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# Methodology for Assessing and Managing the Environmental Performance of Skidding and Feller Buncher Tractors

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**Abstract:** Systematic assessments on the effects of skidding systems on features of forest blueberry pine soil were conducted as part of this study. Assessing the ecological efficiency of forest skidding machines showed that the most significant impact (by 2.0–2.2 times) on soil compaction was observed at loading sites rather than during transportation. Lightweight loam density and sand density increased by 25% and 2%, respectively, after more than two passages of the skidding system. Pressure in 33L-32 tires of forestry machinery in operation on a solid surface varied from 46.5 kPa to 196 kPa at maximum load. Studying the impact of tires on soil compaction showed that the environmental efficiency of forestry equipment can be enhanced if the optimal tire pressure at average loads does not exceed 70 kPa for tracked vehicles and 150 kPa for wheeled vehicles in summer seasons. When ground grips were fully immersed, the pressure of forwarders on soil was reduced. These study results can be used to establish organizational and technological measures in order to manage the negative impact of skidding systems and to increase the environmental effects of their performance.

**Keywords:** ecological effect; forest operations; soil impact; tires; tractor

## 1. Introduction

Over the last decade, the forestry sector's leading and most important task has been the development of sustainable forest management [1], while considering environmental aspects related to forest operations. Elaborating new methods and technologies for sustainable development and wise use of forest resources can aid in minimizing harmful environmental impacts that are mainly caused by heavy forestry vehicles [2]. It is crucial to consider economic and environmental factors that influence productivity and to reduce the negative impact on the forest biosphere [3]. Two of the most harmful and expensive logging operations include timber extraction and forest product transportation. Recently, research efforts have focused on examining forestry operations' impact on soil conditions, restoration dynamics, and stand conditions.

Since soil is highly susceptible to logging [4], prolonged exposure to soil can reduce forest productivity and environmental efficiency [5]. The negative impacts on soil, namely compaction and erosion, are primarily associated with land-based logging operations, such as skidding and rutting by tracked and wheeled vehicles [6,7]. The use of skidding tractors may result in high soil compaction, followed by soil erosion and rutting, especially on skidding tracks [8]. Therefore, the most challenging task in managing environmental efficiency for the forestry sector comprises minimizing various soil disturbances.

Direct assessments of environmental effects are quite challenging. Recent studies have shown that soil compaction due to frequent machine movements reduces reafforestation [9,10]. Other studies indicate that logging operations have altered soil composition, enhancing seedling growth [11,12]. Therefore, many aspects of forest sustainability are quite difficult to assess and analyze shortly after logging and require constant monitoring and studies.

In addition, the impact of skidding operations on residual plantations can reduce the quality of future trees and increase the likelihood of damage due to various infections, fungi, and harmful insects [11,13,14]. Eventually, this may result in trunk deformation and may decrease the taxonomic specification of trees and forest products. It should also be noted that excessive damage to remaining plantations during logging can alter ecosystems, as a whole, and disrupt their natural balance [15].

Hence, all logging operations using heavy wheeled and tracked vehicles should be planned on larger scales and for extended periods and should focus on economic and environmental aspects [16]. Over the last decade, numerous studies have examined the impact of forestry operations on the resilience of forest ecosystems and new methods of development [12–15].

The operation of forestry machinery, including skidding tractors, can be represented as a process that consists of individual technological operations. In general, the operation of winning machinery and the execution of the operations of technical winning processes should be considered by using a systematic approach [17]. Kormanek et al. [18] applied a systematic approach to examine the operating efficiency of skidding tractors.

Thus, an inclusive approach was used to examine the forest/technological process/machine-tractor unit/finished product system [19], which comprises subsystems with objects, properties, connections, and functions performed by the forest machine. Each subject of this system was regarded as an independent low-level system or subsystem. Every object is a set of interrelated elements, each directly or indirectly linked to other elements.

Potential properties including numerous parameters and characteristics of specific units and entire machines, which determine service properties and reliability of the skidding tractor, are grouped and presented in the flowchart below. The system of indicators and factors specifying the operating conditions of a skidding tractor is illustrated in Figure 1, and its service properties and operational effectiveness are presented in Figure 2 [20].

