PATTERNS OF SOIL BULK DENSITY CHANGES RESULTING FROM REPEATED IMPACT OF MACHINE-AND-TRACTOR UNIT RUNNING GEAR

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Abstract. In modern agricultural production, the issue of soil compaction is highly significant. Crop cultivation technologies are continuously improving, and the number of machinery passes over the field surface is constantly changing. Each subsequent pass of machinery increases stress and bulk density in the soil, thereby reducing the ability of agricultural plants to achieve their maximum growth and development. Therefore, it is relevant to investigate how repeated passes of agricultural machinery running gear affect the same field area. It is also important to determine how soil density resulting from repeated passes influences crop yield. This study investigates several repeated passes of a vehicle along the same track. Repeated movement of agricultural machinery along the same tracks significantly increases soil density. After three passes, the soil bulk density was 1.148 $g\cdot cm^{-3}$; after five passes, it increased to 1.152 $g\cdot cm^{-3}$. The maximum value was recorded after ten passes of the machine, with the soil bulk density reaching 1.158 $g\cdot cm^{-3}$. The results indicate that changes in soil bulk density affect the yield of different agricultural crops in different ways. Therefore, when planning the cultivation of a specific crop, it is necessary to more carefully select tillage technologies and the type of agricultural machinery running gear. The obtained results make it possible to predict, prior to the start of field operations, how the number of repeated machinery passes over the field will affect changes in the soil bulk density and the resulting reduction in crop yields. This predictive capability allows agricultural producers and engineers to optimize field traffic management, reduce excessive soil compaction, and select appropriate machinery configurations. In addition, the results can be used to justify the choice of tillage systems and the type of agricultural machinery running gear in order to minimize negative impacts on soil structure.

Keywords: wheels of machinery, soil compaction, repeated passes over the soil, crop yields.

Introduction

Soil density is one of the key indicators characterizing the physical condition of soil. It reflects the ratio between the mass of soil and its volume in its natural state and is an integral characteristic of the structural composition of the soil environment. The value of bulk density is directly related to soil porosity, water permeability, air permeability, and the ability to provide optimal conditions for the growth and development of plant root systems [1-3]. During the operation of agricultural machinery in the field, there is an effect of constant soil compaction. During the growing season, agricultural machinery may pass over the field surface 5 to 15 times. This, in turn, leads to a constant increase in soil density. An increase in bulk density is usually accompanied by a decrease in total porosity and the number of macropores, which leads to deterioration in the water-air regime and decrease in the efficiency of nutrient movement in the soil [4; 5].

Changes in bulk density also affect the mechanical properties of soil, in particular its resistance to deformation and root penetration. A steady increase in soil density hinders plant growth and development by reducing the pore space and impeding the penetration of moisture to the plant roots. As a result, we have a further decrease in the efficiency of soil resource use [6]. Therefore, studying the patterns of changes in soil bulk density under the influence of loads from the running gear of machine-tractor units is important for substantiating the rational parameters of mechanized technologies and preserving soil fertility.

Despite the continuous development of soil cultivation technologies and the reduction in the number of technological operations, some agricultural crops require significant mechanized intervention. Traditional practices include primary soil cultivation, sowing, application of plant protection products, and harvesting. Such intervention is characterized by repeated passes of machinery, which leads to gradual accumulation of deformations in the soil environment [7].

During the first pass of the machinery, the most intense compaction of the topsoil occurs, as its structure has not yet undergone preliminary destruction [8]. Subsequent passes of the machinery significantly reduce deformations, but the density at this point has a cumulative effect and continues to increase. As a result, a compacted layer is formed in which the physical properties of the soil differ significantly from the initial state. Such a layer can spread not only in the surface horizon, but also be transferred to deeper soil layers depending on the mass of the unit, the design of the drive wheels, the contact pressure and soil moisture [9].

The repeated impact of machine running systems is also characterized by uneven spatial compaction. The greatest changes in physical properties are observed directly in the area of contact between the wheel and the ground, where the loads are at their maximum. In the inter-track space, the degree of compaction is significantly lower; however, during repeated passes and due to the heavy weight of the machine-tractor combination, stresses and deformations propagate in all directions. Thus, we have a complex picture of the spatial distribution of soil density, which depends on the movement pattern of the units, the working width of the machines and the number of operational steps [10].

