

Article

Timber Extraction by Farm Tractors in Low-Removal-Intensity Continuous Cover Forestry: A Simulation of Operational Performance and Fuel Consumption

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Abstract: Farm tractors represent a possible option for forwarding operations in continuous cover forestry, given the generally lower removal intensities, relatively high dispersion of timber, and heightened concerns regarding the environmental impact of operations. This study evaluated the performance of a farm tractor fitted with an externally operated crane and a bunk for forwarding operations, using field-documented data on operational speed, production, and fuel use, as well as data from high-resolution video recordings for a detailed time-and-motion study. Using this knowledge, performance simulations were run based on extraction distance and log size, to describe the variability in fuel use, cycle time, and productivity, and to estimate the operational cost. The results of the simulation showed important differences in operational speed across different work elements, involving machine movement. Although the extraction distance had effects, log size was found as the important factor driving the variability in cycle time, productivity, fuel use, and cost. The differences in performance based on the variability in extraction distance and log size may serve as a guideline for operational planning, costing, and environmental assessment regarding emissions under various operating conditions.

Keywords: environmental impact; fuel consumption; silvicultural operation; time consumption; productivity; operational costing



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1. Introduction

Forest operations are crucial in providing renewable energy sources and building materials while supporting global biodiversity [1,2]. Particularly, forest operations that mimic natural disturbances, retain key habitat elements like deadwood and old-growth trees, and maintain a diversity of forest ages and structures can enhance biodiversity by providing a variety of habitats and resources for a wide range of species [3,4]. Nevertheless, conventional clearcutting and modern industrial forestry methods have resulted in the loss of approximately 420 million hectares of forest due to deforestation between 1990 and 2020, with an annual rate of approximately 10 million hectares in 2015–2020 [5,6]. This poses a significant threat to ecosystems worldwide, including soil degradation and carbon emissions. Therefore, there is a need to develop sustainable and eco-friendly forest management strategies [7–9]. Continuous cover forestry (CCF) involves low-intensity silviculture and selective harvesting methods that maintain the forest canopy at one or more levels, promoting sustainable forest conservation and minimizing adverse effects compared to conventional clearcutting [7–15]. Furthermore, low-removal-intensity CCF involves harvesting trees at levels of around 10%–30% of standing volume to maintain the forest cover, vertical and horizontal diversity, and natural regeneration of the forest while minimizing soil disturbance, damage to residual trees, and negative impacts on the forest ecosystem [7,9,13–15]. This approach is particularly important in mitigating the

effects of climate change [9,15]. However, implementing CCF's low-intensity harvesting methods has its operational challenges, especially in terms of extracting and transporting timber due to the need for specialized equipment that can efficiently operate in the forest environment [12,13].

Forwarding operations using specialized machines have been employed in different parts of the world [10–13]. Forwarders and skidders are commonly used for timber extraction and have proven to be efficient in various operational contexts in Europe [16–29]. However, their suitability for CCF harvesting depends on the specific type of machine [18] and the unique requirements of CCF practices [5–7,22]. For instance, their bulky size and weight make it challenging to use them in low-access CCF, since they require careful maneuvering to avoid residual tree damage and soil compaction. Furthermore, their expensive price as compared to farm tractors discourages such investments targeted to operate in CCF operations with low removals. Although some traditional logging equipment, such as forwarders and skidders, can be adapted for selective and low-intensity harvesting methods in CCF, modified farm tractors are often considered as the best option for wood extraction [30–34]. In some European countries, including Romania, the use of farm tractors for wood extraction is an important technical option, while forwarders are not widespread [26,35]. For instance, in small-scale forestry operations, farm tractors were used in 82% and 77% of all harvesting operations during the logging seasons of 1982–1983 and 1989–1990, respectively, in Finland [36], and modified farm tractors are commonly used for timber extraction in European countries like Turkey, Italy, and Croatia [37]. However, modifications are needed to adapt these tractors, which are not originally designed for forest operations [38–40], and they are often equipped to facilitate timber extraction. Additionally, farm tractors offer versatility as they can be used in both agricultural and forestry applications year-round with a range of equipment and attachments [41]. Consequently, farm tractors used for forwarding operations in low-removal-intensity CCF are popular in some countries such as Romania [42], but limited research has been conducted on their operational performance and cost.

The forest industry values high productivity, low time consumption, and low cost achieved by using minimal resources during extended work periods [34,43,44]. Productivity in forwarding operations is measured by the quantity of material extracted within a specific time frame, and loading and unloading of logs are critical components of the process [44]. Several studies have evaluated the productivity of farm tractors used for forwarding based on the amount of timber payload transported within the productive system time [33,34,37,41,45]. According to [41], the productivity of a farm tractor with a trailer equipped with a hydraulic crane can be influenced by factors such as forwarding distance and load volume. However, at the moment there are no scientific studies regarding the simulation of their productivity as a function of extraction distance and log size, although productivity in forest operations depends on various factors, including the organization of work [46].

Besides, fuel consumption significantly impacts the economic and environmental sustainability of forest operations [23,47–49], but limited research exists on fuel use by farm tractors in forwarding operations, making it difficult to develop effective fuel-saving methods [49]. The use of fossil fuels contributes to greenhouse gas emissions, air pollution, and climate change, making it essential to identify fuel-efficient, cost-effective, and environmentally friendly forwarding systems to promote low-intensity removal CCF while reducing greenhouse gas emissions, fossil fuel use, and air pollution in forest operations [23,48].

Moreover, forwarding wood with farm tractors can be a cost-effective alternative to using specialized forwarders, because compared to specialized forwarders, farm tractors have a lower purchase price [50] and their equipment purchase costs are recovered faster [51]. For instance, a study by [50] revealed that replacing a forestry trailer with a two-wheel trailer attached to the farm tractor could result in cost savings of up to 44% if only the economic goal of wood extraction is considered. Several studies suggest that forwarding costs using a farm tractor can be accurately calculated by considering machine

hour costs and productivity rates, which are commonly expressed as forwarding costs per cubic meter of wood, allowing for a comprehensive approach that reflects economic efficiency of the forwarding process [41,52–54]. However, the costs may vary depending on the type of cuts and forwarding productivity [41]. For example, higher direct costs of forwarding may be recorded for stands with group cutting due to lower forwarding productivity [41]. Nevertheless, there is no scientific study on simulations of the costs of farm tractor forwarding in low-removal-intensity continuous cover forestry. Therefore, this study hypothesizes that the cycle time, productivity, fuel use, and production cost are influenced by the extraction distance and log size, such that longer distances and smaller log sizes result in lower productivity and higher unit fuel consumption, as observed in, e.g., [34,41,55].

Simulation modeling involves creating a computer model that imitates a real-life system or process to study its behavior under different scenarios and inform better decisions about its design, operation, and management [56–59]. Researchers have developed various simulation models to optimize forest operations, including using network simulation, interactive graphics, a systems dynamic model, and the Monte Carlo Simulation (MCS) method [58–60]. These models are useful in representing the complexity, variability, and interconnectivity of forest operations, and have been used for planning and evaluating various harvesting operations, including the performance of farm tractors used in forwarding operations in comparative designs and assessing operational costs [61–63]. These models can estimate productivity, time consumption, and operational costs of farm tractors for forwarding in CCF under specific conditions such as load size, travel distance, and terrain slope [63]. According to [64], the current state of computer simulation is well understood, as much learning has occurred during the generation of relevant models. Despite this progress, various modeling and implementation issues have been identified that remain unresolved [64]. Specifically, there is currently no simulation model for predicting productivity or operational fuel consumption for benchmarking and estimating productivity in low-intensity removal operations, despite numerous studies evaluating the cost and productivity of farm tractors for forwarding operations in different regions worldwide, e.g., [41,49,55,65].

This study aimed to simulate the time consumption, productivity, fuel use, and cost of modern farm tractors used in forwarding operations implemented in low-removal-intensity continuous cover forestry settings. The objectives were to (i) develop the descriptive statistics needed for simulating time consumption, productivity, fuel use, and cost, and to (ii) develop and run time consumption, productivity, fuel use, and cost simulation models that account for different extraction distances and log sizes.

2. Materials and Methods

2.1. Study Area

The study area was in the Racovița forest, Timiș County, Romania, bounded by agricultural fields and roads. The area of the study site was about 80 hectares with a network of extraction roads and log landings (Figure 1). The forest is located on a generally flat terrain with an average inclination of less than 5 degrees, at geographical coordinates of approximately 45°43.644' N and 21°33.713' E and at an altitude of approximately 116 m above sea level. This forest is in the Banat region, which is characterized by a temperate continental climate with high tree diversity and productivity. The forest is composed mainly of pedunculate oak (*Quercus robur* L.), Austrian oak (*Quercus cerris* L.), and Hungarian oak (*Quercus frainetto* Ten.).

