SCIENTIA
AGRICULTURAE
BOHEMICA

Article

Analysis of the Hardness Dynamics of Typical Chernozem Under the Influence of Stress Factors in Different Agrophytocenoses

Yurii Dehtiarov[1], Zinaida Dehtiarova[1]

[1] Faculty of Agronomy and Plant Protection, State Biotechnological University, Kharkiv, Ukraine
degt7@ukr.net; zinaidasamosvat@gmail.com

* Correspondence: degt7@ukr.net (Ukraine)

Studying the hardness of typical chernozem is of key importance, as this indicator is an indicator of the physical properties of the soil that affect its fertility and suitability for agronomic practices. Hardness tests help identify compaction problems that can limit plant root growth and impair water and air movement in the soil. Analysis of changes in hardness over the seasons allows us to develop optimal strategies for soil cultivation and preservation of its structure. Hardness analysis was carried out directly in the field in spring, summer and autumn using a LAN-M penetrometer, an electronic device for measuring soil hardness in fields in accordance with ASAE S313.3. It was found that in the spring, before the start of grass regrowth, there is a noticeable decrease in hardness. The reason for this is hydrothermal factors and, above all, an increase in soil moisture during the autumn and winter period. The absence of precipitation for a long period of time (summer, autumn) contributes to a noticeable increase in soil hardness in all research variants. At the same time, the cultivation of different crops can have some effect on the increase or decrease in the hardness of typical chernozem. The hardness of typical chernozem depends on soil cultivation methods, the presence of moisture as an abiotic stressor, and the seasons of the year.

Keywords: hardness; typical chernozem; agrophytocenosis; cultivation; abiotic factors

Received for publication on March 04, 2025

Accepted for publication on August 18, 2025

1. Introduction

Soil compaction is a predominantly anthropogenic problem and is mainly related to the impact of agricultural machinery and vehicles (Komisar and Zubko, 2020). The main task in soil cultivation is to create optimal conditions for growing crops. Agrophysical parameters such as soil density and hardness are important here (Tsentylo and Tsiuk, 2019, Dehtiar'ov Y et al.). Hardness is one of the main indicators that characterizes the physical condition of the soil and assesses the environment in which a plant grows and develops. An increase in hardness leads to an increase in the energy consumption of tillage activities and worsens the conditions for the emergence of plant seedlings on the soil surface. The high level of soil hardness, especially in dry soil, is a significant obstacle to the growth and development of the plant root system (Shilina et al., 2006, Tsentylo and Tsiuk, 2019).

DOI: 10.7160/sab.2026.570110

Hardness is an important genetic and agricultural indicator that allows us to characterize in detail the physical and mechanical properties of soils. In particular, hardness reflects the resistance of the soil to plant root growth, as well as the resistance that the tillage implement must overcome during tillage. This is a critical parameter, as it affects the efficiency of agrotechnical measures and the growth of cultivated plants (Medvedev, 2009; Demidov et al., 2013). Studying and controlling soil hardness allows us to optimize agricultural practices, reduce energy costs for cultivation, and improve conditions for plant development. Taking this indicator into account is essential for increasing yields and ensuring the sustainability of agroecosystems.

Soil hardness is an indispensable indicator for assessing the conditions for seed germination and their development in the early stages of ontogeny. It is critical for determining the ability of root hairs to explore the inter- and intra-aggregate space of the soil. During root growth and movement of tillage tools, various physical and mechanical processes occur in the soil, such as wedging, shearing, and overcoming internal adhesion forces. Hardness is a generalized and adequate indicator of these processes, as it allows us to assess not only the strength of the clods, but also the quality of soil compaction. Such a comprehensive assessment is practically impossible when using only the traditional indicator of compaction density. Adding the hardness index to the compaction density index allows for a more sophisticated assessment of the physical condition of the soil. This, in turn, helps to improve tillage tools and increase the efficiency of their use in agriculture. This integrated approach allows us to more accurately determine the optimal conditions for plant growth and development, which is a key factor in increasing the yield and quality of agricultural products. According to Medvedev (2009), soil hardness is an important component for improving agricultural practices.

Depending on the level of moisture, soil can become plastic, elastic, or almost solid. The study of soil hardness in each of these states is of both practical and theoretical importance. Soil hardness provides much more information than compaction density, which estimates the mass of dry soil per unit volume, but has limited information capabilities.

