018**, *5*, 77–82.
32. Sabo, A.; Poršinsky, T. Skidding of fir roundwood by Timberjack 240C from selective forests of Groski Kotar. *Croat. J. For. Eng.* **2005**, *26*, 13–27.
33. Boja, N.; Borz, S.A. Energy inputs in motor-manual release cutting of broadleaved forests: Results of twelve options. *Energies* **2020**, *13*, 4597. [CrossRef]
34. Berendt, F.; Fortin, M.; Suchomel, C.; Schweier, J. Productivity, costs, and selected environmental impacts of remote-controlled mini forestry crawlers. *Forests* **2018**, *9*, 591. [CrossRef]
35. Balimunsi, H.; Grigolato, S.; Picchio, R.; Nyombi, K.; Cavalli, R. Productivity and energy balance of forest plantation harvesting in Uganda. *For. Stud. China* **2012**, *14*, 279–282. [CrossRef]
36. Maesano, M.; Picchio, R.; Lo Monaco, A.; Neri, F.; Lasserre, B.; Marchetti, M. Productivity and energy consumption in logging operation in a Cameroonian tropical forest. *Ecol. Eng.* **2013**, *57*, 149–153. [CrossRef]
37. Picchio, R.; Maesano, M.; Savelli, S.; Marchi, E. Productivity and Energy Balance in Conversion of a Quercus Cerris L. Coppice stand into a High Forest stand in Central Italy. *Croat. J. For. Eng.* **2009**, *30*, 15–26.
38. Airoldi, G.; Calvo, A.; Manzone, M. Oil consumption in 4WD farm tractors used in forestry operations. *Croat. J. For. Eng.* **2020**, *41*, 333–345. [CrossRef]
39. Ottaviani Aalmo, G.; Magagnotti, N.; Spinelli, R. Forest workers and steep terrain winching: The impact of environmental and anthropometric parameters on performance. *Croat. J. For. Eng.* **2016**, *37*, 97–105.