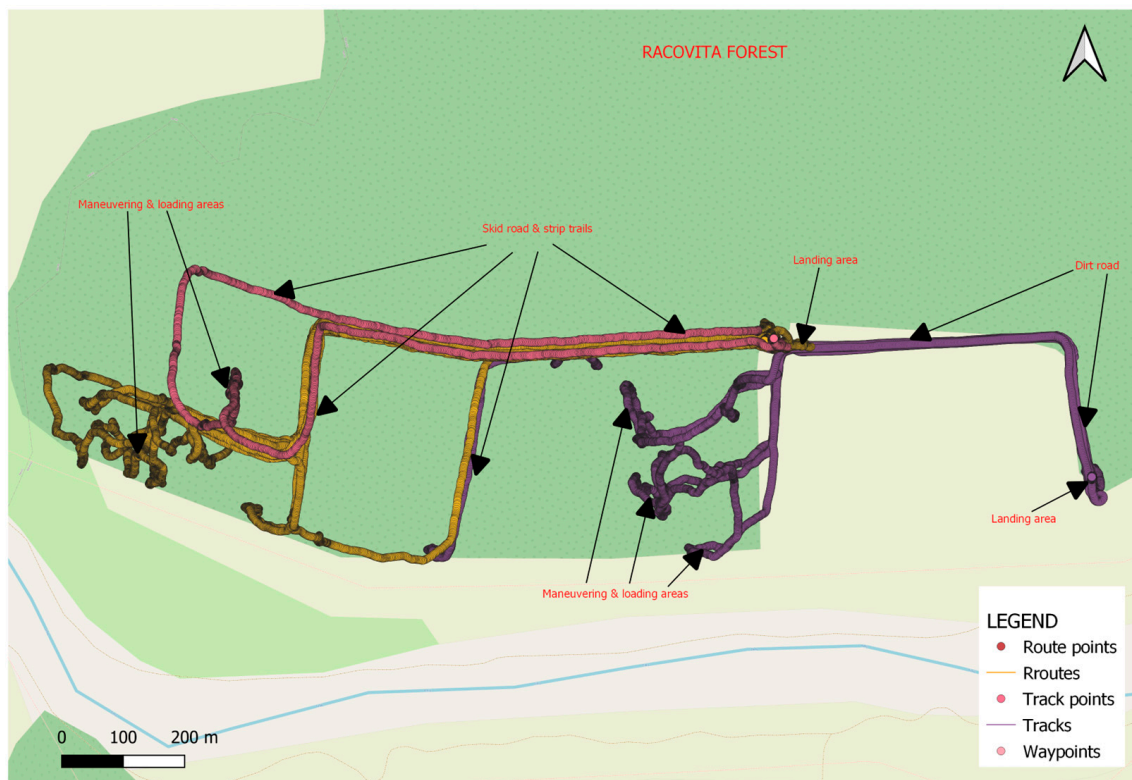


Figure 1. Study area map showing the tracks and routes used for wood extraction with the farm tractor.

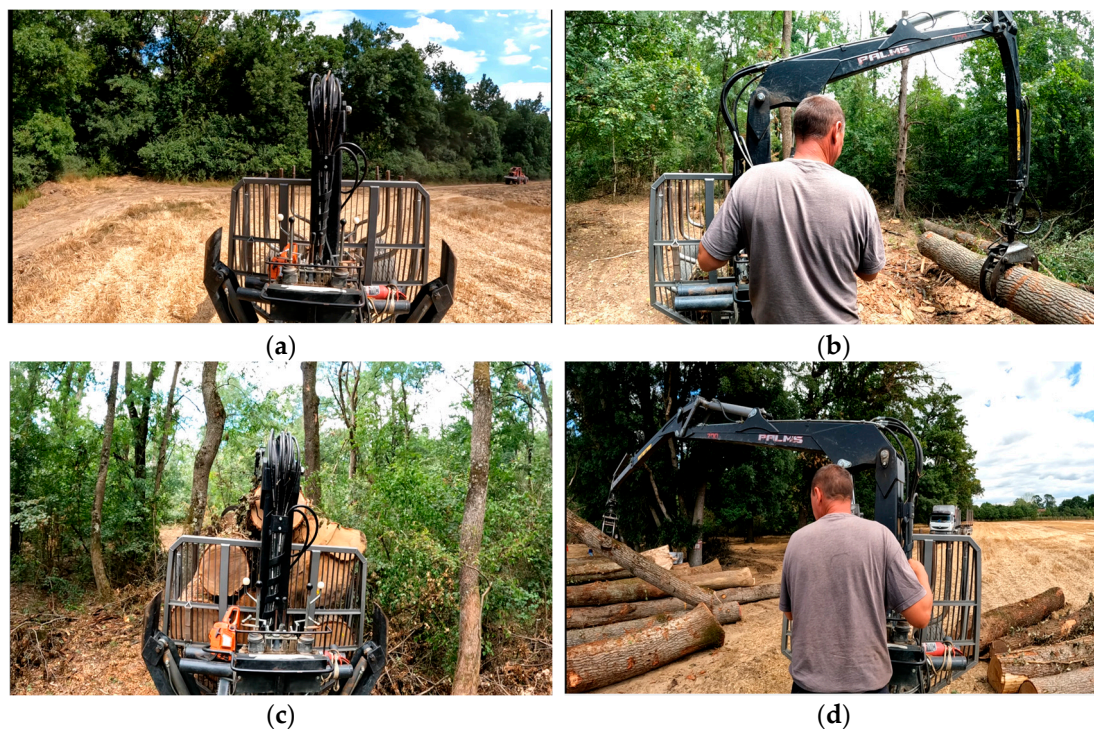
Felling intensity at the study area is managed based on established forestry principles that aim to maintain a balance between timber harvesting and natural regeneration. The prevailing harvesting method is the tree length, where trees are felled and processed by chainsaw and then the tree lengths are extracted to the roadside. When the local conditions and available machines allow it, and typically on flatlands, the cut-to-length method is used, as in this study. The main wood assortments that were produced in the area of study included sawlogs and some firewood from the tree tops and branches. The extracted logs, including tops and branches, had a wide range of diameters over bark ranging from 8 to 82 cm, with a mix of quality grades, and common defects like buds, insect holes, wane, and biotic damage. The logs were typically 3–4 m long. The skid trails already in place were utilized to extract the wood to the roadside where it was piled. Wood piling was performed along the forest road and required the tractor with payloads to move to reach the individual pile locations. By field observation, the extraction took place under favorable soil conditions, with good bearing capacity, and some of the logs were pre-bunched most likely by horses.

2.2. Description of the Equipment

This study considered a Deutz Fahr Agrofarm 430 as the base machine for forwarding operations. The tractor was fitted with a PALMS 15U trailer with a payload capacity of about 10 m³ and a PALMS 7.94 crane that was used for loading and unloading (Table 1; Figure 2).

Table 1. Description of the extraction set used in this study. Source: [66,67].

Machine Specifications					
Deutz Fahr Agrofarm 430		Forest Trailer PALMS 15U		Forest Crane PALMS 7.94	
Cylinders	4	Loading area cross section, m ²	3.2	Max outreach, m	9.4
Engine power (kW)	80	Loading area length, mm	4175	Lifting capacity at full reach, kg	540
Weight (kg)	4100	Frame extension length, m	1.085	Lifting capacity at 4 m, kg	1410
Engine type	Diesel engine				
Engine capacity (L)	4.038	Gross weight, kg	19,000	Brutto lifting torque 215 Bar, kN m	83
Wheelbase (mm)	23,400				
Travel speed (km/h)	40	Total length, mm	6415	Telescopic boom stroke length, m	3.8
Transmission	30/30	Width with standard wheels	2450	Slewing torque, kN m	21
Length (mm)	3990	Frame	Unibody	Working pressure, bar	215
Height (m)	2810	Max crane size by lifting torque, kN m	120	Rotator maximum load, kN	60
Width (mm)	2458				
Three-point hitch performance	56 L/min	Standard wheel size	500/50-22.5	Crane weight without support leg and valve block, kg	1310
Maximum torque (N m/rmp)	400 N m/rmp			Pillar slewing angle, degrees	380

**Figure 2.** The key operational activities involved in forwarding with the farm tractor: (a)—empty turn, (b)—loading, (c)—loaded turn, (d)—unloading.

This forwarding equipment is ideal for transporting wood harvested in varying lengths, thanks to the trailer's appropriate spacing and number of stanchions. The PALMS 15U forest trailer, with a 15-ton nominal load capacity, is built for professional forestry work in challenging conditions, with a high clearance and oval frame to avoid getting stuck on stumps and securely housed hydraulic and electronic components [67]. Moreover, the PALMS 7.94 forest crane has a double telescopic extension boom, making it suitable for daily professional forestry operations and compatible with PALMS double-beam and unibody trailers, with a higher lifting capacity and slewing torque that also makes it suitable for working with chippers and harvester heads [67]. The Deutz Fahr Agrofarm 430 is a tractor that can be fitted for timber extraction operations [66,68–73]. Additionally, the tractor's long wheelbase and high ground clearance provide stability and traction, enabling it to operate effectively on rough terrain [66,68,72]. However, its suitability for timber extraction depends on specific requirements, terrain conditions, and the extraction scale [34,41].