Unlike the bulk density, which is a weight, mass characteristic of soil (Grunwald et al., 2001), hardness is a force characteristic that determines the strength of soil (Medvedev, 2009; Alvarez et al., 2009). It allows us to estimate the amount of soil resistance when it is impacted by bodies of a certain shape. Thus, the use of soil hardness in addition to the soil density index allows for a more complete and accurate assessment of soil physical properties. This helps to improve tillage methods and increase the efficiency of agrotechnical measures, which in turn improves the conditions for plant growth and development and increases the yield and quality of agricultural products. According to Medvedev (2009), soil hardness is an important indicator for optimizing agricultural practices and ensuring sustainable agricultural development. So, soil hardness is the most important characteristic when assessing it as an environment for the development of the plant root system and for mechanical processing.

Soil hardness can replace soil resistivity, which is a very popular and currently indispensable indicator for rationing mechanized field work. This is because hardness reflects the soil's resistance to various types of deformation when choosing the intensity and depth of tillage, as well as when designing tillage tools (Medvedev, 2009). If hardness is measured using plungers of various shapes, it can serve as a fairly accurate indicator of physical (primarily the density of the soil), physico-mechanical (various types of resistance, including the most important for practice, the soil resistivity during plowing), and technological properties of soils.

Soil hardness depends on its moisture content, organic matter content, composition of absorbed cations, ratio of structural aggregates and, to a large extent, on the particle size distribution (Young et al., 2000; Grunwald et al., 2001; Topp et al., 2003). All these factors make hardness a promising indicator for use in soil genetic and agronomic research. Of all the soil physical factors affecting hardness, the most important is the water content of the soil and its energy state (Medvedev, 2009; Young et al., 2000). In addition, physical factors such as particle size distribution, density, structural composition, pore size, and the ratio of large to fine pores also influence soil hardness (Bussoher et al., 2000; Grunwald et al., 2001; Bolenius et al., 2006).

The dependence of soil hardness on its moisture content is almost linear, which opens up the possibility of wider use of this indicator in production conditions. For example, soil hardness can serve as an indicator of soil maturity, and help in choosing an active or passive method of soil preparation for sowing or for basic tillage.The purpose of the study is to determine seasonal changes in the hardness of typical chernozems of cultivated and natural agrophytocenoses under the influence of abiotic and biotic stress factors.

2. Materials and Methods

The research was conducted within the Forest-Steppe zone of Ukraine, on the territory of the Dokuchaevske Experimental Field Research and Production Center of the State Biotechnological University (Kharkiv region).

The hardness analysis was carried out directly in the field during the year, namely in spring (measurements on 03/10/2024), summer (measurements on 07/13/2024) and autumn (measurements on 10/11/2024). The variants were the fallow land - the experimental field of the Department of Soil Science, which has been left to grow with natural grass vegetation since 1956 and the fields of crop rotation with agricultural crops - the experimental field of the Department of Agriculture and Herbology named after O.M. Mozeiko, where the influence of winter wheat predecessors, sunflower saturation and cultivation is studied.

The predecessors of winter wheat were: pure steam; corn; sunflower; soybeans.

The saturation of short rotations with sunflower was studied at levels of 20, 40 and 60%.

Different types of cultivation are used, in particular: plowing at 25-27 cm; chisel local cultivation at 33-35 cm; moldboardless cultivation at 33-35 cm; disk cultivation at 10-12 cm.

The soil cover in the study area is represented by typical chernozem, which was formed under conditions of well-developed herbaceous vegetation and moderate moisture on non-saline loess rocks.

Here is a macromorphological description of the profile of a typical arable heavy loamy chernozem on loess loam (Tykhonenko and Degtiarov, 2016):

A 0-42 cm humus-accumulative, fresh, dark gray, heavy loam, arable (0-20 cm), weakly grainy, lumpy-powdery, compacted; below - subsoil, moist, heavy loam, lumpy-grainy, compacted, well humified, plant roots are often found, gradually turning into:

AB/k 42-73 cm upper transitional, moist, dark gray with a fawn tint, heavy loam, lumpy-grained, poorly compacted, less humified, in some places plant roots are found, up to 70 cm carbonate-free, transition gradual in:

BAk 73-100 cm lower transitional, moist, spotted, darkish gray with a fawn tint, heavy loam, lumpy-grained, poorly compacted, unevenly humified, many molehills, calcium carbonates in the form of pseudomycelium, gradually turning into:

Ck 100-145 cm parent rock, moist, brownish-pale, heavy loamy loam, somewhat compacted, porous, very carbonate with carbonate “veins”, in some places carbonate “pseudomycelium”.

Hardness measurements were carried out using a LAN-M penetrometer, an electronic device for measuring soil hardness in fields in accordance with ASAE S313.3 standard.

With the LAN-M penetrometer, you can quickly find out if there is a problem with soil compaction and determine the depth of the plough sole.

The choice of the LAN-M soil hardness tester was driven by the need for a fast, accurate and representative analysis of the hardness of typical chernozem under conditions of abiotic and biotic stress factors. Compared to mechanical penetrometers, LAN-M significantly outperforms them in terms of functionality, sensitivity, and the ability to record the depth of the plow sole. This was critically important for studying the seasonal dynamics of the physical state of the soil and optimizing tillage methods.

