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ANALYSIS OF THE OPERATION OF FOREST HARVESTING MACHINES ON SLOPES

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At present, various machine systems are used in the forest harvesting sector of Ukraine, ranging from powerful specialised machines (harvesters and forwarders) to medium- and low-traction-class machines, often based on general-purpose agricultural or industrial tractors. These machines may be equipped with wheeled, tracked, or semi-tracked running gear, which makes a comparative analysis of their impact on forest soils particularly relevant.

The aim of this study is to carry out a comparative analysis of the main technological indicators of forest harvesting operations and the impact of different types of running gear during the operation of forest harvesting machines on forested slopes. The paper presents the results of investigations into the influence of forest machine running gear on the soils of cutting areas. During the study, various parameters were identified and analysed, including slope angle, soil porosity, and particle density, and a comparison was made between different types of running gear–wheeled, semi-tracked, and tracked. The results showed that wheeled machinery has a significant effect on these parameters. The passage of tracked machinery has a lower impact on forest soils compared to wheeled and semi-tracked forest machines. These findings indicate a potential disturbance of soil structure and changes in its physico-chemical properties as a result of the operation of forest machines.

The results of the study are of considerable importance for understanding the impact of machinery on the ecological condition of forest ecosystems and for the development of effective strategies for sustainable forest management. Further research in this field will make it possible to refine these results and to identify optimal methods for the use of forest machines with minimal impact on forest soils.

Keywords: *forest soils,forestry machines,engines,compaction,deformation.*
Eq. 3. Fig. 5. Table. 2. Ref. 30.

1. Problem formulation

Logging operations are an integral component of the production system of the forest complex. It is extremely important that logging operations are carried out efficiently from an economic, technological and environmental point of view [1-4, 17]. In this regard, key aspects of logging production, such as the selection and use of optimal machine systems for logging operations [10, 11], determine fundamental decisions when determining and justifying provisions for the selection of forest machines regarding the type of engine, which functionally determines and regulates the direct impact on the efficiency and productivity of work in the forest [24].

Among the various factors affecting the performance of logging equipment, terrain slope plays a crucial role and significantly influences the choice and efficiency of such equipment in logging operations [14], as it is a key factor determining both the speed and stability of the machines involved. The use of skidders on slopes is of particular importance in logging operations [16].

Logging operations have a significant impact on the soil, especially in terms of compaction and the formation of ruts formed by the machines [26]. Compaction occurs when mechanical forces acting on the soil cause the soil particles to compress, reducing the pore space and leading to an increase in the bulk density of the soil. This process is more pronounced at high soil moisture levels, as repeated passes of the machines can cause deformation of the soil [7, 8].

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The interaction of forestry machines with the ground surface occurs when the machines are moved by the feller. In modern logging practice, machines with wheeled, tracked and, much less often, half-track drives are widely used. Skidding tractors, such as tracked and half-track models, provide great opportunities for working on slopes [19]. Machines with wheeled drives have high maneuverability and speed of movement, which makes them the optimal choice for performing operations on flat or slightly sloping areas [30]. Tracked machines, on the other hand, provide high cross-country ability in difficult conditions, such as mountainous terrain or poorly bearing soil. Half-track machines combine the advantages of both types, providing both maneuverability and cross-country ability [3].

Wheeled skidders are one of the most common types of machines used in logging [11, 23, 27]. An important aspect of using wheeled skidders is their ability to maneuver in confined spaces [21]. Wheeled skidders also have significant lifting capacity and can transport large volumes of harvested wood. This reduces the amount of time and labor spent on skidding and increases the productivity of logging operations [5]. Tracked and semi-tracked tractors have better traction and surface adhesion, which allows them to move effectively on slopes and overcome obstacles. This is especially important when working on steep and uneven terrain, where wheeled tractors may experience difficulties [25, 26].