2.3. Work Structure and Data Collection

The fieldwork for this study was carried out over five days, from 4 to 8 August 2022, during favorable weather conditions on dry land. The tractor used in the study was operated by a male Romanian who was about 50 years old and had extensive experience operating the machine for Romsilva, the Romanian National Forestry Agency, who owns the tractor. Initially, trees were motor-manually felled and processed using a chainsaw. The tractor-based extraction produced both sawlogs and fuelwood, which were stored at a landing area for subsequent transportation. Different assortments were transported mixed-up in a load, and after that, sorting was done at the landing and at the processing facility, respectively. Following felling and processing, the logs were placed irregularly in small bunches at the skid trails before extraction. The driver performed all forwarding tasks, including driving, loading and unloading logs, occasional repairs, and maintenance. A total of nineteen work cycles were observed during the study, with logs extracted to the landing area. These work cycles were segmented into elemental tasks for easy monitoring (Figure 2; Table 2). The way the work was organized in this study was similar to previous research on tractor forwarding operations [34,41,43,55]. The study used a time and motion approach, based on the principles of time consumption and productivity evaluation presented in [74,75]. The process of wood extraction using the farm tractor involved several steps, including driving the empty tractor from the roadside to the felling area (hereafter empty turn, ET), positioning the tractor with its bunk towards the wood to be loaded (hereafter maneuvering, MAN), loading the wood (hereafter loading, LD), which included swinging the crane to reach the log, grappling the log, lifting the log to load it, and releasing the log into the bunk, moving between bunches (hereafter MV), driving the loaded tractor from the forest roadside to the designated area (hereafter loaded turn, LT), and landing operations, which involved unloading the log by lifting it and releasing it onto the landing (hereafter unloading, UL).

Field data collection involved recording the farm tractor's cycle time, operational speed, travel distance, production, and fuel consumption. Using the method of cumulative timing [75], time consumption was documented at an elemental level by studying the work elements described in Table 2. Operational activity was documented using a GoPro 10 Black video camera (GoPro Inc., San Mateo, CA, USA) mounted at the rear of the cabin. After each day of observation, the video files were downloaded and stored onto a personal computer, where they were organized for further analysis. Time consumption and operational speed were measured using a Garmin GPSMAP 64 STC unit fixed at the rear of the tractor's cab with a sampling rate of one second. The extraction distances for the ET and LT were documented by downloading and storing the resulting data in the form of .GPX files onto a personal computer. The video files were coded and organized into days and paired with GPS data to extract time elements related to various stages of the wood extraction process (Table 2).

Table 2. Description of the work and time consumption elements.

Code	Time Component	Description
SDs	t_{SD}	Study delay: delays resulting from human, mechanical, or operational factors that prevent the tractor from doing its usual tasks.
ET	t_{ET}	Empty turn (traveling unloaded): starts when the tractor departs from the landing location and ends when it stops to start loading or to perform another activity.
PL	t_{PL}	Prepare for loading: starts when the operator gets out of the cabin, climbs the trailer, and begins to adjust the crane/boom from its stationary position to reach the logs for loading.
LD	t_{LD}	Loading: starts when the tractor begins to load logs including adjusting the logs in the bunk and finishes when the boom is rested in a stationary position, prepared for a machine movement.
MV	t_{MV}	Moving between bunches: starts when the crane or boom is positioned on the bunk and ends after the tractor has stopped moving after reaching another bunch of logs.
LT	t_{LT}	Loaded turn (traveling loaded): begins when the crane/boom is rested stationary on the bunk, and ends when the tractor stops at the landing area.
PU	t_{PU}	Prepare for unloading: starts when the operator exits the cabin, ascends to the space between the trailer and cabin, and starts to operate the crane or boom from its still position to reach the logs for unloading.
UL	t_{UL}	Unloading: starts with the crane moving near the tractor's bunk with an empty grapple and ends when the tractor starts another element or with the boom being rested immobile on the bunk for a trip back to the forest or other tasks. It incorporates adjustments to the log stack.
MAN	t_{MAN}	Maneuvering: maneuvers taken to enter or exit the strip road once arrived or leaving a given bunch of logs.

Additionally, fuel consumption was measured using the method of refilling to full, which involves estimating the amount of fuel used based on the amount of fuel needed to refill the tank to its maximum capacity [74,76]. In this study, fuel consumption was measured at the forwarding work cycle level, with readings taken using graded hard-polymer recipients and recorded to the nearest 100 centiliters. Measurements were taken after the tractor engine was shut down and the machine was situated on leveled ground. Data on extraction distance, log biometrics, fuel consumption, and other relevant events were documented using a pen-and-paper approach [77].

2.4. Data Processing and Statistical Analysis

Data processing and statistical analysis were conducted using Microsoft Excel[®] software (Microsoft, Redmond, WA, USA, 2013 version) equipped with the Real Statistics add-in (<https://www.real-statistics.com/> accessed on 19 April 2024). Simple computations and descriptive statistics were performed using Microsoft Excel, while Real Statistics enabled advanced statistical analysis. In the office phase of the study, time consumption data were obtained by processing the video files. Although video-based analysis allowed for detailed observation of events, it required significant time resources for data processing [42]. However, this method was selected for its accuracy and the ability to track any potential data-related issues. Using a Microsoft Excel[®] spreadsheet, the initial and final times of each work element were recorded based on the concepts outlined in Table 2. Elemental

time consumption was calculated by subtracting the final and initial times in seconds and corresponding codes (Table 2) were assigned to each observed event. Delays resulting from the study and technical reasons were documented separately.

Standard data transfer protocols were used to download location data from the GPS unit as a .GPX file, which was then uploaded into Garmin® BaseCamp (version 4.7.4.0; Garmin International Inc., Olathe, KS, USA) for additional analysis. The time labels for each collected location, as well as the time (s) and speed (km/h), were extracted as text strings and recorded in a Microsoft Excel® spreadsheet, where time and speed were transformed into numerical values using basic Excel functions. The data extraction and processing techniques used in this study were comparable to those of previous studies [25]. The .GPX files of the five days of observation were merged into a single Microsoft Excel® spreadsheet. Video files were analyzed using the time and date labels included in the .GPX files, and two additional attribute fields were established to document the engine state and the task performed by text coding. The GPS track data were examined in the running mode of Garmin BaseCamp® software (version 4.7.4.0) to identify events that took place in the field, the beginning and ending times of these events, and the operational distances, all of which were noted.

Work elements and events such as the empty turn (ET), study delays (SD), preparing for loading (PL), maneuvering (MAN), moving between piles (MV), loaded turn (LT), preparing for unloading (PU), and unloading (UL) were encompassed in the time consumption data recorded in this study. The duration of the primary tasks involved in moving the grapple of the crane in a three-dimensional space path was identified and recorded solely through video files to estimate the time consumption for the crane's movements for subsequent simulation.

Volumes of individual logs, payloads, and production were estimated using data on the biometrics of the logs. These estimates were manually entered into the database. Moreover, operational distances, including empty turn distance, distance covered by moving between bunches of logs, maneuvering distance, and loaded turn distance, were estimated from the collected GPS location data. These distances were extracted cycle-wise using the measurement capabilities of Garmin BaseCamp® software. The estimated distances were included in the database developed at the work cycle level, which enabled the calculation of total moving distance and average forwarding distance. Additionally, to categorize the movement speed per work task, including maneuvering speed (MANS), empty turn speed (ETS), moving between bunches or locations speed (MVS), and loaded turn speed (LTS), logical functions similar to those used to extract time consumption data were employed. The speed datasets were examined and prepared for simulation of productivity outside the range of data gathered for the lowest and highest extraction distances.

Hourly fuel consumption (L/h) and unit fuel consumption (UFC , L/m³) data were also processed at an overall forwarding operations level using recordings from the 22 observed work cycles. The data included the engine running time at different engine output levels, including idle running. These data were manually transferred into the database and used to compute HFC based on engine working time. UFC was also estimated at this resolution. Cycle-wise fuel consumption data were then prepared to develop simulation models explaining the variation in UFC as a function of extraction distance and log size at an overall resolution.

The statistical methods used in this study were comparable to those described and used in previous studies on time consumption and productivity [34]. The statistical analysis was performed in a Microsoft Excel® spreadsheet to provide a description of the data and generate simulation models that predict the time consumption, productivity, and fuel use in relation to the extraction distance, distance between bunches of logs, log size, number of logs, and movements. The statistical analysis involved a series of descriptive steps that were used to statistically analyze time consumption and operational distances, including empty turn (dET), moving between locations (dMV), loaded turn (dLT), and maneuvering (dMAN) distances. Specifically, descriptive statistics were calculated to represent the central

tendency and dispersion of the operational distances and time consumption, including minimum, maximum, mean, median, standard deviation, and sample variance values. Additionally, descriptive statistics and boxplots were developed to analyze and visualize the GPS speed data. Key descriptive statistics, such as the minimum and maximum values, median (second quartile), mean, first and third quartiles, and inter-quartile range, were calculated for the GPS speed data. Then, boxplots were constructed to graphically display the tractor speed data, including the minimum, first quartile, median, third quartile, and maximum values. All outliers in the data were removed by unchecking the “show outlier points” in the “format data series options” in the MS Excel spreadsheet.

2.5. Simulation of Time Consumption, Productivity, and Fuel Use

A simulation-based approach using an MS Excel spreadsheet was taken to model the farm tractor forwarding operations, based on the work elements and time components described in Table 2. Consequently, a simulation method was employed to study how the full load capacity and different extraction distances, distances between bunches of logs, log size, number of logs, number of movements, and number of logs per location affect the time consumption, as well as to obtain productivity and fuel use functions that describe such systems [63,78]. The simulations on time consumption, productivity, and fuel consumption were run by considering the extraction distance and log size as main factors affecting these performance metrics. The simulations were similar to the tractor simulation models developed in previous studies [34,41], with extended functionalities derived from other published simulation models [79,80], harvesting operations in similar forest environments to those considered in this study [42], the type of cuts performed, e.g., clear cutting, low removal intensity, and thinning [8,9,81] and farm tractor working patterns [34,41,43,82].