To conduct the research, the measurement site was prepared by levelling the soil surface (Figure 1). A reflective plate was placed on the prepared area. Measurements were made using a 1.27 cm tip and the hardness value in kg/cm^2 was recorded every 2.5 cm (1 inch).

Figure 1. General view of the hardness measurement site.

The force measurement scale of the density meter consists of 3 ranges:

1) 0-14 kg/cm² (0-200 psi) - *green* - favorable conditions for growth;

2) 14-21 kg/cm² (0-300 psi) - *yellow* - satisfactory conditions for growth;

3) more than 21 kg/cm² (more than 300 psi) - *red* - unsatisfactory conditions for growth (plow sole).

3. Results and Discussion

Soil hardness is the most widely used indicator of soil physical condition in agriculture and agronomy. The hardness is used to determine the configuration of the plow sole and whether it needs to be destroyed. Similarly, the hardness of the soil crust determines the choice of tools for loosening the soil. Hardness values are also used to determine the bearing capacity of soils, which is important when interpreting the slippage of mobile units and their passability in difficult conditions, as well as to determine the physical maturity of soils. Hardness is widely used in modern research to assess the quality of tillage (Bussoher et al., 2000; Herrick and Jones, 2002; Arriaga et al., 2011; Castrignano et al., 2004; Medvedev, 2007, 2009, 2010, 2013; Tsiz and Holii, 2024; Tsilyuryk and Sudak, 2014; Plisko et al., 2024).

The advantages of penetration become even more apparent if the hardness tester is mounted on a mobile vehicle, which significantly increases the productivity of the territory survey (Rooney et al., 2001). The use of a hardness tester in agricultural research allows for the detailed identification of areas with varying degrees of deformation on the field that are not detected by other methods (Medvedev et al., 2004). In general, this indicator is unique to agricultural practice. It can be used by specialists in various fields, such as agrophysicists, land reclamation specialists, agricultural mechanics engineers, practicing agronomists during monitoring work, and even geologists (Rooney et al., 2001). There are detailed methodological guidelines for the use of hardness gauges in various studies (Grunwald et al., 2000).

Soil hardness changes significantly during the season. In general, researchers identify the main patterns of hardness change depending on its determining factors:

- high sensitivity to soil moisture,

- high sensitivity to changes in soil humus content, absorbed bases, the ratio of structural aggregates, and even particle size distribution,
- high sensitivity to the agrophysical environment.

Soil hardness varies widely and depends on the soil condition.

As a result of our research in the spring (Figure 2), it was found that the soil hardness on the fallow land variant was within the range of low values and did not exceed the optimal values (0-14 kg/cm^2) up to a depth of 45 cm. From a depth of 47.5 cm, there is a noticeable increase in hardness to medium and high values. In the upper part of the profile of arable chernozem, as well as other variants studied, we have optimal hardness indicators, where, at this time, the horizon of the plow sole is not traced.