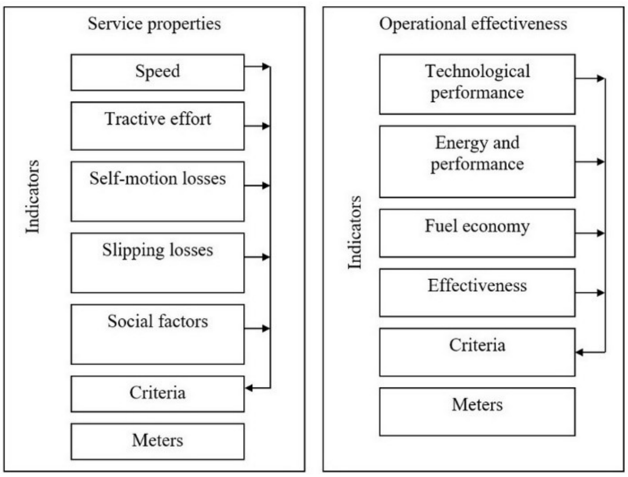


**Figure 1.** Indicators characterizing the system's service properties and operational effectiveness.

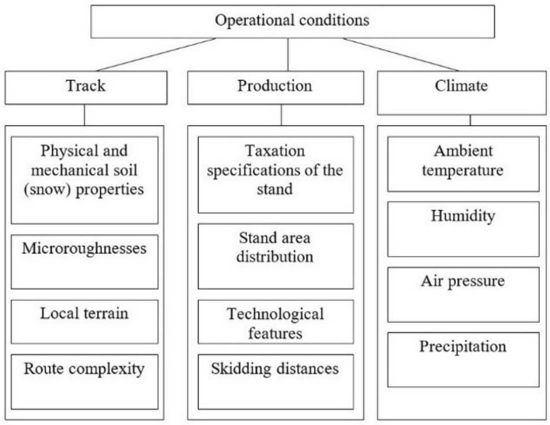


**Figure 2.** Features characterizing the operating conditions of skidding tractors.

The skidding tractor's operational efficiency scheme developed in [21] was complemented by factors affecting environmental efficiency. When the methodology adopted in the study of mobile systems is combined with an inclusive approach, the operation of a skidding tractor can be depicted as a system object.

However, this systematic study of the effect caused by forest machinery on ecological effectiveness is relatively rare in the literature. The operation of forest machines, including skidding tractors, may be represented as a process that consists of distinct technological operations (work, transportation, and mixed) for achieving a single objective. Furthermore, studies examining the operation of forest machinery have, to some extent, expanded in scope and have become highly relevant.

The impact of dry soil compaction on the growth of beech and pine seedlings was studied [22]. It was established that increased soil density adversely affects the development of the root system, particularly for small-diameter roots [23]. In another study conducted on soil compaction in the cold season, compaction in winter seasons was reported to occur mostly on the surface, affecting roots much less than in summer [24]. No significant difference between the compaction of arable land resulting from logging in post-wildfire and control areas has been demonstrated [25]. For tracked skidders, soil compaction degree depends on the weight of the transported log and the extension length of the crane [26].

This study aimed to achieve the following: (a) examine the influence of various logging aspects on the environmental effects of skidding vehicles; (b) evaluate the effectiveness of skidding tractors by using system analysis; and (c) analyze tractor landing gear and other impacts on soil that reduce damage to natural regeneration and remaining stands in logging operations.

The following section describes the methodology of the experiments. Section 3 presents the results of this study. In Section 4, data are discussed, relevant literature sources are reviewed, and examples of results obtained for subsequent research are provided. The Section 5 presents the study's findings.

## 2. Materials and Methods

### 2.1. System Method of Studying the Operation of Forest Machines

Factors influencing the environmental efficiency of skidding tractors can be grouped as follows: changes in physical and mechanical properties of soils in the felling area, the impact on undergrowth, and environmental pollution (Figure 3).

The aforementioned factors allowed soil density increase resulting from the impact of forest machines, including skidding tractors, to be selected as the primary indicator of environmental friendliness. Soil compaction in theoretical and experimental studies was assumed to be influenced by tracked wood packaging parameters, engine mode, and potential tractor properties. The latter is determined by parameters and technical solutions used in systems, mechanisms, and machine components (Figure 4).