A total of 300 simulations were run on operational variables (extraction distance, distance between bunches of logs, log size, number of logs, and number of movements) resulting in outputs on total cycle time, productivity, unit fuel consumption, and net unit cost in different forwarding scenarios. The simulations considered a full loading capacity (10 m^3), 5 variations in extraction distance (100, 200, 300, 400, and 500 m, respectively), 6 variations in distance between locations/log bunches (10, 20, 30, 40, 50, and 100 m, respectively), 10 variations in log size (0.10 to 1.00 m^3 , with a step of 0.10 m^3), and 8 variations in the number of movements (5 to 20). Some of the parameters, such as the number of logs per turn and the number of logs per location, were directly computed from the simulation scenarios. It was assumed that the extraction distance affects the empty turn time and the loaded turn time linearly, based on knowledge from previous studies [34,41,43,82].

The performance indicators for each scenario, such as total time consumption/cycle time (CT), productivity (P), unit fuel consumption (UFC), and net unit cost (NUC), were calculated according to Equations (1)–(9).

$$CT = tTE + tMV + tPL + tPU + tLD + tUL, \quad (1)$$

where CT is the cycle time in hours, and the other terms denote the elemental time consumption in hours: tTE is the extraction time including empty and loaded turns, tMV is the time consumption of moving between locations, tPL is the time consumption of preparing for loading, tPU is the time consumption of preparing for unloading, tLD is loading time, and tUL is unloading time.

$$tTE = \left(\frac{DE}{1000} \times \frac{1}{SET} \right) + \left(\frac{DE}{1000} \times \frac{1}{SLT} \right), \quad (2)$$

where DE is stimulated extraction distance in meters, SET is the average speed of empty turn ($SET = 5.36 \text{ km/h}$), and SLT is the average speed of loaded turn ($SLT = 5.49 \text{ km/h}$).

$$tMV = 0.0011 \times DP^{0.764} \times NM, \quad (3)$$

where DP denotes simulated distance between bunches/locations in meters, and NM denotes the simulated number of movements. Equation (3) was modeled based on the field-collected data on distance between the piles and the time consumption during movement, whereas the simulated number of movements was taken from the scenarios.

$$tPL = 0.007 \times NM, \quad (4)$$

$$tPU = 0.008, \quad (5)$$

$$tLD = 0.0011 \times NL, \quad (6)$$

where tPU is a fixed portion taken as the average from the field-collected data whereas NL denotes simulated number of logs.

$$tUL = 0.008 \times NL, \quad (7)$$

Moreover, the productivity (P) was computed using Equation (8). The productivity was defined as the ratio of the total volume of logs forwarded to the total time spent on forwarding operations.

$$P = \frac{LC}{CT}, \quad (8)$$

where LC denotes the full load capacity of 10 m³.

Then, using the COST model developed by [53], and the productivity, expressed as m³ × PMH⁻¹, the unit cost of each scenario (€/m³) was calculated and recorded into a Microsoft Excel spreadsheet. The assumptions for the cost calculation are shown in Table 3. Moreover, the unit fuel consumption (UFC) was calculated using Equation (9).

$$UFC = CT \times HFC, \quad (9)$$

where HFC is the hourly fuel consumption rate, which was 3.117 L/h in this study. The HFC was calculated based on the engine running time and the amount of fuel consumed in the field.

Table 3. Cost elements used in calculation.

Parameter	Description
Machine type	Deutz Fahr Agrofarm 430
Currency	€
Unit of costing	m ³
Machine fixed cost inputs	
Purchase price (base machine/attachment)	33,000.00/23,000.00
Salvage price (base machine/attachment)	10% of purchase price
Expected economic life (base machine/attachment)	15,000.00/15,000.000 per PMH
Interest rate	10%
Machine tax/registration (base machine/attachment)	50.00
Machine insurance (base machine/attachment)	250.00
Machine transfers	2000.00 per annum
Garaging for machine	0.00 per annum
Machine variable cost inputs	
Fuel cost (€/L)	1.50
Fuel consumption (L/PMH)	3.12
Oil and lubricant cost	10% of fuel cost per PMH of base machine

Table 3. Cont.

Parameter	Description
Maintenance and repair cost (base machine/attachment)	(80%/100%) of purchase price
Tire cost per set of 4	2000.00
Operator costs	
Number of operators/shift	1
Average net wage	10 per hour
Social charges	48% of operator wages
PPE (cost per annum)	100.00
Productivity and operations (general inputs)	
Number of working days per year	210.00
Scheduled hours per shift	8.00
Scheduled hours per annum	1680
Production (unit/PMH)	variable
Productive hours per annum	1176
Productivity: m ³ /PMH	variable
Machine utilization: MU (%) = PMH/SMH	0.70
Overhead costs as absolute value (costs per annum)	12,000.00

2.6. Development of Performance Simulation Models

Simulation models were developed to examine the dependence relationships between total time consumption (cycle time), productivity, unit fuel consumption, and net unit cost as dependent variables (response/target variables), and extraction distance and log size as independent variables (predictor or explanatory variables). These were carried out in Microsoft Excel by varying the independent variables, based on which the values of response variables were computed.

3. Results

3.1. Descriptive Statistics of the Operational Variables and Time Consumption

Table 4 presents the descriptive statistics of operational variables and time consumption, as these were observed based on field-collected data. On average, empty and loaded turn elements required a time that was proportional to their respective travel distances. On average, the maneuvering time accounted for approximately 1.28 min. The first category of time consumption shown in Table 4 (study delay) describes the activities undertaken during clearing and crosscutting long logs which were difficult to load due to obstruction from neighboring trees and branches, waiting or resting, and fixing and removing the GPS unit from the machine, and it was excluded from simulation. Based on the information shown in Table 4 and the supporting data for these statistics, the average distance for wood extraction was approximately 1126 m, ranging from 1099 to 1152 m. The average maneuvering distance was approximately 46 m. Overall, the data reveal that there is a wide range of values for both distance and time variables, with certain factors returning relatively high standard deviations, indicating significant variability in the observed datasets. According to the provided statistics, the most variable factors were found to be loading time and empty turn distance.

Table 4. Descriptive statistics of operational distances and time consumption.

Variable (Description and Code)	Descriptive Statistics					
	No. of Observations	Minimum Value	Maximum Value	Mean Value	Median Value	Standard Deviation
Distance (m)						
Empty turn distance, <i>dET</i>	19	176	2128	1152.37	1195	398.91
Distance covered when moving between locations, <i>dMV</i>	19	93	988	392.84	334	266.73
Loaded turn distance, <i>dLT</i>	19	626	1428	1099.32	1199	231.76
Maneuvering distance, <i>dMAN</i>	19	4	109	46.16	33	28.54
Time (s)						
Study delay, <i>tSD</i>	19	173	4005	1623.95	1428	1100.73
Empty turn time, <i>tET</i>	19	221	1207	775.26	771	248.96
Time spent when preparing for loading, <i>tPL</i>	19	44	302	162.37	165	64.67
Loading time, <i>tLD</i>	19	292	1819	695.84	537	441.79
Time spent when moving between locations, <i>tMV</i>	19	184	1351	510.63	438	285.02
Loaded turn time, <i>tLT</i>	19	378	973	720.32	748	176.56
Time spent when preparing for unloading, <i>tPU</i>	19	18	64	32.68	30	11.78
Unloading time, <i>tUL</i>	19	155	722	354.37	341	126.54
Maneuvering time, <i>tMAN</i>	19	15	311	104.05	77	85.12

In the observed time, productive time accounted for 67.25%. In this category, the work elements ET, PL, LD, MV, LT, PU, UL, and MAN accounted for 22.84, 5.07, 20.67, 15.28, 21.40, 1.00, 10.54, and 3.20%, respectively.

3.2. Descriptive Statistics of the Operational Speed

The results shown in Figure 3 describe how the speed differed meaningfully across the work elements and provide important insights into the operational speed of the studied farm tractor during different work elements that involved movement. For MANS, the median and mean speeds were low, and the IQR was narrow ($Q1 = 0.9$ km/h, $Q3 = 1.9$ km/h), indicating little variation in observed speed. Additionally, the range of maneuvering speed recorded in the study was 3.3 km/h. However, ETS had the highest speed overall, while MVS had an intermediate speed range between MANS and ETS, with a median of 2.5 km/h. LTS outputted a higher speed than MANS, but a lower speed than ETS, with a median and mean of 6 and 5.49 km/h, respectively. The finding that each work element had varying speed profiles is important, as it highlights the need to optimize different tasks to enhance the process efficiency. For example, maneuvering speed was low, reflecting the careful and

precise nature of maneuvering tasks, whereas empty turns allowed for faster movement between locations without payload restrictions.