Consequently, repeated passes by machine-tractor units are an important factor in shaping the physical condition of the soil, as they cause the accumulation of residual deformations and a change in its structural characteristics. Studying the patterns of change in soil bulk densit³y depending on the number of passes of machinery allows for a more reasonable assessment of the technogenic load on the soil environment and the development of measures to reduce the negative impact of mechanized technologies on soil fertility.

Today, a large number of scientists are paying attention to the problem of the impact of agricultural machinery running systems on the physical condition of the soil. The main focus is on studying the stress-strain state of the soil environment under the action of external loads caused by wheels and tracks. Researchers have established that the magnitude of soil deformation depends on the weight of the machine-tractor unit, the contact area between the drive and the soil, the internal pressure in the tires, as well as the physical condition of the soil, in particular its moisture content, density and structural composition [11].

At the same time, most studies focus on the impact of a single load or a limited number of passes by machinery, whereas in real agricultural production conditions, the soil is repeatedly affected by the running systems of machines in the course of various technological operations. At the same time, changes in the physical properties of the soil are cumulative in nature and manifest themselves in a gradual increase in bulk density and the formation of compacted layers [12].

Despite existing research in this area, the patterns of soil density change due to repeated passes of machine and tractor units remain insufficiently studied. In this regard, further research aimed at establishing the relationship between the number of passes of machinery and changes in the physical state of the soil is relevant and has important scientific and practical significance.

It is therefore relevant to investigate the patterns of change in soil density under the influence of repeated passes by tractor-mounted machinery. The aim of this article is to investigate the effect of the number of passes by agricultural machinery running gear on changes in soil bulk density and to determine the nature of the spatial distribution of compaction within the soil. To achieve this objective, the study will analyze the patterns of deformation accumulation in the soil and assess changes in its physical state depending on the number of passes made by the machinery.

Materials and methods

The research was conducted in August 2025 on experimental plots of the Sumy National Agrarian University, located in the north-eastern part of Ukraine in the Sumy region. The soil cover is mainly represented by typical medium loamy and dark grey forest soils, which are characteristic of this region. The humus content in the upper horizon was 2.5-3%. The initial bulk density of the soil in the 0-10 cm layer averaged 1.12 $g \cdot cm^{-3}$, and the soil moisture during the experiment was 15-25%. The tractor's front wheels were fitted with 360/70R20 tires inflated to 1.5 bar, whilst the rear wheels were fitted with 420/85R38 tires inflated to 1.0 bar. The speed during the field trials and when driving onto the trial plots was 5 km/h. The experimental studies were conducted in several stages over the course of a week.

To study the impact of the running gear, wheeled machine-tractor units were used, namely the MTZ-892 tractor. The studies were conducted using a wheeled tractor unit weighing 4.4 tons with a track width of 1.9 m and a wheel contact patch of 0.7-1.0 m^2 depending on the tire pressure. The load on the soil was formed by the tractor passing repeatedly over the same technological track.

The experiment was conducted using a scheme involving multiple passes of machinery over the test plot. The number of passes was 0 (before the machinery passed), 1, 3, 5 and 10 times. After each pass, changes in soil stress were determined and soil samples were taken to determine the physical properties of the soil. Measurements were taken in three layers of the soil profile: 0-10 cm, 10-20 cm and 20-30 cm.

The bulk density of the soil was determined by selecting undisturbed samples using metal rings of standard volume, followed by drying to a constant mass. Soil porosity was calculated based on the ratio of bulk mass to the density of the solid phase of the soil. Penetration resistance was determined using a LAN-M field penetrometer.

To assess the agronomic consequences of compaction, soil moisture and crop yields (winter wheat and maize) were additionally determined. To determine the effect of soil compaction on crop yield, we used literature data and the results of previous experimental studies [4; 11]. Soil moisture content was determined using a ZD-06 moisture meter and additionally in the laboratory by drying.