2. Analysis of recent research and publications

Wheeled skidders are one of the most common types of machines used in logging [11, 22, 27]. An important aspect of using wheeled skidders is their ability to maneuver in confined spaces [21]. Wheeled skidders also have significant lifting capacity and can transport large volumes of harvested wood. This reduces the amount of time and labor spent on skidding and increases the productivity of logging operations [5]. Tracked and semi-tracked tractors have better traction and surface adhesion, which allows them to move effectively on slopes and overcome obstacles. This is especially important when working on steep and uneven terrain, where wheeled tractors may experience difficulties [25].

Currently, there is a trend towards increasing the weight and productivity of forestry machines, the engines of which create dynamic pressure on the soil surface, while the degree of impact of wheeled machines is primarily influenced by tire properties, such as diameter, width, stiffness and inflation level, and for tracked machines, by the width of the track [9, 18]. Soil compaction, characterized by the destruction of soil pores and surface aggregates, is influenced by factors such as the mechanical composition of the soil, moisture level, and the number of machine passes [6, 23, 28, 29]. Studies show that soil compaction is most significant during the first passes of forestry machines, with most of the compaction occurring during the first three passes. Subsequent passes usually have minimal additional impact. However, the relationship between the slope (both longitudinal and transverse) and the direction of movement of the machines (uphill or downhill) and their changes in the impact of forest machines on the forest soil environment has not yet been fully studied. It can be assumed that on steep slopes, machines can slip, which leads to an increase in the dynamics of track formation by the engines due to the tangential forces implemented by the engine.

For many logging entities in Ukraine, especially in mountainous areas, the issue of effective and moderately economical development of mature and overgrown forest stands on steep and very steep slopes is extremely relevant. In a number of regions located in the western regions of Ukraine, this issue is exacerbated by the very specific properties of the cryolithozone soils in the warm season, primarily due to their specific structure and melting of the soil layer.

Most large and medium-sized logging enterprises currently use heavy, energy-intensive imported wheeled forestry machines (Fig. 1).

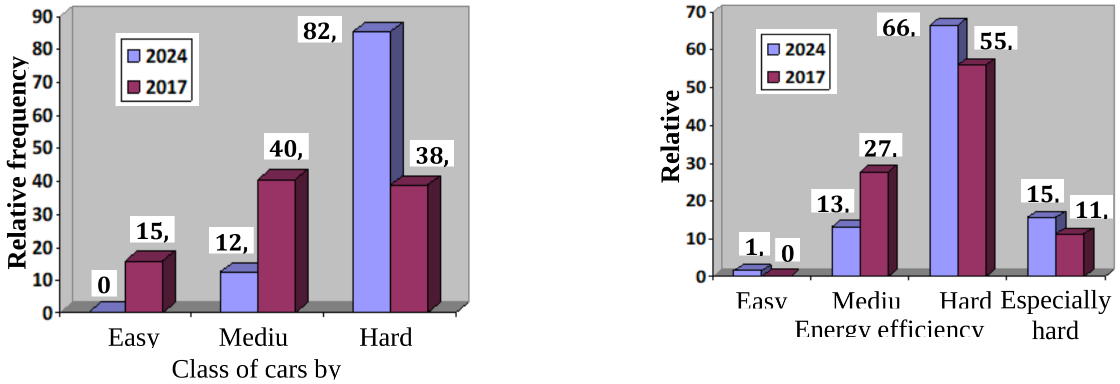

Fig. 1. Distribution of skidding tractors by mass and energy density classes at logging enterprises

In difficult operating conditions, such as weakly bearing soils, deep snow cover, and significant terrain slopes, they are usually equipped with sets of wheeled tracks (monotracks), which are installed in tandem on wheel pairs.