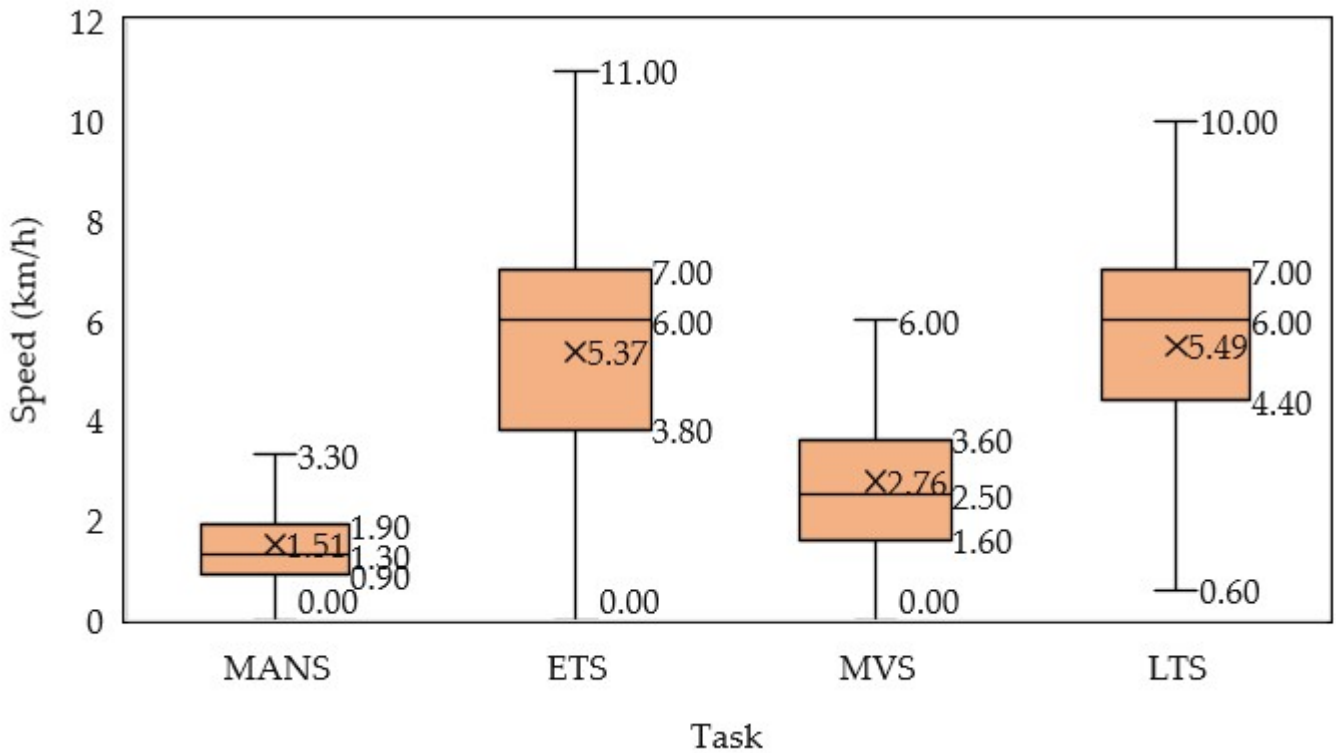
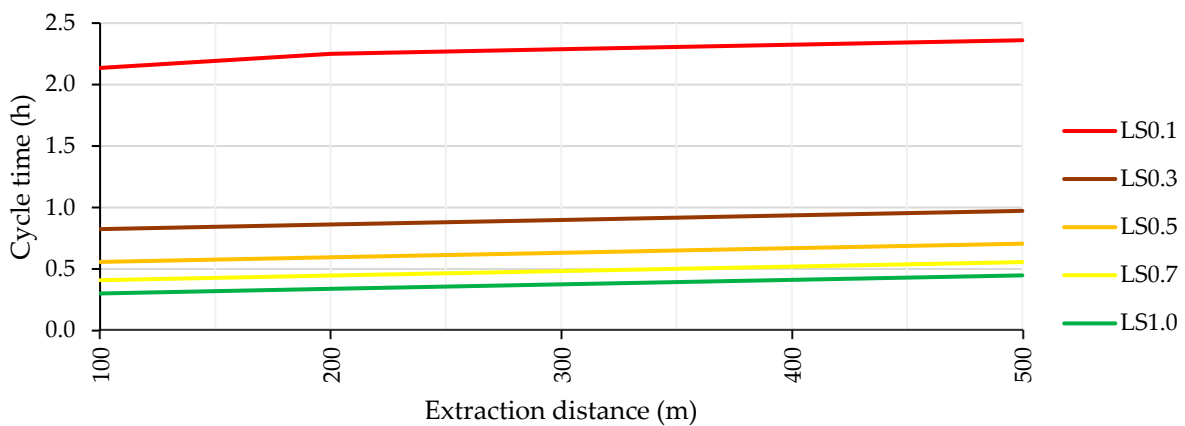


Figure 3. Boxplots showing the descriptive statistics of operational speed in different types of tasks involving machine movement: MANS—maneuvering speed, ETS—empty turn, MVS—moving between bunches, LTS—loaded turn.

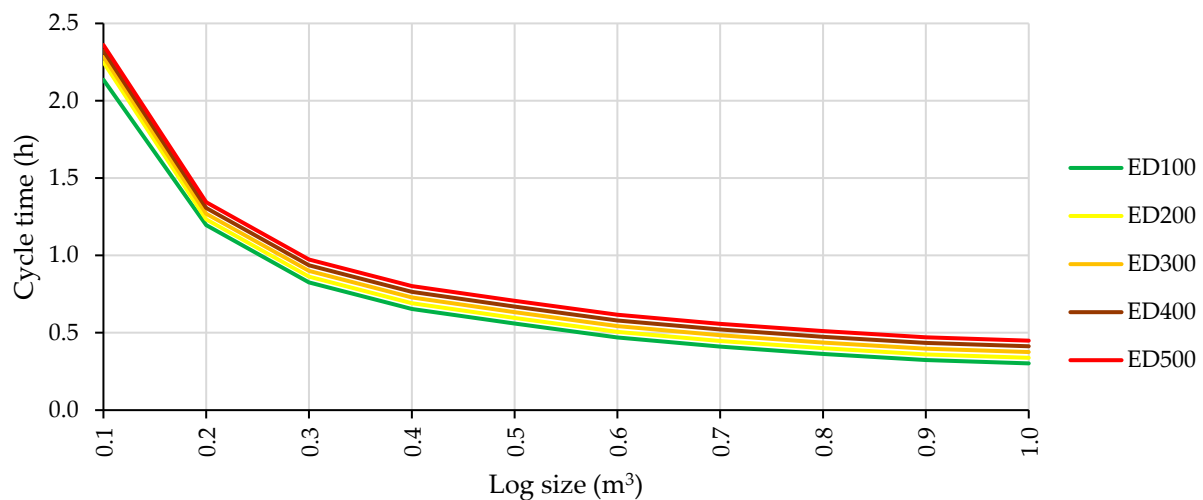
3.3. Models of Time Consumption, Productivity, Fuel Use, and Unit Cost

The simulation models shown in Figure 4a,b indicate that increasing the size of logs forwarded can enhance operational productivity by reducing the cycle time consumption. The results show that at every extraction distance, the largest log size of 1.0 m³ leads to the lowest cycle time, while the smallest log size of 0.1 m³ leads to the highest.

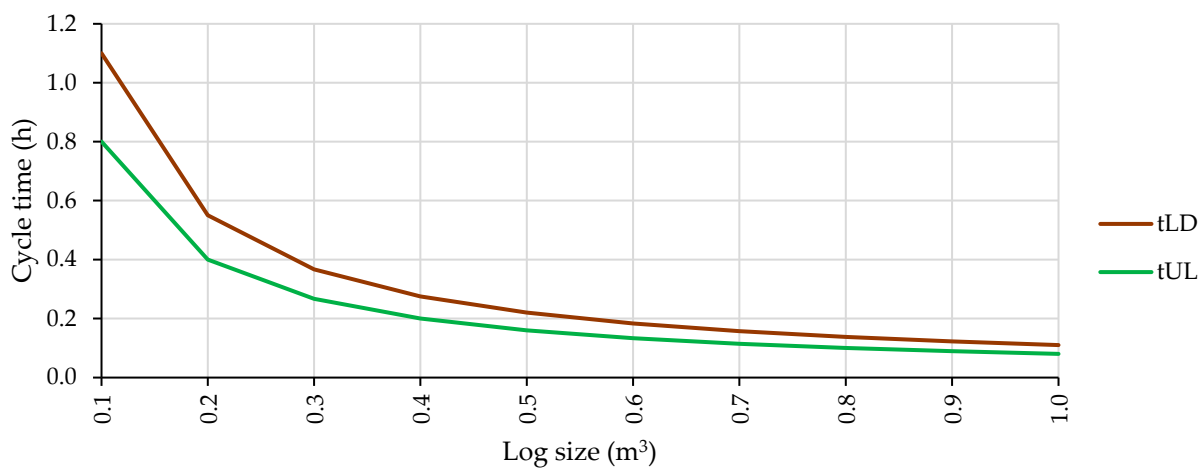


(a)

Figure 4. Cont.