Statistical processing of experimental data was performed using methods of variational statistics with Microsoft Excel software. Correlation and regression analysis were used to analyze the relationships between the number of passes of the equipment and changes in the soil bulk density.

Results and discussion

The results obtained confirm that repeated passes of machine-tractor units significantly affect the physical condition of the soil and cause gradual changes in its structural parameters. The initial characteristics of the soils studied indicate that the experimental plots were predominantly represented by typical chernozems and dark grey forest soils, which are widespread in the north-eastern region of Ukraine. The bulk density of the topsoil (0-10 cm) was 1.12-1.15 g·cm^{-3}, while the porosity reached 54-57% (Table 1). These parameters correspond to favourable agrophysical conditions for the growth and development of agricultural crops.

Table 1

Initial characteristics of the soils under study

Depth, cm	Soil type	Particle size distribution, %	Moisture content, %	Initial density, g·cm^{-3}	Porosity, %
0-10	Typical chernozem	Sand 25, Loam 55, Clay 20	18	1.12	57
10-20	Typical chernozem	Sand 27, Loam 53, Clay 20	17	1.18	52
0-10	Dark grey forest soil	Sand 30, Loam 50, Clay 20	20	1.15	54
10-20	Dark grey forest soil	Sand 32, Loam 48, Clay 20	19	1.20	50

At the same time, research results show that repeated impact of the running gear of machines leads to noticeable changes in the bulk density and porosity of the soil (Table 2). The first pass of the equipment causes the most significant deformation of the soil structure. In particular, the bulk density of the 0-10 cm soil layer increased from 1.12 to 1.135 g·cm^{-3}, while porosity decreased from 57 to 54%. During subsequent passes, soil compaction continued, but the rate of change gradually decreased due to the increased resistance of the compacted soil mass to further deformation.

After three passes, the bulk density of the soil reached 1.148 g·cm^{-3}, and after five passes, it increased to 1.152 g·cm^{-3}. The maximum value was recorded after ten passes of the machine, when the bulk density of the soil was 1.158 g·cm^{-3}, which corresponds to an increase of approximately 3.4% compared to the initial state. At the same time, soil porosity decreased to 48%, indicating a deterioration in the soil air-water regime. The results confirm that the impact of multiple passes of the machine is cumulative and leads to gradual soil compaction.

The results obtained are consistent with studies [9; 13], which also found that the most intense compaction occurs during the first passes of machinery. In particular, study [9] recorded an increase in soil density of 6.6-7.8%, which is slightly higher than the figure obtained in this study (3.4%). This is primarily explained by the use of heavier agricultural machinery in the field studies. At the same time, the penetration depth in study [9] was up to 40-50 cm, whereas under our conditions the main changes are localized in the layer up to 30 cm. This is precisely due to differences in soil moisture and the mass of the machinery.

Table 2

Changes caused by repeated passes of machinery

Num. of passes	Soil density at different depths, $g \cdot cm^{-3}$			Porosity at different depths, %			Water perme-ability, $mm \cdot h^{-1}$	Resist-ance to penetrati on, MPa	Soil tempe-rature, °C
	0-10 cm	10-20 cm	20-30 cm	0-10 cm	10-20 cm	20-30 cm			
0	1.121	1.17	1.20	57	50	48	32	0.80	15
1	1.135	1.20	1.22	54	48	46	28	0.95	15.5
3	1.148	1.21	1.23	52	46	44	25	1.05	16
5	1.152	1.22	1.24	50	44	42	21	1.18	16.5
10	1.158	1.24	1.24	48	42	40	18	1.25	17

The distribution of compaction along the depth of the soil profile also showed a clear pattern. The most significant changes were observed in the upper soil layer (0-10 cm), while the deeper layers were less affected. In the 10-20 cm layer, the bulk density increased from 1.17 to 1.24 $g \cdot cm^{-3}$, while in the 20-30 cm layer it increased from 1.21 to 1.24 $g \cdot cm^{-3}$ (Table 2) after ten passes of the machinery. This indicates that the mechanical stresses transmitted through the soil profile gradually decrease with depth, but repeated loading still causes noticeable changes in the deeper layers.