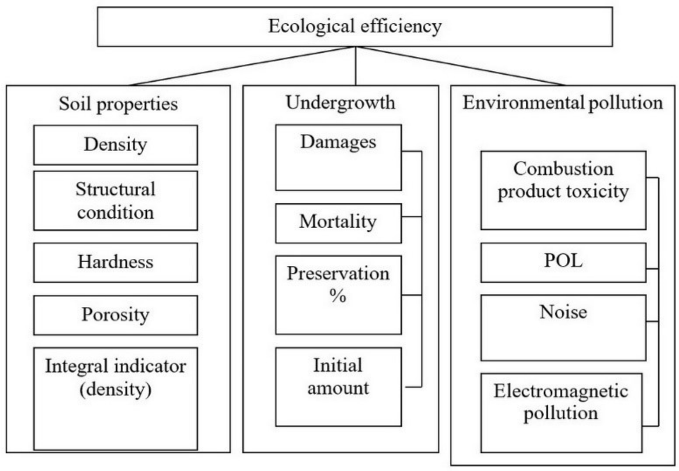


**Figure 3.** Structure of ecological efficiency of the performance of logging equipment.

| | |
|---|---|
| Parameters | Operational weight of a tractor, M |
| | Wheel formula |
| | Rated engine capacity, $N_{en}$ |
| | Torsion torque, $N_{en}$ |
| | Adaptability factor |
| | Crankshaft rotation speed |
| | Energy content $N_{en}$/M |
| | Transmission gear ratio |
| | Dynamic wheel radius |
| | Running system |
| | Technological equipment |

**Figure 4.** Potential tractor properties that affect soil compaction. Note: M—mass of a tractor; $N_{en}$—Net engine capacity (nominal).

*2.2. Experimental Procedure*

Tests were performed on 1-hectare plots in the territory of Yakutsk forestry.

A TLC 4-01 skidding tractor and chocker skidders after felling with chainsaws were used to examine the effects of logging different types of timber (freshly cut and wet) on soil density. We also examined the impact of skidding on different soil types (sandy, sandy clay, and light loam) with three models of skidding tractors (TLC 4-01, LP-19, and LP-49) (Table 1).

**Table 1.** Technical specifications and dimensions of skidding tractors.

| Tractor Model | Specifications | | | | | |
|---|---|---|---|---|---|---|
| | **Engine Power, kW** | **Maximum Speed, km/h** | **Width, m** | **Length, m** | **Height, m** | **Mass, kg** |
| TLC 4-01 | 147 | 32.2 | 3.04 | 8 | 3.505 | 14,500 |
| LP-19 | 126 | 15 | 3.15 | 8 | 3.19 | 26,000 |
| LP-49 | 84.6 | 30 | 2.8 | 7.9 | 3.6 | 17,300 |

Soil density was measured with an SC 900 penetrometer (Spectrum Technologies, Fort Worth, TX, USA).

All measurements were performed three times in order to facilitate statistical data processing (i.e., calculate variance).

This study used two types of wood: freshly cut wood, i.e., wood that was transported to the preservation sites on the same day after felling, and wet wood, i.e., wood that was transported to the platforms 1–2 weeks after felling.

Tire pressure estimates for wheeled timber tractors were performed in accordance with GOST 23734-79 [27], GOST 7057-81 [28], and other accepted standards for mobile agricultural machinery [29]. The average pressure (kPa), as per GOST 7057-81, of a single forwarder on a solid base is estimated by the following formula:

$$q_{av} = \frac{m_{fw} \cdot g}{10^3 F}, \tag{1}$$

where $t_{fw}$ is the load-creating mass of each forwarder, kg; $F$ is the contour contact area of the tire tread; and $g$ is the gravitational constant (9.8 m/s$^2$).

The contour area of wheel-tire contact with the ground was determined as per GOST 26953-86 [30]:

$$F_{ks} = F \cdot K_1, \tag{2}$$

where $F$ is the contact surface of the tire tread, determined on a solid base; and $K_1$ is the coefficient according to the external tire diameter. For tires with an external diameter greater than 1500 mm, $K_1$ = 1.10.

The following formula defines the maximum tire pressure on soil:

$$q_{\max} = q_{cp} \cdot K_2, \tag{3}$$

where $K_2$ is the longitudinal nonuniformity coefficient of the pressure distribution on the tire contact zone. According to GOST 26953-86, $K_2$ = 1.5 when the tire is immersed into soil by 50 mm.

In this study, research was conducted on TLK 4-01 tractors used in lumber industries. This model is widely used in Russia and is equipped with large 33L-32 tires with 66 × 43.00-25 size in various tread areas with developed ground grips of 130 mm in height, assuming that the bearing surface area of the skidding track is pressured only by the bearing surface of the ground grips, which is 390 cm$^2$ in area. Measurements of the wheeled tractor were compared with ground modifications following the passage of LP-19 and LP-49 feller bunches (crawler machines).