(b)

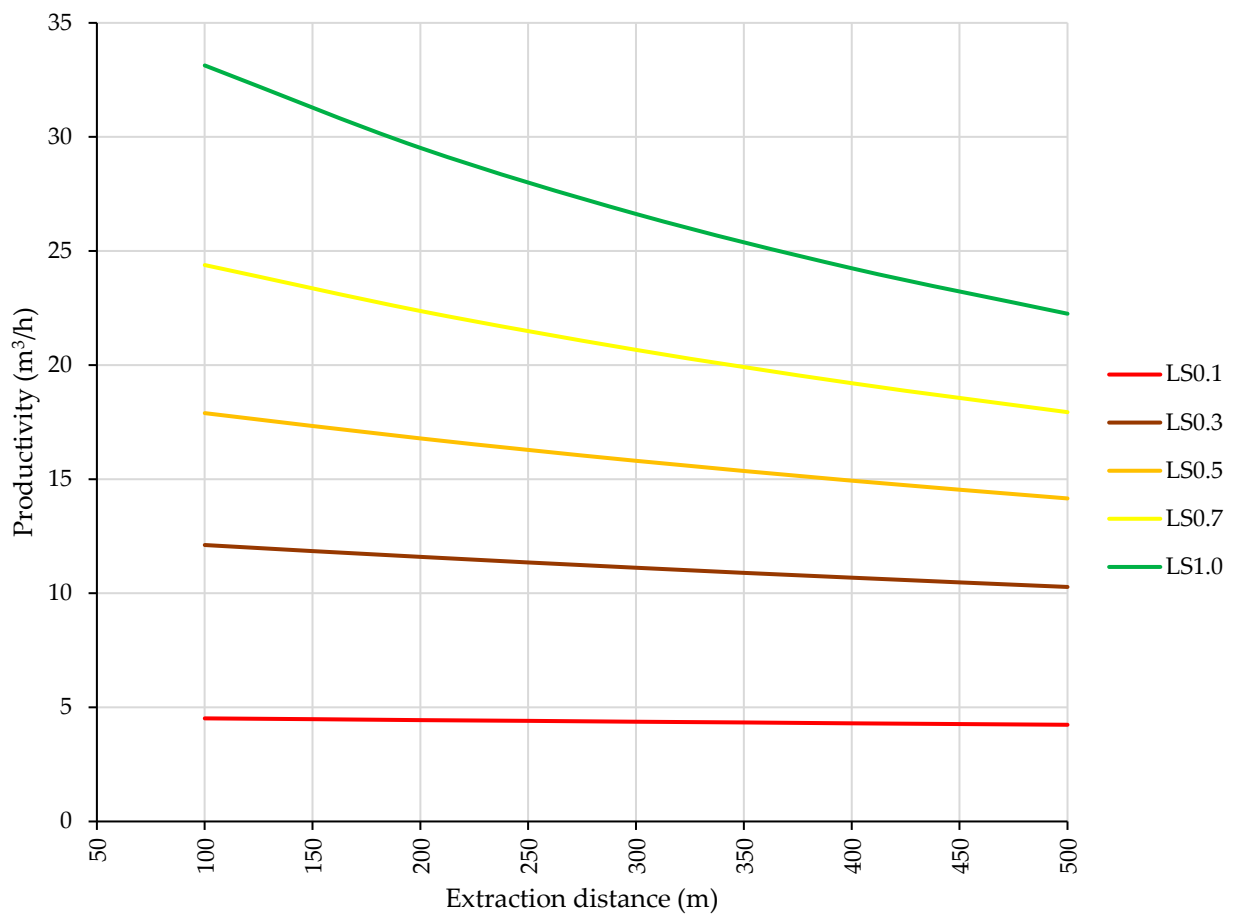


(c)

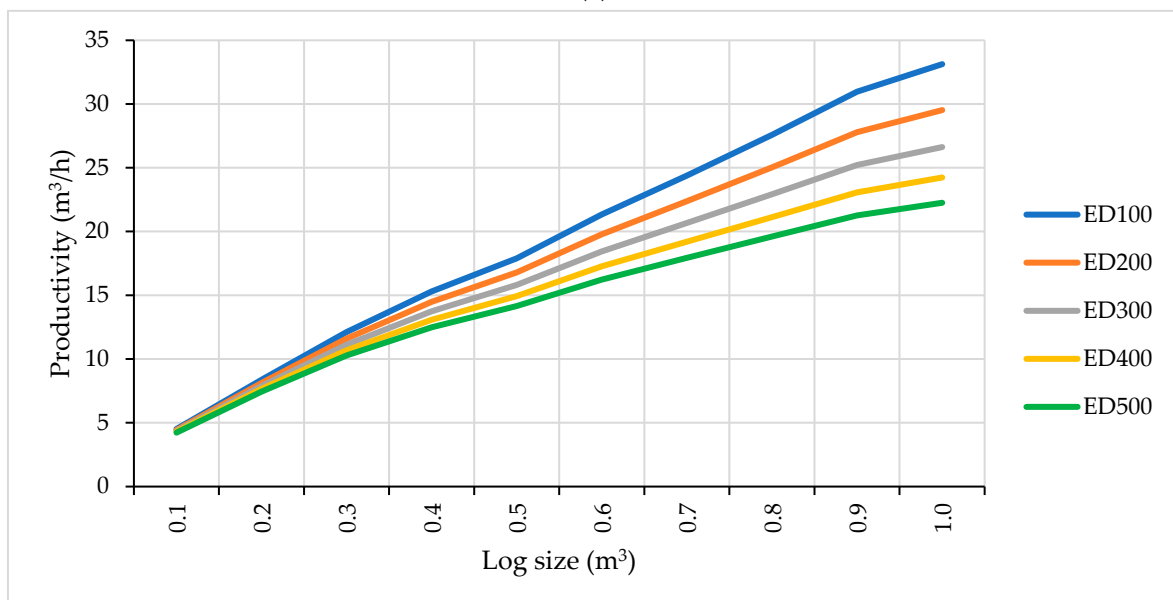
Figure 4. Simulated cycle time against the extraction distance and log size: (a)—cycle time depending on extraction distance for the same log size, (b)—cycle time depending on log size for the same extraction distance, (c)—loading and unloading time depending on log size. Legend: LS0.1 to LS1.0 stand for log sizes between 0.1 and 1.0 m³, ED100 to ED500 stand for the extraction distances from 100 to 500 m, *tLD* denotes loading time, *tUL* denotes unloading time.

Moreover, the rate of decrease in cycle time with increasing extraction distance becomes lower as the log size increases. Additionally, the simulation models in Figure 4c suggest that loading and unloading times reduce with an increase in log size, and both loading and unloading times decrease gradually as log size increases. This is a valuable insight for forest management practices, since larger logs can be more efficient to handle as they may require fewer movements to load and unload, ultimately leading to reduced time consumption and increased productivity. However, there may be limitations to log size, such as the capacity of the equipment and trailer used.

The simulation models presented in Figure 5a,b indicate that productivity tends to increase with increasing log size but decreases with increasing extraction distance, and the rate of increase in productivity becomes steeper for larger log sizes.



(a)



(b)

Figure 5. Simulated productivity against the extraction distance and log size: (a)—productivity depending on extraction distance for the same log size, (b)—productivity depending on log size for the same extraction distance. Legend: LS0.1 to LS1.0 stand for log sizes between 0.1 and 1.0 m^3 , ED100 to ED500 stand for the extraction distances from 100 to 500 m.

The results suggest that working with larger logs can lead to increased productivity, but these benefits can be canceled by increased extraction distances. Moreover, the study found that the effects of extraction distance and log size on productivity tend to be more pronounced for log size.

The results presented in Figure 6a show that there is a consistent trend of increasing unit fuel consumption with increasing extraction distance. This highlights the importance of optimizing the extraction distances to minimize fuel consumption. Additionally, Figure 6b shows that unit fuel consumption decreases sharply with larger log sizes. Therefore, shortening the extraction distance and operating with larger logs ultimately reduces the fuel consumption.