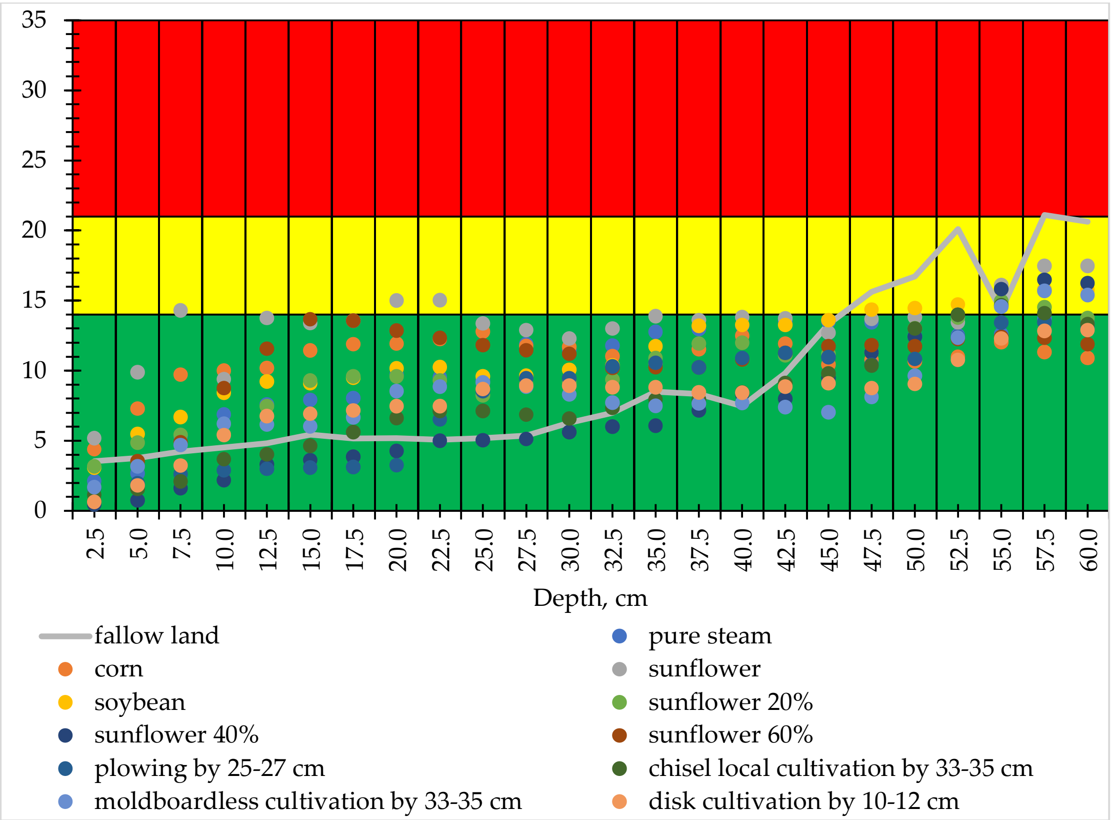

Figure 2. Hardness of typical chernozem of different phytocoenoses in spring

In the spring, before the grasses begin to grow back, there is a noticeable decrease in hardness. The reason for this is hydrothermal factors and, above all, an increase in soil moisture during the autumn-winter period, which is confirmed by other studies (Tsentylo and Tsiuk, 2019).

Thus, there is no significant variation in spring in the upper part of the typical chernozem profile, which is caused by early hardness measurements and high moisture content at that time, as well as unripe soil. The possibility of early field work was due to favorable climatic factors. Despite this, the soil had sufficient moisture reserves from the winter period, which affected the hardness index.

Insufficient precipitation and its reserves during the cultivation of crops in variants with different depths of cultivation and different predecessors significantly affected the increase in hardness in the summer (Figure 3).

In the fields where wheat was grown after various predecessors such as sunflower, corn (with and without plant residues), soybeans, and pure steam, we have a significant increase in soil hardness. The hardness ranges from a minimum of 23.0 to a maximum of 64.6 kg/cm^2, which is unsatisfactory for plant growth. This can also be caused by the type of root system of the predecessors. For example, corn and sunflower have deep and powerful roots that can change soil hardness. Growing wheat after such crops can lead to an increase in soil hardness.