For efficient use of tire resources, manufacturers regulate tire air pressure according to the values listed in Table 2.

**Table 2.** Tire air pressure values for different operating modes of a tractor.

| No | Tractor's Operation Mode | Air Pressure, MPa | |
|---|---|---|---|
| | | Front Wheels | Rear Wheels |
| 1 | No load when passing with the rear-wheel drive off | 0.18 | 0.15 |
| 2 | On a skidding track with dense soil | 0.18 | 0.18 |
| 3 | On a skidding track with soft soil and virgin snow | 0.15 | 0.15 |

In terms of the influence of tires on forest soil compaction, the second and third operating modes are of particular interest. Experimental studies were performed on a solid base and on soil that allowed deepening tire treads in order to determine the contact spot area and the force of gravity (weight) acting on particular wheels.

Pine and blueberry forest soils with podzolic sandy soil and wet loam soil were selected for the study. The stand consisted of pine of II–III quality classes with a mix of birch and aspen and a sparse undergrowth—mountain ash and juniper. Plant cover consisted of blueberries, bright mosses, and cuckoo flax.

This study was conducted within the framework of the scientific school "Progress in the wood and forestry industry".

## 3. Results

Table 3 shows the results of analyzing transportation route density in logging operations in order to develop production engineering measures. As shown in Table 3, loading platforms (upper warehouses) represented 22–28% of the land area.

**Table 3.** Density of transport routes on fellings, km/ha.

| Type of Forest after Logging | Length of Transport Routes, km/ha | | | |
|---|---|---|---|---|
| | **Total** | **Roads** | **Skidding Tracks** | **Places of Skidder Pass** |
| Logging with feller bunchers and tractors with pincer grab | | | | |
| Freshly cut | 0.89 | 0.08 | 0.47 | 0.34 |
| Wet | 1.26 | 0.14 | 0.44 | 0.68 |
| Felling with gasoline-powered saws, skidding with choker-skidding tractors | | | | |
| Freshly cut | 0.9 | 0.08 | 0.82 | |

The most significant change in soil occurred not on skidding tracks but on loading platforms (Table 4). Thus, Table 4 indicates a 2.0–2.2-fold increase in soil density under the influence of forest machinery.

**Table 4.** Changes in soil under the influence of multifunction equipment on loading platforms.

| Type of Forest after Logging | Density, g/cm$^3$ | | Track Parameters | | |
|---|---|---|---|---|---|
| | **Loading Platform** | **Control** | **Area, m$^2$/100 m$^2$** | **Depth, cm** | **Volume, m$^3$/100 m$^2$** |
| Freshly cut | 5.8 ± 0.04 | 2.8 ± 0.14 | 40.0 | 14 | 56.0 |
| Wet | 8.2 ± 0.02 | 3.7 ± 0.04 | 47.5 | 10 | 47.5 |

After loading and repeated passages of machinery, compression, and soil mixing, soil microstructures change dramatically. Physical and mechanical properties largely determine soil behavior that is subjected to technological influence. In the case of only two skidder passes, the increase in light loam density was 25% greater than that of sand density (Table 5).

**Table 5.** Change in soil density * under the influence of logging machines at depths of 5–10 cm (g/cm$^3$).

| Number of Passes | Sand | | | Sandy Clay | | | Light Loam | | |
|---|---|---|---|---|---|---|---|---|---|
| | **TLC 4-01** | **LP-19** | **LP-49** | **TLC 4-01** | **LP-19** | **LP-49** | **TLC 4-01** | **LP-19** | **LP-49** |
| 0 | 1.31 | 1.33 | 1.31 | 1.02 | 1.03 | 1.27 | 1 | 1.15 | 1.09 |
| 1–2 | 1.33 | 1.37 | 1.41 | 1.1 | 1.17 | 1.4 | 1.25 | 1.33 | 1.37 |
| % to control | 2 | 3 | 8 | 8 | 15 | 10 | 25 | 16 | 26 |

* Arithmetic mean error—from 0.02 to 0.05 g/cm.

The results presented in Tables 3–5 indicate a 3–5 m wide skidding track in the cutting strip when skidding wood by tractors with sliding rope-choker or choker-free equipment. The total area of the cutting and main skidding tracks comprised 15–20% of logging areas, and the width varied within 30–35 m. When using a full-turn feller buncher of the LP-19 type, the distance between tracks is reduced by 2–3 times, and track width increases 1.5-fold. The total track area, using such a technique, can comprise between 35% and 40% or more of the logging area [31].