The vast majority of small and small-scale logging enterprises use either outdated tracked forestry machines or machines based on wheeled agricultural tractors with a 4x4 wheel formula, which under adverse operating conditions can be re-equipped for half-track operation, when monotracks are installed on the rear drive wheels using additional driven wheels or sprockets (Fig. 2). Analysis of the use of each type of machine in logging will help determine their impact on the forest in different conditions and tasks. This will allow logging enterprises and specialists to make informed decisions when choosing the most suitable equipment for specific natural and production conditions. Having received the best idea of the capabilities and limitations of forestry machines in rough terrain, specialists can make informed decisions regarding the most appropriate options for developing logging areas.

Fig. 2. Forwarder based on a tractor with a half-track

3. The purpose of the article

The aim of this study is to investigate the influence of different types of running gear of forest harvesting machines (wheeled, semi-tracked, and tracked) on the physical properties of forest soils on slopes and to determine their comparative effectiveness in terms of minimizing soil compaction and deformation during logging operations.

To achieve the stated aim, the following objectives were formulated:

- to investigate the influence of different types of forest machine running gear and terrain slope on the interaction between machines and forest soils;
- to determine changes in the main physical properties of forest soils, including porosity, particle density, and compaction, under the impact of wheeled, semi-tracked, and tracked machines;
- to perform a comparative assessment of different running gear types and substantiate recommendations for their environmentally sustainable use in forest harvesting operations.

4. Results and discussion

The research was conducted in the western regions of the forest massif of Ukraine. The average daily temperature was 6-9 °C. The soils were mainly sod-gley, with an average humidity of 30-82% and an organic matter content of 3-19%. The approximate area of the tested area was 1 ha. The maximum slope of the relief was 20%. The predominant wood species was Cajanderi larch (L. cajanderi) with the following characteristics: average height – 23.4 m, average diameter at a height of 1.3 m was 0.36 m.

The territory was divided into experimental plots depending on the slope of the terrain, thus 4 types of plots were formed: 0-5% inclusive; 5-10%; 10-15%; 15-20%. The average skidding distance was 250 m. Samples were taken from the track after 3 passes of the forest machine. Samples with a diameter of 50 mm were taken after removing the organic layer at a depth of 50-200 mm.

For control, samples obtained from the drags before the start of the work were used. On-site, the resistance to penetration of the RP soil was measured using a hand-held penetrometer. The samples were transported to the laboratory in plastic bags, where they were immediately weighed and dried for 24 h at 105 °C.. The density of soil particles and the bulk density of the soil were measured, which were calculated by the formula [15]:

$$w_p = \frac{w_w M_{d.s}}{M_{d.s} - M_{p.s.w} - M_{p.w}}, \qquad (1)$$

where w_w – water density, г/дм^3; $M_{d.s}$ – dry mass of soil sample, г; $M_{p.s.w}$ – mass of penetrometer with soil and water, г; $M_{p.w}$ – mass of penetrometer with water, g;

$$w_г = \frac{M_{d.s}}{V_{s.v}}, \qquad (2)$$

where $V_{s.v}$ – soil volume, g/dm^3.

The obtained values were used to determine the porosity of the soil.

$$P_г = \frac{w_p - w_г}{w_p} 100\%. \qquad (3)$$

Sampling was carried out at three points, analyzing each of them separately. Statistical analysis was performed using one-way ANOVA test at the level of α = 0.05. Before the experiment, the value of RP was 1.319-1.474 MPa.

Technical characteristics of forestry machines are given in Table 1.

Table 1.

Technical characteristics of machines

Brand	Wheeled	Half-track	Crawler
Type	PONSSE Buffalo K100	МТЗ-82	TT-4M 01
Weight, kg	18600	3270	12600
Engine power, kW	210	59	98
Maximum speed, km/h	20	35	20
Dimensions, mm: - length	9610	3930	5927
- width	3085	1970	2700
- height	3860	1665	2957

As can be seen in Fig. 3, with an increase in the slope of the terrain, the value of the resistance to penetration into the soil (soil resistance) R_P increases by 4-140 kPa, or 3.2-10.5%, depending on the depth of sample extraction. After the passage of wheeled equipment, R_P increases by 23-263 kPa, half-tracked equipment - by 51-259 kPa, tracked equipment - by 3-172 kPa with an increase in the slope of the terrain.