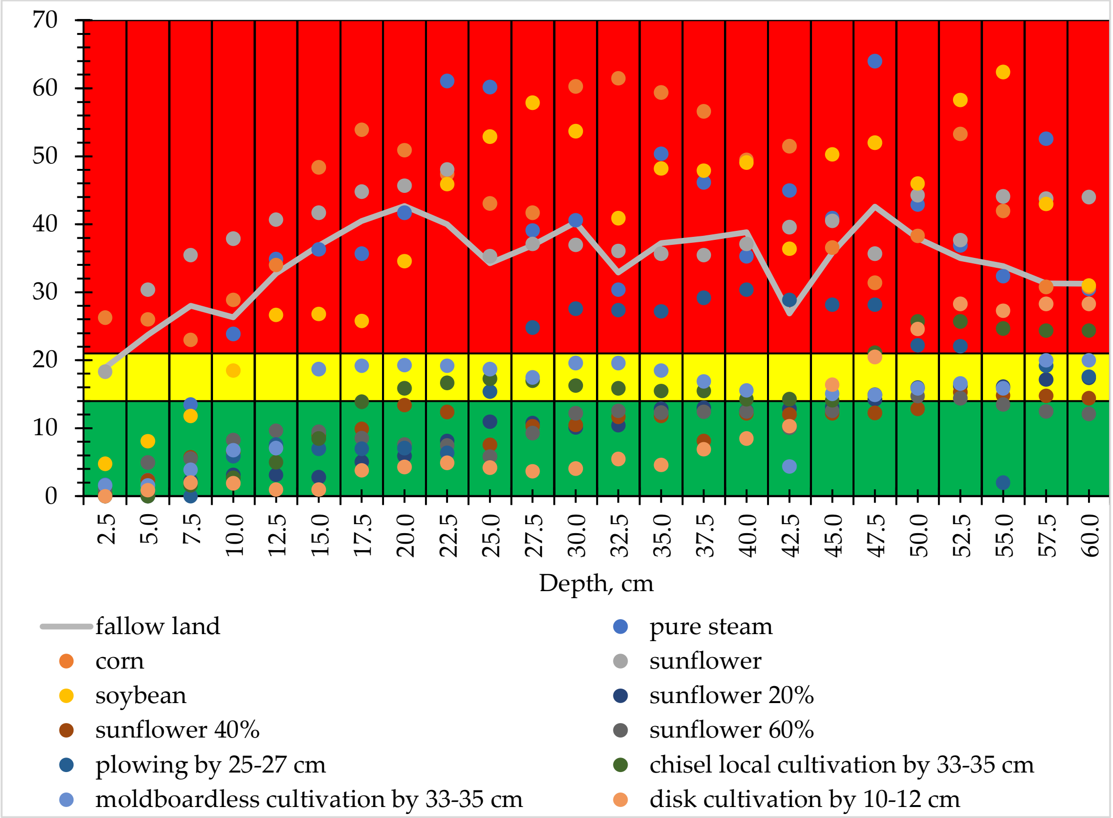

Figure 3. Hardness of typical chernozem of different phytocoenoses in summer

At the same time, different tillage methods, such as no-till or chisel tillage, can have different effects on soil hardness. Some methods can lead to an increase in hardness, while others can reduce it. Thus, up to a depth of 15-20 cm in the fields where different depths of cultivation were carried out, we have an almost dispersed topsoil with a hardness ranging from 0.0 to 7.6 kg/cm^2. In the variant with plowing, an increase in soil hardness was recorded at a depth of 25 cm to 15.4 kg/cm^2, and at depths of 27.5-52.5 cm, the hardness increased to 22-30 kg/cm^2.

On the contrary, variants with different sunflower saturation of crop rotations show a decrease in hardness. Up to a depth of 45 cm, we have optimal hardness values that gradually increase with depth from 0.1 to 13.0 kg/cm^2. A slight increase is observed only in the layer of 47.5-60.0 cm to values of 14.4-17.4 kg/cm^2. Sunflower can effectively accumulate moisture and nutrients in the upper layers of the soil, which helps to reduce its hardness. The gradual increase in hardness with depth can be explained by the natural compaction of the soil at depth, where the effects of the root system and organic matter are less pronounced.

Without human intervention, the soil gradually compacts under the influence of its own weight and natural processes, which is especially noticeable in hot summers. This effect can be observed on the variant of fallow use of typical chernozem, where the hardness ranges from 18.9-42.7 kg/cm^2.

The significant influence of such an important abiotic factor as precipitation affects the increase in hardness of all the studied variants in the fall (Figure 4). The lack of moisture in the soil leads to its drying out, which contributes to its compaction and increase in hardness. Water also stimulates plant growth and the development of microorganisms that loosen the soil. Without water, their activity decreases, which leads to an increase in hardness. The water regime is an important factor in the formation of soil physical characteristics, such as structural condition and soil porosity. Without moisture, structural aggregates are destroyed and the soil becomes harder.