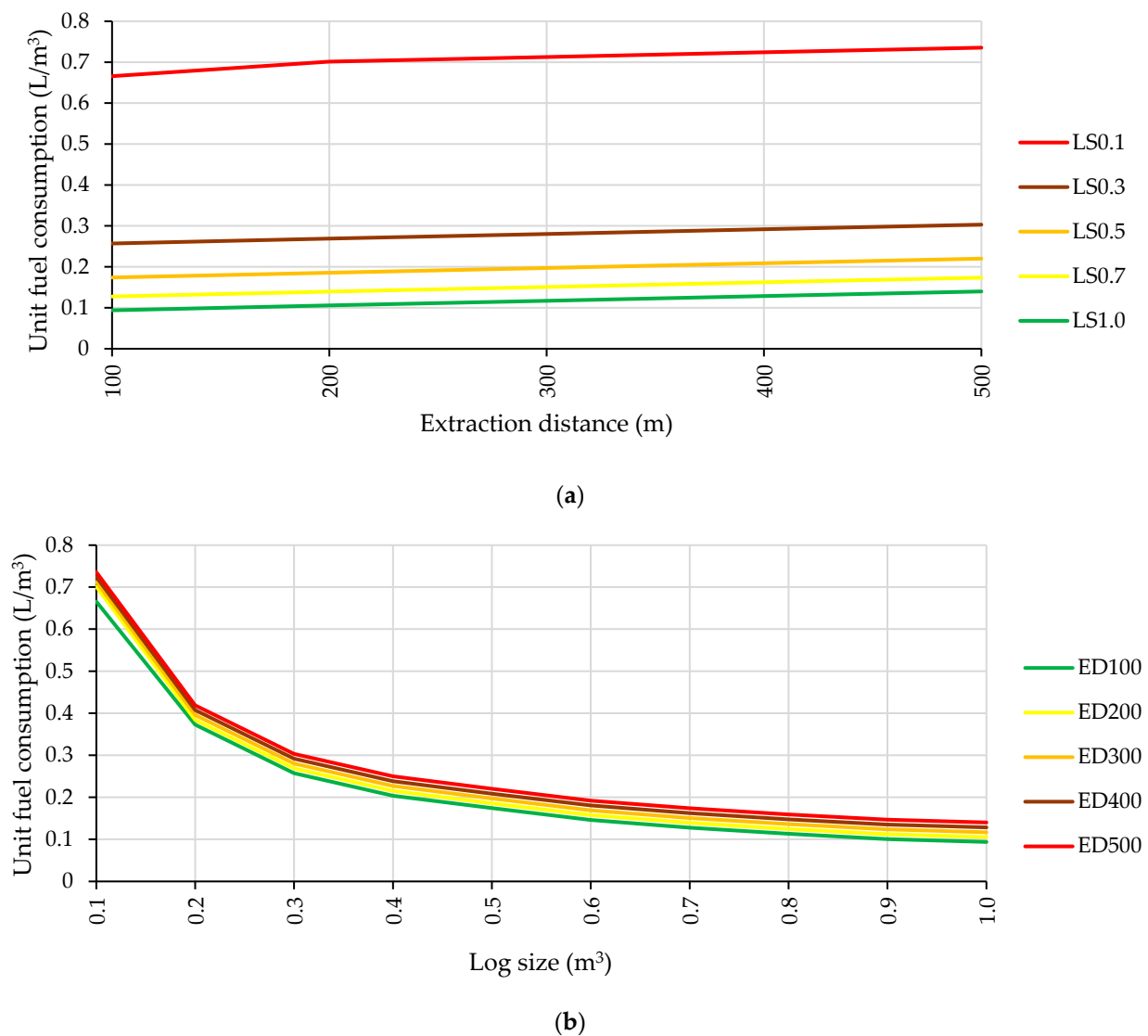
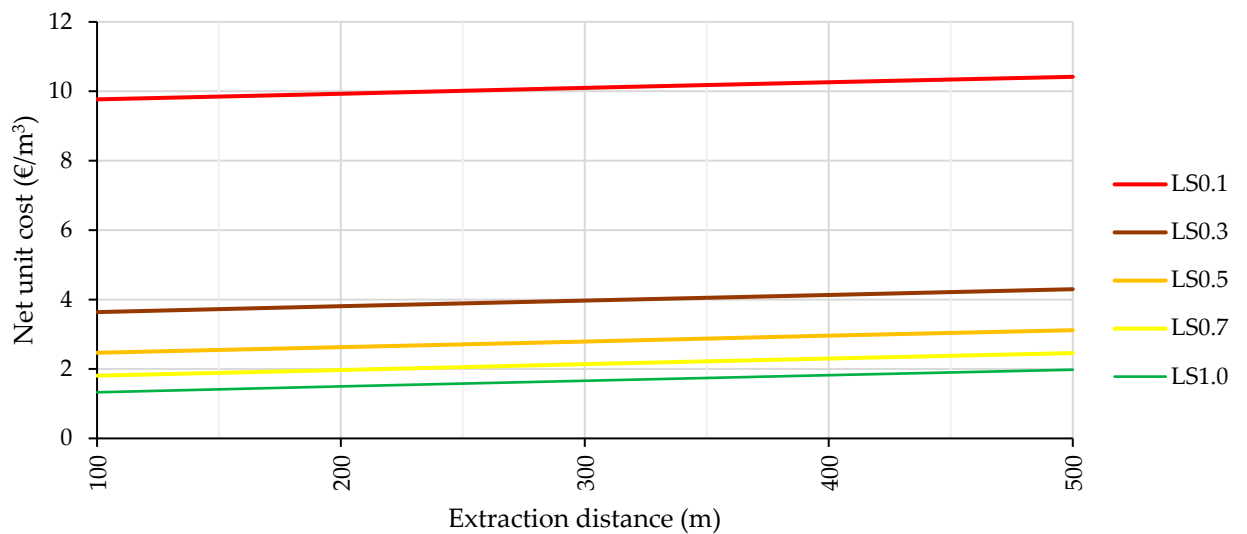
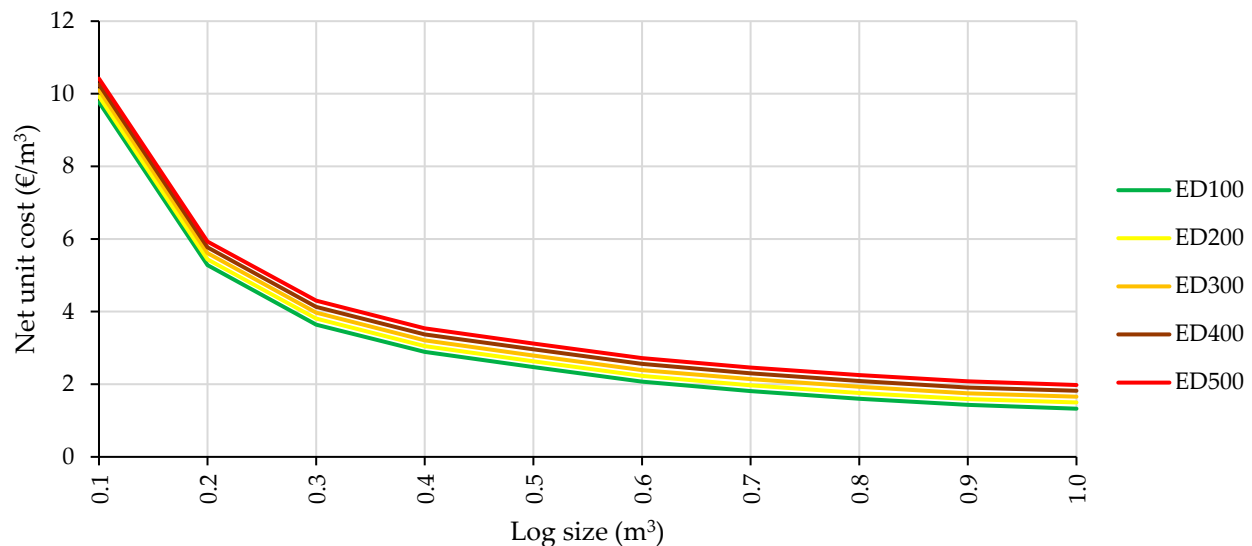


Figure 6. Simulated unit fuel consumption against the extraction distance and log size: (a)—unit fuel consumption depending on extraction distance for the same log size, (b)—unit fuel consumption depending on log size for the same extraction distance. Legend: LS0.1 to LS1.0 stand for log sizes between 0.1 and 1.0 m³, ED100 to ED500 stand for the extraction distances from 100 to 500 m.

The simulation models presented in Figure 7a,b show that as extraction distance increases, net unit cost increases, indicating that longer distances increase the cost of forwarding operations. On the other hand, an increase in log size results in a decrease in net unit cost.



(a)



(b)

Figure 7. Simulated net unit cost against the extraction distance and log size: (a)—net unit cost depending on extraction distance for the same log size, (b)—net unit cost depending on log size for the same extraction distance. Legend: LS0.1 to LS1.0 stand for log sizes between 0.1 and 1.0 m³, ED100 to ED500 stand for the extraction distances from 100 to 500 m.

This suggests that larger logs are more cost-efficient than smaller logs in forwarding operations, as well as the fact that the size of the logs forming a payload would be the driving cost factor for the considered extraction distances.

4. Discussion

Time-and-motion studies have been widely used to evaluate the performance of logging equipment and harvesting systems, even under similar working conditions [42,81,83]. These studies helped determine the machine's productivity and utilization rates, hence helping in predicting the logging practices' economic worth [84], since it is important to economically plan and implement logging practices while maintaining knowledge of their limitations and potential [85]. Numerous studies have been carried out on different site

characteristics to evaluate the performance of various wood extraction methods using farm tractors and to establish the logistics of extraction activities [85,86]. Previous research indicates that loading and unloading processes consume considerable amounts of time, although the time spent decreases as the size of logs increases [34]. As the extraction distance increases, there is a subsequent increase in travel time, resulting in decreased productivity [87]. Accordingly, reducing the extraction distance can have a significant impact on the overall cost and productivity [87,88].