The maximum value of R_P was recorded for a depth of 150-200 mm after the passage of the wheeled vehicle and is 1.64 MPa.

On sections with a slope of 0-5%, there is a general trend of increasing R_P with increasing measurement depth and differences between machine types.

For example, at all measurement depths of 50-200 mm, tracked vehicles have a lower impact on penetration resistance (1.42-1.43 MPa) than wheeled (1.44-1.49 MPa) and half-track vehicles (1.43-1.45 MPa).

On sections with a slope of 5-10%, R_P also increases with increasing depth of measurement. Here, tracked vehicles demonstrate lower penetration resistance (1.44–1.47 MPa) compared to wheeled (1.48–1.53 MPa) and half-tracked (1.46–1.47 MPa). A similar trend is observed on sections with a slope of 10-15% and 15-20%.

Penetration resistance increases with increasing measurement depth.

Tracked vehicles in these areas also demonstrate lower penetration resistance (1.44-1.53 MPa in areas of 10-15% and 1.52-1.64 MPa in areas of 15-20%) compared to wheeled vehicles (1.5-1.54 MPa and 1.67 MPa and 1.48 MPa) and wheeled vehicles (1.52-1.6 MPa and 1.58-1.68 MPa, respectively).

Analyzing the values of soil bulk density at different sections of slope and sampling depth, the following observations can be made, Fig. 4.

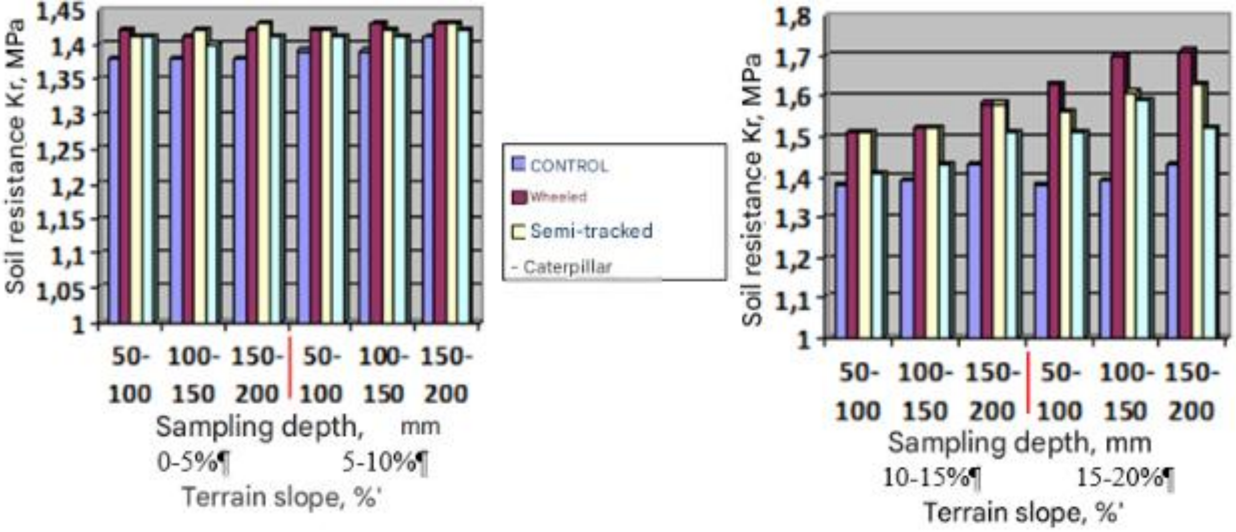

Fig. 3. Diagram of the change in the resistance of penetration into the soil of the penetrometer