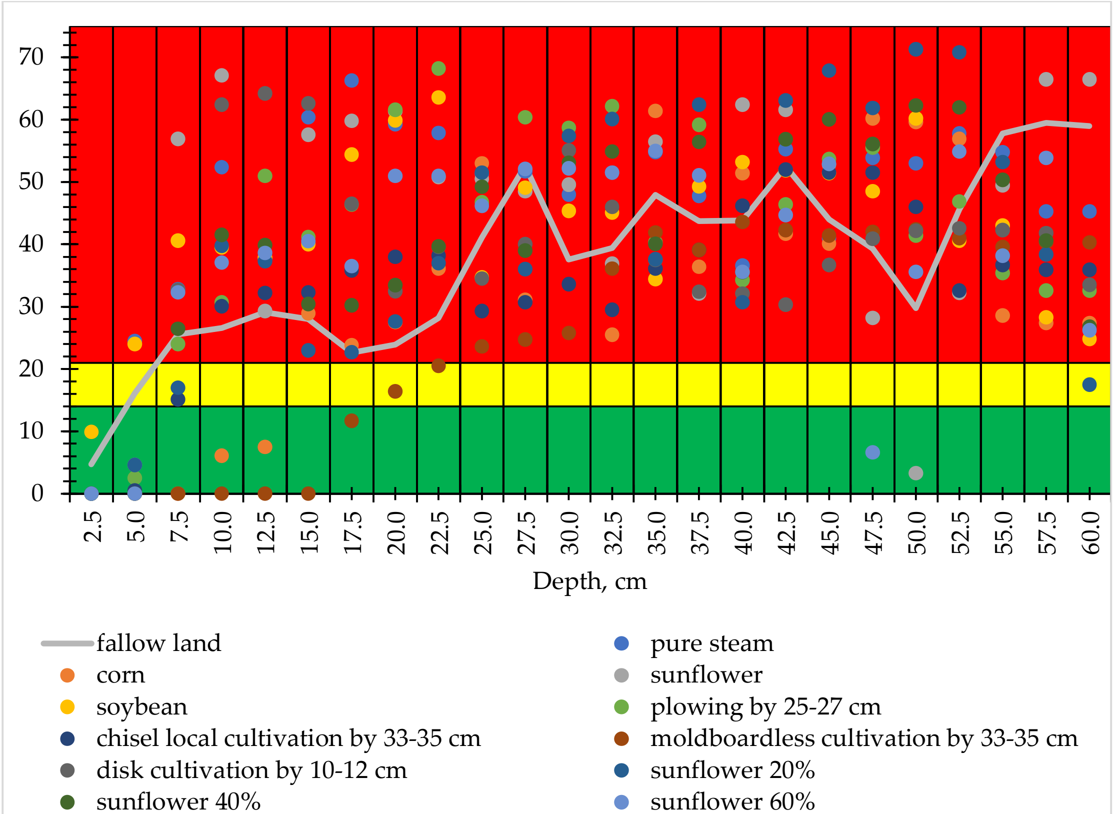

Figure 4. Hardness of typical chernozem of different phytocoenoses in autumn

Thus, in all variants, without exception, soil hardness increased significantly in the fall compared to the summer and especially the spring period. The values range from 24 kg/cm² to 40-50 kg/cm², and in some variants even up to 60-70 kg/cm². It is worth noting that in the field after harvesting winter wheat, it was not possible to measure the hardness of the lower soil layers at all, and in the upper thickness up to 15 cm, the hardness was also very high - 30-60 kg/cm².

On variants with different sunflower saturation of crop rotations (20, 40 and 60%) during the harvesting period, the hardness of typical chernozem increased by 2.5-4 times, ranging on average from 40-45 kg/cm². This is due to the anthropogenic load on the soil and low moisture reserves during this period.

At the same time, different depths of tillage contributed to a decrease in hardness, but only to a depth of 5 cm - 0.0-2.5 kg/cm². In the following layers, in the variants with plowing, chiseling and disking, the hardness reached an average of 33-43 kg/cm², and some decrease in hardness was observed in the variant of moldboardless tillage - 25.5 kg/cm².

It is well known that a reliable indicator of soil fertility is the yield of agricultural plants, and in natural grass communities, the stock of aboveground mass (phytomass) formed during the growing season. Observations of changes in aboveground phytomass on typical chernozem under fallow land during the year showed that in spring the stock of aboveground phytomass was 9 t/ha; in summer - 8 t/ha; in autumn - 7 t/ha. On the fallow land, the productivity of dry biomass of grasses harvested in spring is significantly higher than in autumn. Consequently, the soil hardness on fallow land increases during the year, and the stock of aboveground phytomass decreases.

Cultivation of winter wheat after pure steam provides the highest yield of 5.39 t/ha and the lowest soil hardness at different stages of the year. This contributes to better root development and access to moisture. After corn, the yield is 4.23 t/ha, where we have medium soil hardness, which can limit root development, especially in summer. The yield after sunflower is 3.01 t/ha and leaves the soil with the hardest texture. In the variant with winter wheat after soybeans, we have moderate soil hardness, which allows us to get a better yield compared to sunflower up to 3.85 t/ha.

The saturation of crop rotations with sunflower at the level of 20% contributes to the formation of a yield of 1.42 t/ha. Soil hardness remains relatively low in spring and summer, which contributes to better root development. The 40% saturation provides a yield of 1.52 t/ha. Soil hardness increases, especially at depths above 10 cm, which can affect moisture availability. The highest soil hardness, especially in summer and autumn, in the variant with 60% sunflower crop rotation significantly hinders the development of the root system and reduces the yield to 1.26 t/ha.

The mold boardless cultivation provides the highest yield of 6.40 t/ha. At the same time, the soil hardness remains moderate, which contributes to the development of the root system. In the variant of chisel local cultivation, the yield was 5.80 t/ha. Soil hardness increases slightly in summer and autumn, but remains within acceptable limits. Ploughing contributes to a corn yield of 5.20 t/ha. Soil hardness gradually increases with depth, which can affect moisture availability. The lowest yield of 4.90 t/ha was achieved with the disc cultivation variant. The hardness of the soil increases significantly in summer and autumn, which can have a negative impact on plant development.

Data from authors who conducted parallel observations of soil hardness and density indicate that, despite the more frequent use of density (Hakansson and Lipiec, 2007), hardness is a more visual and objective indicator for assessing soil condition. The degree of change in hardness values is much higher than the change in density. According to V.V. Medvedev (2010), the hardness of typical heavy loamy chernozem under mechanical loading increases much faster than in the control (300-800% compared to 15-20%), while maintaining the same nature of the dependence. In addition, common methods of assessing the quality of soil tillage by crumbling and density are characterized by a significant error, limited information content, and high labor intensity of measurements.