Measurements of longitudinal pressure distributions under the ground-grip tire (Figure 5) show that, at a regular load of 7.0 m$^3$, one tire rests on six ground grips with a total area of 0.234 m$^2$. With a full regular load, the weight of the wheels is approximately 46.5 kN. Therefore, the pressure of a ground grip on the solid support surface should be 196 kPa. At a tire pressure of 33L-32 180 kPa, the maximum average soil pressure must be 194 kPa. The pressure between the "equator" and the sides was shown to decrease (Figure 5).

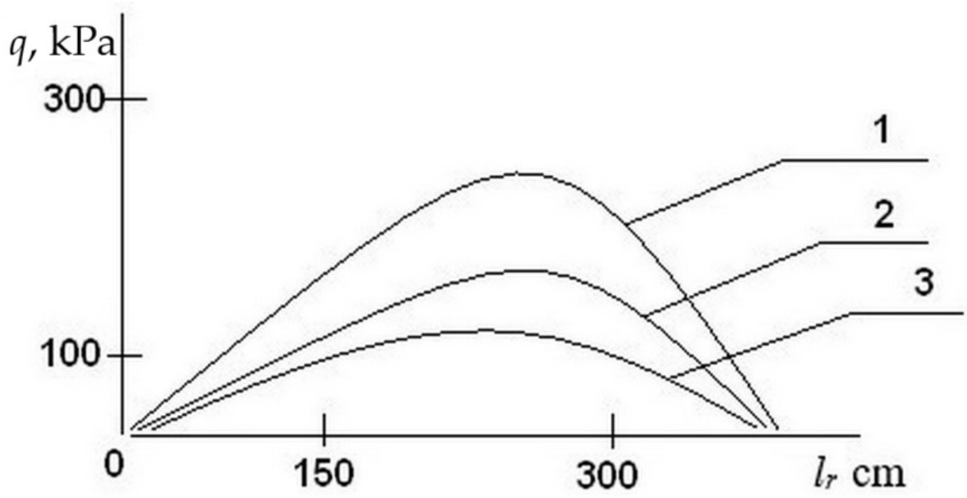


**Figure 5.** Longitudinal pressure distribution $q$ of the ground-grip tire 66 × 43.00-25 in different areas of the tread, $l_r$, at a tire air pressure of 100 kPa and weight acting on the wheel of 25.8 kN. Note: 1, 2, 3—ground grips.

After determining the force of gravity acting on the tractor's wheels and following the recommendations as per GOST 23734-79, it was established that, in an unloaded tractor that weighed 14.670 kg, one wheel of the front axle displayed a force of gravity of 23.0 kN, and the rear axle wheel displayed a force of gravity of 13.0 kN; that is, the weight distribution was 64% on the front axle and 36% on the rear axle. At an optimum flight load of 7.0 $m^3$, each wheel of a loaded tractor was subjected to a force of gravity of approximately 45.0–46.5 kN. The average tire pressure of a wheeled forest tractor on a solid base is 137 kPa, in accordance with GOST 23734-79, and 50 kPa, according to Scandinavian methods. According to GOST 26953-86, $K_2$ = 1.5; as a result, the maximum tire pressure on the firm base is 205 kPa. Therefore, the highest average nominal pressure and calculated pressure exerted by the surface area of the ground grips on a solid base differ by 5.3–5.6% from the maximum pressures obtained according to GOST 23734-74.

Following the typification of natural production conditions in logging areas [32], 40–79% of forest stands are located on soils of categories III and IV, which are overwetted with low bearing capacity and low density. Seryi et al.'s [33] analysis of logging soils showed that natural composition density varied as follows: sand—1.31–1.33 g/$cm^3$; sandy clay—1.03–1.27 g/$cm^3$; and light loam—1.00–1.15 g/$cm^3$. These data are consistent with the results of the present study.

Furthermore, the presence of bedding that is several centimeters thick should be considered in loggers. Long-term observations of wheeled skidding tractors in different soil conditions have shown that, when skidding a bundle on track, the ground grips of large tires are entirely immersed in the soil, and the force acting on the wheel is transferred to the ground grips' surface area and the tire surfaces between them.