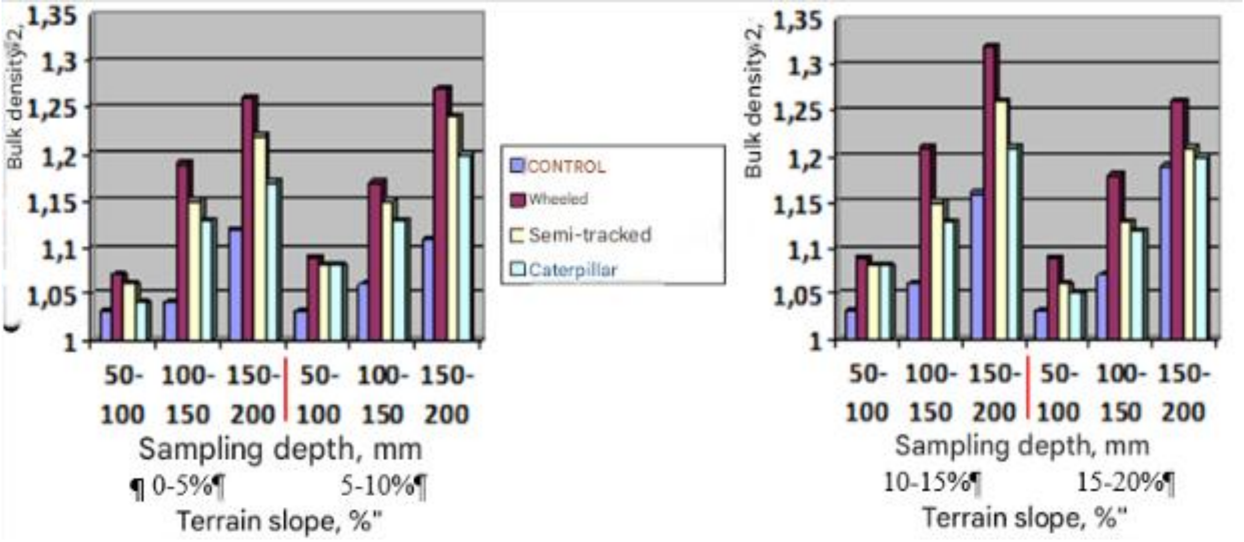

Fig. 4. Diagram of changes in soil bulk density

On a slope of 0–5%, bulk density values range from 1.03 to 1.08 g/cm3 at a sampling depth of 50–100 mm. At a sampling depth of 100–150 mm, bulk density values increase and range from 1.05 to 1.2 g/cm^3, and at a sampling depth of 150–200 mm, they continue to increase and range from 1.12 to 1.3 g/cm^3. The passage of tracked vehicles more often leads to lower bulk density values of the soil compared to wheeled and semi-tracked vehicles.

On a site with a slope angle of 5–10%, a similar trend of increasing soil bulk density with increasing sampling depth is observed. Regardless of sampling depth, the use of wheeled machines is accompanied by higher values of soil bulk density compared to wheeled and semi-tracked machines (Fig. 4).

In areas with a slope angle of 10–15% and 15–20%, an increase in soil bulk density with increasing sampling depth is also observed. After the passage of tracked vehicles, the soil bulk density values are the lowest compared to wheeled and semi-tracked vehicles at most slope areas and sampling depths. The use of tracked vehicles in these areas also demonstrates the minimum bulk density (1.08–1.2 g/cm^3 in areas of 5–10%, 1.07–1.22 g/cm^3 in areas of 10–15% and 1.06–1.2 g/cm^3 in areas of 15–20% g/cm^3, 1.08–1.3 g/cm^3 and 1.09–1.26 g/cm^3 respectively) and semi-tracked vehicles (1.08–1.24 g/cm3; 1.07–1.22 g/cm^3 and 1.07–1.21 g/cm3 respectively).