Hardness is becoming an indispensable indicator for agronomic research and assessing the quality of tillage operations. Using hardness allows for a more accurate assessment of soil condition, which helps to develop more efficient tillage and soil care methods. This, in turn, helps to optimize agricultural practices and reduce energy costs in agriculture.

Unfortunately, this study did not include a separate analysis of the impact of agricultural machinery running systems (wheeled or tracked) on soil hardness. At the same time, the literature (Medvedev, 2009) shows that the running gear of machinery is a key anthropogenic factor that causes local soil compaction, especially at depths of 10-50 cm. This impact can vary depending on the type of surface, soil moisture, and frequency of passes.

Despite the lack of analysis of technical compaction, the results of the experiments clearly show the impact of different depths of tillage on changes in hardness, in particular, a decrease in the upper layers (up to 15-20 cm); the impact of sunflower crop rotation saturation, where excessive saturation (60%) contributed to significant compaction, while optimal (40%) maintained a balance between fertility and physical condition of the soil; different winter wheat predecessors (pure fallow, corn, soybeans, sunflower) had different effects on soil hardness over the seasons, which correlated with yield.

High soil hardness in any layer reduces the movement of moisture through the soil profile and limits the spread of the root system (Medvedev, 2009; Bolenius et al., 2006; Riedell et al., 2006; Bets, 2013; Grzesiak et al., 2002; Bayhan et al., 2002). This has a negative impact on the environment, soil, and plants. High soil hardness restricts the access of plant roots to the necessary resources, thus reducing their viability and productivity.

E. Bolenius et al. (2006) used hardness as an integral indicator of soil physical condition. Whereas earlier in Sweden, yield variability was most often considered to be a consequence of nutrient redistribution in the soil, in this study, the extremely wide variation in yield data across the field (from 4.0 to 11.5 tons of grain/ha) was explained by variability in soil hardness. A fairly clear pattern was established: the yield was higher where the hardness was lower. At the same time, differences in the dynamics of root system development during the barley growing season were found.

Other studies (Medvedev, 2013) have shown that cereal crops can withstand high soil hardness (20-25 kgf/cm²), while such hardness is unacceptable for row crops, root crops, horticultural and vegetable crops. The optimal hardness parameters for these crops do not exceed 5-10 kgf/cm².

Hardness exceeding 30 kgf/cm², and especially over 40-50 kgf/cm², significantly inhibits and even stops the growth of root systems of most crops.

The upper limit of soil hardness for most grain crops, after which the conditions for their development deteriorate sharply, is 15-19 kgf/cm²; for root crops - 5-10 kgf/cm²; for potatoes - 5 kgf/cm². In terms of plowing efforts, the optimal hardness is 10-20 kgf/cm². Data obtained for light loamy soil from South Dakota (USA) showed that corn yields are negatively correlated with soil hardness, with yield reductions being particularly pronounced with no-till (Gao et al., 2016; Riedell et al., 2006).

There are also studies aimed at determining the impact of reduced soil hardness on soil fertility. The soil with the lowest hardness obtained the lowest yield. This fact gives grounds to draw analogies with numerous data on the effect of soil density on yield, which can also negatively affect yield at very low values (Medvedev et al., 2004).

The soil-root hardness system should not be thought of as a one-way influence of hardness on root formation and development. The root also affects the soil, and, depending on the crop and the characteristics of its root systems, this influence can be significant (Montagu et al., 2001; Godefroid and Koedam, 2004). For example, in the crops of bentgrass directly under the bush, the hardness does not exceed 2.0-2.5 kgf/cm² even with a lack of moisture, while in the inter-row (15-25 cm from the plant) it varies from 15 to 53 kgf/cm².

Similar results were obtained by V.V. Medvedev, T.E. Lindina and T.N. Laktionova, who studied the hardness in rows and between rows of corn, sugar beet and even continuous sowing grain crops at a row spacing of 7 cm (Medvedev et al., 2004). The hardness of the soil distinguishes between row crops and continuous crops. As a rule, continuous sowing crops have a hardness of 5-10 kgf/cm² higher (Medvedev, 2009).

Soil hardness is closely related to the size of the aggregates that make up its structure and directly affects plant growth conditions (Langmaack et al., 2002). In soils with high hardness, water, air and biological regimes are disturbed, which negatively affects plant development and yields (Grunwald, 2000; 2001; Medvedev, 2009; Serafim et al., 2008).