An important factor affecting the degree of soil compaction is the type of machine undercarriage. After analyzing the results obtained and the literature data, we concluded that the level of compaction depends on the weight of the tractor and the type of undercarriage systems it uses.

Deterioration of the physical properties of the soil directly affected agronomic indicators. The increase in the soil bulk density led to an increase in resistance to plant root penetration and a decrease in soil water permeability. In particular, resistance to penetration increased from 0.80 MPa under control conditions to 1.25-1.30 MPa after ten passes of the machinery (Table 3). Under such conditions, the rate of water penetration into the soil decreased from 32 $mm \cdot h^{-1}$ to 18 $mm \cdot h^{-1}$, indicating a deterioration in water permeability and water exchange processes in the soil.

Table 3

Effect of changes in soil physical properties on crop yields

Number of passes	Soil density (depth 0-10 cm), $g \cdot cm^{-3}$	Porosity, %	Moisture content, %	Wheat yield, $t \cdot ha^{-1}$	Corn yield, $t \cdot ha^{-1}$	Resistance to penetration, MPa	Water infiltration, $mm \cdot h^{-1}$
0	1.121	57	18	5.6	8.1	0.80	32
1	1.135	53	17.5	5.4	7.8	0.92	28
3	1.148	50	17	5.1	7.5	1.03	25
5	1.152	48	16.5	4.8	7.1	1.16	21
10	1.158	47	16	4.5	6.8	1.25	18

Changes in the physical condition of the soil also affected plant development. The mass of the root system would decrease from 320 g·m-2 under control conditions to 240 g·m-2 after ten passes of the equipment, which corresponds to a decrease of approximately 25%. The reduction in root system development led to a decrease in crop productivity. Wheat yield decreased from 5.0 tons to 4.5 t·ha-1, while corn yield decreased from 8.0 to 7.0 t·ha-1.

These findings are corroborated by research [14], which describes in detail how crop yields decrease (to 59.7% after 21 wheel passes) with each subsequent pass of machinery over the same tracks. Study [15] indicates that after four passes of machinery, the crop yield decreased by 4%, which also confirms the results we obtained in this study. The slight difference is explained by the amount of humus, soil moisture and specific growing conditions.

Thus, the results obtained convincingly demonstrate that repeated passes of agricultural machinery significantly affect the bulk density of the soil, its porosity and other physical properties. The most intense compaction occurs during the first passes of the machinery (Fig. 1), while subsequent passes cause a gradual stabilization of density due to the increase in resistance of the compacted soil structure. At the same time, excessive compaction negatively affects the water-air regime of the soil, the development of the root system of the plants and the crop productivity.