On a site with a slope angle of 0-5%, the density values of soil particles vary in the range from 2.08 to 2.4 g/cm^3 at a sampling depth of 50-100 mm, Fig. 5.

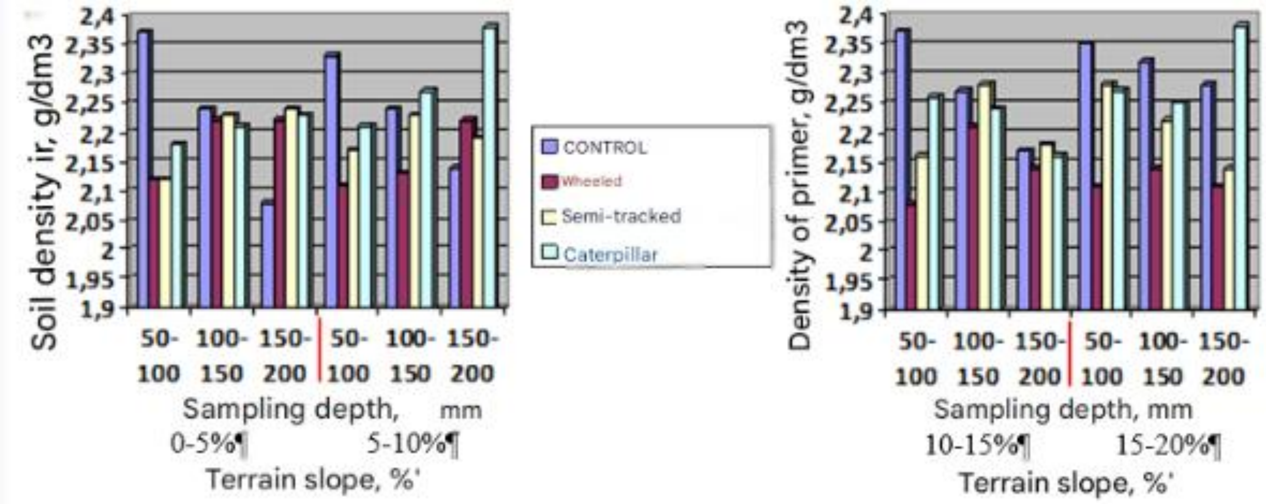

Fig. 5. Diagram of soil density change

At sampling depths of 100-150 mm and 150-200 mm, the particle density values also differ, but the general trend is ambiguous. On the site with a slope angle of 5-10%, there is a slight increase in the soil particle density values after the passage of the equipment, especially at a sampling depth of 150-200 mm. However, the differences between the types of equipment are not significant. On the sites with a slope angle of 10-15% and 15-20%, there is a more pronounced effect of the passage of the equipment on the density of soil particles. The particle density values after the passage of tracked equipment are usually higher, especially at a sampling depth of 150-200 mm.

In the control area, the particle density values vary in the range from 2.08 to 2.4 g/cm^3 (Fig. 5). At sampling depths of 100-150 and 150-200 mm, the particle density values also differ, but the general trend is ambiguous. On the area with a slope angle of 5–10%, a slight increase in the soil particle density values is observed after the passage of the equipment, especially at a sampling depth of 150–200 mm. However, the differences between the types of equipment are not significant. On the areas with a slope angle of 10–15% and 15–20%, a more pronounced effect of the passage of the equipment on the density of soil particles is observed. The particle density values after the passage of wheeled equipment are usually higher, especially at a sampling depth of 150–200 mm.

At a terrain slope angle of 0-5% and a sampling depth of 50-100 mm, all types of machines showed increased values of soil particle density, ranging from 2.12 to 2.4 g/cm^3. A similar trend was observed at a sampling depth of 100–150 mm, where particle density values ranged from 2.13 to 2.3 g/cm^3. At a sampling depth of 150–200 mm, particle density values ranged from 2.12 to 2.4 g/cm^3.