Measuring the 33L-32 tire location showed that the length of the tire contact spot at this load was 105 cm. Moreover, at $K_1$ = 1.1, the length was 115.5 cm. With a tire width of 83.8 cm and a factor of $K_1$ = 1.1, the area of a tire contact point was 9679 $cm^2$. If the force of gravity acting on the wheels is 46.5 kN, the average pressure of the tire, completely immersed in soil, would be 48.0 kPa, and the maximum pressure would be 72 kPa. The mean pressure of the wheeled tractor was 50 kPa. Furthermore, it is preferable to use machines with specific pressure at an average load not exceeding 70 kPa for tracked vehicles and 150 kPa for wheeled vehicles in order to prevent erosion processes, to prevent deterioration of the soil's water-physical properties and fertility, and to preserve the forest's protective properties during logging in the summer.

## 4. Discussion

Several studies on the compacting effect of skidders on forest soils [34–36] have revealed the incorrectness of an applied approach due to a lack of consideration of the nature of tire interaction with soil, its physical and mechanical properties and condition, root system, total tracking area, etc.

This phenomenon may be explained by the inertia of researchers' thinking, formed by research on the "soil of farmland/mechanical harvesting" system [35,37]. According to Solgi et al. [35], various machines pass through fields 5–15 times in preparation for sowing, plant care, and harvesting. Thus, the total passage area is twice as large as the sown area, 10–12% of the field area is exposed to passages from 6 to 20 times, 65–80% of the area from 1 to 6 times, and 10–15% of the area is not affected. This form of exposure occurs nearly every year, and the fact that logging soils are mainly compacted in summer seasons should be considered. According to the literature, one of the largest forestry associations in the Russian Federation (Komi) develops approximately 30% of annual logging in the summer [32].

Furthermore, during the spring–autumn disorder, forestry development is not profitable from an economic point of view [37]. Grigoryev and Kunitskaya [38] reported that the cost of transporting 1 $m^3$ of wood on winter roads is 4-times lower than transportation costs on earth roads. Clearly, soil compaction does not occur in winter seasons when frost depth is greater than 10 cm. However, recent studies have shown that winter slaughter is prone to heavier and more rapid turfing than summer slaughter. Slaughter of winter crops was also found to resume on its own 3–5 years later, particularly in fertile soils [32]. In theory, tire pressure on the tread surface increases with tread speed. However, no study of this kind has been conducted on large forestry tires. Dependencies of the pressure increase in tractor tires with increased rolling speed have been reported by Grigoryev and Kunitskaya [38]. In addition, highly elastic polyurethane 66 × 40.00-25 tires from Lim (Austria) and 28.1R26 tires with a permissible load of 46.0 kN are similar to the large tires of forest skidders. Tires 66 × 40.00-25 and 28.1R26 with rising speeds from 0 to 9.1 km/h increased the pressure on the bearing surface by 11%. However, 9.1 km/h is the actual speed of a wheeled skidding tractor while carrying a load (skidding a bundle of wood).

## 5. Conclusions

This study evaluated how the technological aspects of logging operations affect the environmental efficiency of skidding forest machinery. An evaluation of loading transactions and repeated passes of vehicles on soil density revealed a sharp increase in light loam density compared to sand density after two passes of the skidding system. Furthermore, the most significant increase in soil density (2.0–2.2 times) was recorded on loading platforms. Higher numbers of passes by skidding tractors resulted in greater soil compaction (by 25% for loam and by 2% for sandy soils). Further evaluation of skidding tractor efficiency showed that using machines with pressures not exceeding 70 kPa for tracked vehicles and 150 kPa for wheeled vehicles at average loads during forest thinning is preferable. Additionally, the maximum load of operating equipment increases tire pressure by more than four times, which is more damaging to the ground. It has been established that when the 33L-32 tire of a wheeled skidder interacts with soil, with fully immersed ground grips, the pressure exerted on the soil is lower than the pressure recommended for logging and thinning techniques. Thus, the system "forwarder–forest soil" can be regarded as environmentally friendly. The impact of the skidding tractor's operation in the felling area must be considered when assessing the ecological compatibility of forest machinery with soils and the environmental damage arising from skidding processes.

In order to improve the quality of this study, factors for optimizing the logging system, valuation indicators, and transport routes of machinery must be examined in greater detail.

**Author Contributions:** Conceptualization, I.G. and O.K.; methodology, E.T.; software, E.H.; validation, A.K., O.B. and N.S.; formal analysis, A.Z.; investigation, O.K.; resources, I.G.; data curation, A.K.; writing—original draft preparation, I.G.; writing—review and editing, E.H.; visualization, I.G.; supervision, O.B.; project administration, E.T.; funding acquisition, I.G. All authors have read and agreed to the published version of the manuscript.

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