In this study, simulation models were developed by combining empirical observations of farm tractor forwarding operations analyzed using statistical methods to predict system behavior as an inductive method [89–91], while the deductive approach provided behavior predictions based on particular scenarios relevant to low-removal-intensity continuous forestry settings [8,9,77,81]. This was because simulation models of forest machines have been noted to operate between the inductive and deductive approaches by several studies [63,78,89–91]. The results reveal a broad range of values for both distance and time consumption variables, with certain factors exhibiting considerable variability, as indicated by their relatively high standard deviations. Among the operational variables associated with wood extraction in this study, the most significant variability was observed in study delays, loading time, and empty turn distance, although the mean distance of wood extraction was approximately 1126 m. Similar studies have been conducted in the past and the results differ depending on the location and equipment used. For instance, a study was carried out in a 95-year-old pine stand, where forwarding with the Zetor 8045 tractor combined with a trailer with a capacity of 12 tons was characterized by an average extraction distance of about 200 m [86], whereas another study by [43] found that the mean extraction distance for tractor forwarding was 167 m in plantations in even-terrain conditions. These differences in results can be attributed to the variability in forest conditions and management practices [34,41]. Moreover, average maneuvering distance was found to be 46 m, while maneuvering time accounted for roughly 1.28 min. The distance variables reported in this study appear to be significant factors that influence the overall time consumption in wood extraction. These findings underscore the diverse operational challenges and complexities inherent in wood extraction processes in this condition [11]. The variability in key operational variables poses a challenge for forest managers to ensure the efficiency and sustainability of wood extraction, but addressing these sources of variability presents opportunities for improving forest management practices [11]. Therefore, the study highlights the need for landowners and forest managers to explore new approaches and consider the most appropriate method of wood extraction concerning accessibility, environmental impact, and cost-effectiveness [11]. In this regard, the use of farm tractors in low-removal-intensity CCF settings can be an attractive alternative method to meet these requirements. The implications of the findings for forest management and operations are significant. It is important for forest managers to consider the terrain and density of the stand when choosing an appropriate machine for wood extraction [40,41,43,92]. Low-intensity-removal CCF settings require sustainable harvesting practices that minimize soil damage and protect the residual stand [11]. While the use of farm tractors is feasible in low-impact harvesting, other factors such as cost, operator experience, and labor availability must also be considered when making decisions regarding their use in forest management and operations [40,41,43].

The operational speeds observed in four different types of tasks involved in machine movement were consistent with previous studies. For instance, [43] found that the average speed of loaded travel of the farm tractor was slower than the average speed during empty travel. Similarly, the study's simulation results showed that loaded turn speed (LTS) was higher than maneuvering speed (MANS) but lower than empty turn speed (ETS), potentially due to the absence of a loaded trailer. Maneuvering (MAN) speed, on the other hand, was found to be lower in this study as compared to that found by [93]. Additionally, results of previous research showed that average speeds up to 9 km/h can be specific to farm tractors [62], which matched the top speed recorded for empty turn in this study, supporting the plausibility of outliers eliminated from the dataset. The lower

quartile value of 1.6 km/h suggested that a significant proportion of movements occurred at relatively lower speeds [93]. Besides, loaded turn (LT) exhibited a speed distribution ranging from 0.6 to 10 km/h, with a median speed of 6 km/h and a mean of 5.49 km/h. This suggests that the speed during loaded turns is similar to those observed during empty turns [41,93], highlighting the consistency in tractor behavior during turning maneuvers. Generally, the speed of these tasks is low due to the complexity and difficulty of movement in low-removal-intensity continuous cover forestry [8,9,77,81]. Nonetheless, the identified trends in speed for the four work elements provide valuable insights for forest management practices and operational planning. The speed distributions observed in this study have various implications that may affect productivity, safety, workload distribution, time, cost considerations, and equipment selection. Therefore, understanding these distributions can help in streamlining operations and minimizing the time lost by identifying slower tasks or bottlenecks to optimize efficiency [94]. It can also aid in determining the time required for specific work elements, ensuring a balanced workload distribution among tractor operators, and guiding the selection of equipment and infrastructure design [45]. Overall, leveraging this information can enhance forest operational efficiency, productivity, and sustainability.

Moreover, the study suggests that cycle time consumption decreases with increased log size and decreased extraction distance. This finding aligns with previous studies such as [82,95], who identified the size of the extracted load as an important factor affecting forwarding cycle duration. Additionally, the study found that extraction distance had a greater effect on cycle time for smaller log sizes, and the rate of decrease in time consumption slowed with increasing log size. This trend is similar to the findings of [43] who found that the time consumption was related to the number of logs. Furthermore, the simulation models developed in this study suggest that loading and unloading times decrease gradually as log size increases. According to [96], the number of assortments being extracted, or their concentration, can influence loading and unloading cycle duration. These findings highlight the importance of considering log size, concentration, and extraction distance when planning forwarding operations to optimize productivity and reduce time consumption. Such findings also have significant implications for forwarding with farm tractors, as tractor operators may need to consider the log size being extracted and the distance of the extraction to achieve maximum efficiency.

The study found similar trends in productivity. The simulation models suggest that productivity increases with increasing log size but decreases with increasing extraction distance. However, in a distance range of 100 to 500 m, the log size had a more substantial impact on productivity than extraction distance. These findings are supported by those from previous studies [34,41,42,55]. For example, [55] found that the productivity of farm tractor forwarding increased with an increase in diameter and a decrease in extraction distance. In contrast, [42] reported that productivity decreased as distance increases and trees' size is reduced in low-access and low-intensity timber removals. The implications of these findings for forwarding with farm tractors are important as they demonstrate that managers can plan for optimal productivity by selecting the optimal combination of extraction distance and log size, ultimately leading to more efficient and sustainable forestry practices [34,41]. Thus, foresters in charge with planning can use the results to make their choice on the equipment to be used when several options are available, including that described in this study. As such, selecting large log sizes can significantly improve productivity, but operators must also consider the distance involved [34,41]. Moreover, forestry practices that help reduce time consumption and enhance productivity can lead to sustainable and efficient management practices [34,41]. These findings support decision making by providing indicative figures on what factors there are and how they are affecting productivity.

Furthermore, there were important variations found in unit fuel consumption depending on extraction distance and log size. As the extraction distance increases, there is a general trend of increasing unit fuel consumption, as reported by [42], who found that fuel

consumption increased with extraction distance in skidding operations. However, when log size increases, unit fuel consumption tends to decrease, which suggests that shorter extraction distances and larger logs can be more fuel-efficient compared to longer extraction distances and smaller logs. Moreover, [48] explain that the use of a tractor and forest trailer led to the lowest GHG emissions due to the low fuel consumption of the system. In terms of the implications for forwarding with farm tractors, the findings suggest that factors such as extraction distance and log size need to be carefully considered to minimize fuel consumption. Low-access and low-intensity timber removals may benefit from the use of a tractor and forest trailer or a tractor and winch, as reported by [48]. Additionally, the study carried out by [23] highlights the importance of selecting the most appropriate machines for the given harvest block to avoid high fuel consumption rates. Therefore, choosing the right equipment and managing operational parameters such as extraction distance and log size could lead to more sustainable and fuel-efficient forest operations.

In terms of unit costs, the findings highlight the importance of considering both extraction distance and log size when planning and optimizing forwarding operations to minimize costs. Shorter extraction distances and larger logs are more cost-effective; similarly, [41] found that the unit forwarding cost decreases with an increase in extraction distance and log size. Likewise, [43] found that forwarding with farm tractors is more efficient and cost-effective than skidding in certain situations. The study of [55] shows that using farm tractors for forwarding could be a more cost-effective and sustainable alternative to traditional methods for small-scale forestry. The study of [54], on the other hand, revealed that a combination of elephants and tractors is the most efficient and cost-effective method of timber extraction in steep terrain.

The limitations of this study include a lack of consideration for the effect of terrain and weather conditions, which may impact the productivity and fuel use of the farm tractor. Another limitation is that the study was carried out on a single farm tractor and may not be representative of the performance of other farm tractors or forwarding machines. Still, the methodological approach described by this study could be used to simulate cycle time, productivity, fuel use, and costs for other machines and operational settings. Additionally, the simulation results are based on local cost assumptions and may not accurately reflect the actual costs and performance of the machine in other places [79]. Therefore, some results should be interpreted with caution and further research is needed to confirm the findings and address these limitations. For instance, future studies may focus on investigating the influence of terrain conditions or operator experience on the observed speed patterns to optimize efficiency and productivity in tractor operations within continuous cover forestry systems. For instance, [65] suggest further studies to optimize productivity and reduce energy consumption in operations. The development of a general model to predict and benchmark productivity levels could be a significant contribution towards efficiency and profitability in tractor forwarding operations. Overall, the study suggests that careful planning, optimization, and consideration of variables impacting productivity are necessary for efficient and profitable forwarding operations in low-removal-intensity continuous cover forestry systems.

5. Conclusions

This study successfully measured and simulated time consumption, productivity, fuel use, and cost of modern farm tractors used in forwarding operations in low-removal-intensity continuous cover forestry settings for different extraction distances and log sizes using deductive and inductive reasoning. The study's descriptive statistics of operational speeds provided valuable insights into optimizing task efficiency and highlighted the varying speed profiles of each work element. Moreover, the simulation models highlighted the critical impact of log size and extraction distance on time consumption, productivity, fuel use, and net unit cost. These findings are consistent with earlier research and emphasize the importance of considering various factors to streamline operations, enhance efficiency, and promote sustainability. Additionally, the findings provide essential information for

operational planning, costing, and environmental assessment in terms of emissions under various operating conditions, supporting better decision making in the forestry industry. Future research should investigate the influence of terrain conditions and operator experience, with an aim to develop a general model predicting productivity levels in pursuit of more efficient and profitable forwarding operations with farm tractors.

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