At a relief slope angle of 5-10% and a sampling depth of 50-100 mm, an increase in the density of soil particles was observed for all types of equipment, where the values ranged from 2.1 to 2.2 g/cm^3. At a sampling depth of 100-150 mm, the particle density values varied from 2.13 to 2.3 g/cm^3, also indicating an increase in density. At a sampling depth of 150-200 mm, the particle density values ranged from 2.14 to 2.34 g/cm3. A similar trend was observed for relief slopes of 10–15% and 15–20%. At a sampling depth of 50-100 mm, all types of equipment caused an increase in particle density, where the values ranged from 2.07 to 2.3 g/cm^3. At a sampling depth of 100-150 mm, particle density values ranged from 2.2 to 2.3 g/cm^3, indicating increased values. At a sampling depth of 150-200 mm, particle density values ranged from 2.2 to 2.4 g/cm^3, also indicating increased density..

As can be seen (Table 2), at a relief slope angle of 0–5% and a sampling depth of 50–100 mm, the porosity of the soil is 56.4% for the control area. After passing the wheeled, semi-tracked and tracked vehicles, the porosity values are 49.1; 50.1 and 51.6%, respectively.

At a sampling depth of 100-150 mm at the same terrain slope angle of 0-5%, the soil porosity values are 53.1% for the control value. After passing the wheeled, semi-tracked and tracked vehicles, the porosity values are 46.5; 48.4 and 49.5%, respectively.

Similar trends are observed for the sampling depth of 150-200 mm at a relief slope angle of 0-5%. The soil porosity is 46.2% for the control value. After the impact of wheeled, semi-tracked and tracked equipment, the porosity values are 43.2; 45.6 and 47.5%, respectively. When changing the relief slope angle and sampling depth, similar trends are observed. The general trend is that the soil porosity values decrease after the passage of the equipment compared to the control value.

The calculated soil porosity data are provided in Table 2.

Table 2

Soil porosity values

Tilt angle, %	Sampling depth, mm	Porosity, %			
		CONTROL	Wheeled	Half-track	Crawler
0-5	50-100	55,3	48,0	50,1	52,7
	100-150	52,0	45,4	48,4	50,6
	150-200	45,1	42,1	45,6	48,6
5-10	50-100	54,8	47,1	50,4	52,3
	100-150	51,6	44,0	48,5	51,4
	150-200	47,1	41,9	43,5	49,3
10-15	50-100	55,0	46,7	50,3	53,7
	100-150	51,6	44,7	49,7	51,2
	150-200	45,7	37,5	42,3	44,7
15-20	50-100	54,7	47,3	53,2	54,7
	100-150	52,3	44,0	48,5	51,3
	150-200	46,5	39,4	43,5	50,9

Thus, all three types of machines (wheeled, semi-tracked and tracked) affect soils by compacting, reducing porosity and increasing particle density. However, wheeled machinery has the greatest impact on these indicators, while semi-tracked and tracked machinery has a more moderate impact.

The results suggest that tracked machines generally have lower resistance to soil penetration compared to wheeled and half-track machines at all slope sections and depths measured.

Soil particle density is an important indicator related to its forest vegetation properties. High particle density may indicate soil compactness, which limits the penetration of water, air, and roots of woody plants. Measuring particle density allows us to assess the structural properties of the soil and determine its ability to air and water permeability, as well as to develop the root system of plants [12, 13]. The studied characteristics are also one of the indicators of soil cover stability.

High density can lead to erosion, loss of fertility and reduced soil resistance to external factors such as wind and water flows [20]. Measuring particle density helps to assess the state of the soil in terms of its stability and to take measures for its conservation and restoration.

Half-tracked equipment, compared to wheeled machines, can have better cross-country ability over difficult terrain and weakly bearing soils, as well as over deep snow cover. This allows to reduce soil damage and minimize compaction, especially when performing work on wet or unstable soil. The tracks of half-tracked equipment distribute weight and pressure more evenly over the soil surface, unlike wheeled equipment, which can create more point loads and, accordingly, greater pressure. At the same time, the maneuverability of the equipment is improved compared to tracked equipment.