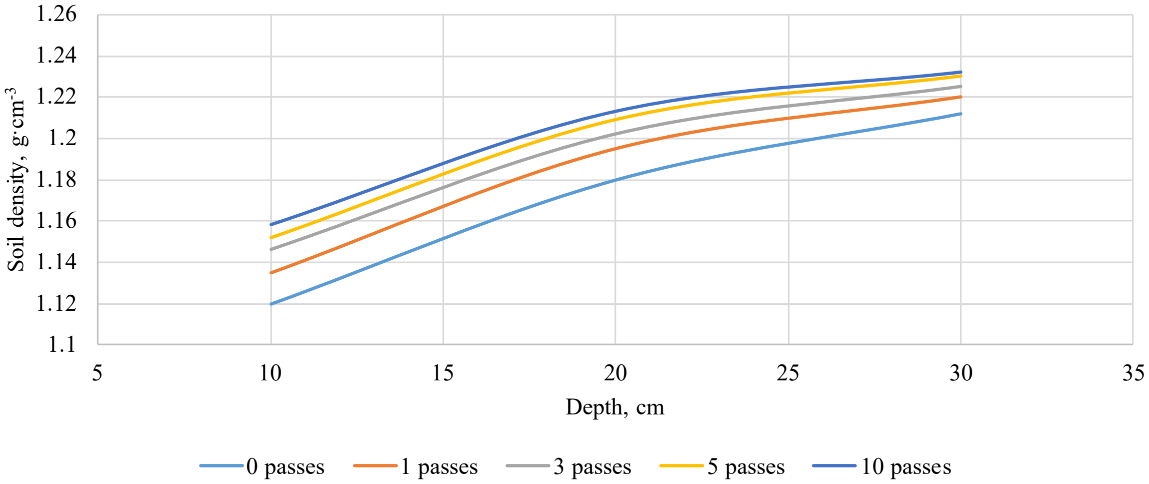

Fig. 1. **Relationship between changes in soil density and the number of passes by agricultural machinery**

Soil porosity during the first pass of the equipment, as well as density, is of utmost importance and, as can be seen from the graph in Fig. 2, hardly decreases after 5 passes.

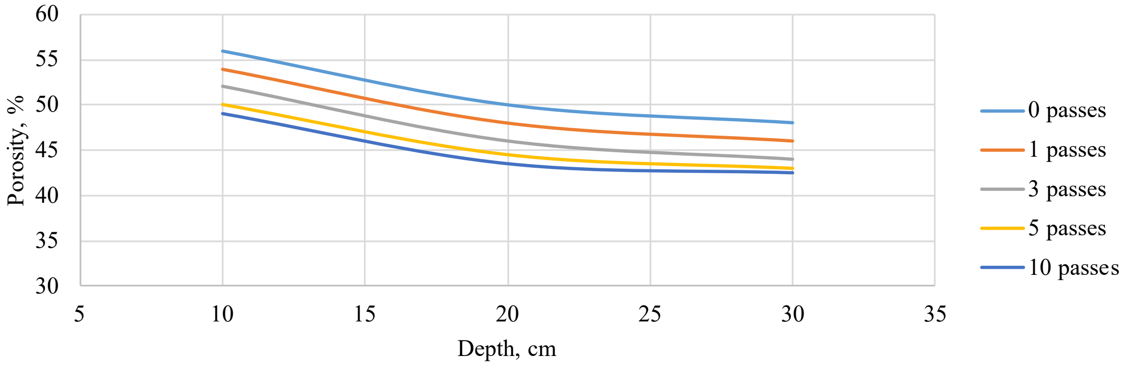

Fig. 2. **Relationship between changes in soil porosity and the number of passes by agricultural machinery**

Therefore, optimizing the movement of machinery across fields and making rational choices regarding the type of undercarriage used are important measures for reducing the negative impact of agricultural machinery on the soil structure and preserving the productivity of agroecosystems.

Conclusions

1. As a result of laboratory and field studies, patterns of changes in soil bulk density were established on the experimental fields of the Sumy National Agrarian University in Sumy Region under the influence of repeated passes of the running gear of machine-tractor units (MTU).
2. The bulk density of the soil increases with the number of passes of MTU, with the most significant compaction observed in the upper layer 0-10 cm. Thus, after one pass, the density increased from

1.12 g·cm^{-3} to 1.135 g·cm^{-3}, after 5 passes – to 1.152 g·cm^{-3}, and after 10 passes – to 1.158 g·cm^{-3}. Porosity decreased accordingly from 57% to 48%.
3. The depth of compaction is evident up to 20-30 cm, but the lower soil layers are compacted more slowly: the density in the 20-30 cm layer increased from 1.21 g·cm^{-3} to 1.25 g·cm^{-3} after 10 passes.
4. The scientific value of the work lies in establishing a clear quantitative relationship between the number of MTU passes, soil bulk density and agronomic indicators, which allows predicting the effects of equipment operation on different soil types in the Sumy region and developing practical recommendations for minimizing compaction.
5. Practical application: the results can be used to optimize routes and loads for machine-tractor units, improve soil cultivation technologies and increase the efficiency of crop production.

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Author contributions

Conceptualization, V.M. and O.So; methodology, V.M. and O.So.; investigation, O.Sa.; software, V.K., O.T.; writing – original draft preparation, O.So., O.Sa; writing – review and editing, V.K., O.T. All authors have read and agreed to the published version of the manuscript.

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