Strandgard et al., 2014 studied the effect of slope angle on the productivity of logging equipment. They analyzed the operation of equipment on two classes of terrain slopes: 12–19° and 20–26°. It was shown that increasing the slope angle negatively affects the process, as a result, the process time increases. At the same time, the contact time between the engine and the soil increases, which can be accompanied by a decrease in soil fertility as a result of organic matter removal and compaction. This study analyzed three main types of forestry machines by type of engine. It was found that with increasing terrain slope, the negative impact on the soil increases.

In turn, the authors of the work [2-4] analyzed the impact of skidding equipment on slopes with an inclination angle of 25%. The authors show that the bulk density of the soil at the points of contact of the wheeled motor increases by 40%, while in this study the maximum value is 15.3%.

5. Conclusion

The type of equipment has a significant impact on the soil particle density. When working on slopes of 0-5% and 5-10%, wheeled equipment shows better results in terms of particle density, while semi-tracked and tracked equipment have similar values. When working on slopes of 10-15% and 15-20%, tracked equipment shows the best results, while wheeled and semi-tracked equipment have approximately similar values, although the latter tends to be similar to that of tracked equipment.

The angle of inclination also affects the particle density. At slopes of 0-5% and 5-10%, particle density decreases with increasing sampling depth in all types of equipment. At slopes of 10-15% and 15-20%, particle density has various values depending on the type of equipment and sampling depth.

Thus, the type of equipment and the slope of the terrain have a significant impact on the particle density indicators in the soil.

These results provide important information for decision-making in logging production and forestry, and can also be the basis for the development of new machine systems and technologies for felling.

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АНАЛІЗ РОБОТИ ЛІСОЗАГОТІВЕЛЬНИХ МАШИН НА СХИЛАХ

Наразі в лісозаготівельній галузі України використовуються різні системи машин – від потужних спеціалізованих лісозаготівельних комплексів (харвестерів і форвардерів) до машин середнього та малого тягового класу, створених на базі сільськогосподарських або промислових тракторів загального призначення. Ці машини можуть бути обладнані колісним, гусеничним або напівгусеничним рушієм, що зумовлює актуальність порівняльного аналізу їхнього впливу на лісові ґрунти.

Метою даного дослідження є проведення порівняльного аналізу основних технологічних показників лісозаготівельних робіт та впливу різних типів рушіїв лісозаготівельних машин на лісові *ґрунти під час роботи на лісових схилах. У роботі наведено результати досліджень впливу рушіїв лісових машин на ґрунти лісосік. У ході дослідження було визначено та проаналізовано низку параметрів, зокрема кут нахилу схилу, пористість ґрунту та щільність його частинок, а також проведено порівняння різних типів рушіїв – колісного, напівгусеничного та гусеничного. Отримані результати показали, що колісні машини мають найбільш суттєвий вплив на зазначені параметри. Прохід гусеничних машин спричиняє менший вплив на лісові ґрунти порівняно з колісними та напівгусеничними лісовими машинами. Це свідчить про можливе порушення структури ґрунту та зміну його фізико-хімічних властивостей унаслідок експлуатації лісозаготівельної техніки.*

Результати дослідження мають важливе значення для розуміння впливу машин на екологічний стан лісових екосистем і розроблення ефективних стратегій сталого ведення лісового господарства. Подальші дослідження у цьому напрямі дадуть змогу уточнити отримані результати та визначити оптимальні способи використання лісозаготівельних машин із мінімальним негативним впливом на лісові ґрунти.

Ключові слова: *лісові ґрунти, лісогосподарські машини, рушії, ущільнення, деформація.*

Ф. 3. Рис. 5. Табл. 2. Літ. 30.

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