Thus, high soil hardness can have serious negative consequences for the agroecosystem. They affect the overall condition of the soil and its ability to provide optimal conditions for plant growth. Therefore, it is important to take soil hardness into account when developing agronomic practices aimed at improving soil structure and increasing yields.

4. Conclusions

In general, soil hardness depends on hydrothermal factors, precipitation, the type of root system of the predecessors, and tillage practices. Appropriate management of these factors can help optimize soil hardness for better plant growth.

In the course of research, several important regularities were revealed regarding the influence of different tillage methods on the hardness of chernozem. It has been established that the patterns of changes in the hardness (the process of de-compaction) of typical chernozem are related to the method and depth of primary tillage, the principle of operation of working bodies and the amount of by-products of the predecessor that are incorporated into the soil. With non-shelf tillage methods, the bulk of the predecessor's by-products are placed in the upper 0-10 cm soil layer, while with shelf tillage, including plowing, they are localized in the 20-30 cm layer. Plowing creates a more homogeneous environment with saturation of the cultivated layer with biomass of crops compared to non-shelf tillage, which leads to the formation of a looser top layer (0-10 cm) and compacted lower layers within 10-60 cm.

Sunflower and corn usually increase soil hardness. This is due to their deep root system. The roots of these plants penetrate deep into the soil and can compact it, which leads to an increase in hardness. Growing wheat after corn and sunflower, which have deep roots, led to an increase in soil hardness. At the same time, sunflower helped to reduce soil hardness in the summer to a depth of 45 cm due to its ability to accumulate moisture and nutrients.

Studies have also shown that hardness is a dynamic quantity that changes over the seasons. Under the influence of such an abiotic factor as lack of moisture, hardness increases significantly in summer and especially in autumn compared to spring. This emphasizes the importance of monitoring soil properties in different seasons to ensure optimal cultivation conditions.

The choice of preceding crops has a significant impact on winter wheat yields, and to maximise yields, soil hardness at different stages of the year should be considered. Excessive saturation of the crop rotation with sunflower leads to soil compaction and reduced yields. The best variant is 40% saturation, which provides the best balance between soil hardness and yield. No-mould board cultivation provides the best balance between soil hardness and yield, while disc cultivation can lead to excessive soil compaction and reduced yields.

No-mould board cultivation (33-35 cm) provided the highest yield of winter wheat - 6.40 t/ha, which is 31% more than plowing (4.90 t/ha) and 107% more than in the variant with 60% sunflower saturation (3.09 t/ha, on average). Crop rotation with sunflower saturation of up to 40% allowed to achieve a yield of 1.52 t/ha, which is 21% more than at 20% saturation (1.26 t/ha) and 115% more than at 60% saturation (0.71 t/ha). Adherence to deep tillage (chisel, mold boardless) and moisture monitoring allows us to maintain the hardness index within the optimal range (up to 14 kg/cm^2), which helps to increase yields by 25-45% depending on the crop.

Thus, the implementation of agrotechnical recommendations based on soil hardness monitoring can increase crop yields by 20-100%, depending on the predecessor, type of cultivation and the level of saturation of the crop rotation with sunflower.

Author Contributions: Conceived the research idea Yu.D.; conceptualization Yu.D. and Z.D.; methodology Yu.D.; analysed the data and wrote the paper Yu.D. and Z.D.; writing-review and editing Yu.D., Z.D.; funding acquisition Z.D. All authors have read and agreed to the published version of the manuscript.

Acknowledgments: The authors would like to express their gratitude to the Ministry of Education and Science of Ukraine for the appreciation of the research area, the results of which are presented in this article and are the basis for the tasks of the project «Development of measures to ensure the sustainable productivity of agrophytocenoses under the influence of abiotic and biotic stress factors» (state registration number 0124U000457).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

5. References

1. Alvarez CR, Taboada MA, Gutierrez Boem FH, Bono A, Fernandez PL, Prystupa P (2009): Topsoil properties as affected by tillage systems in the Rolling Pampa region of Argentina. Soil Science Society of America Journal 73(4), 1242-1250. https://doi.org/10.2136/sssaj2008.0246
2. Arriaga FJ, Lowery B, Raper R (2011): Soil penetrometers and penetrability. In: Encyclopedia of Earth Sciences Series. Springer Netherlands, 757-760. https://doi.org/10.1007/978-90-481-3585-1_207
3. Bayhan Y, Kayisoglu B, Gonulol E (2002): Effect of soil compaction on sunflower growth. Soil and Tillage Research 68(1), 31-38. https://doi.org/10.1016/S0167-1987(02)00078-8
4. Bets TYu (2013): Spatial variability of the soil mechanical impedance and its connection with electrical conductivity and productivity of sunflower. Biological Bulletin of Melitopol State Pedagogical University named after Bohdan Khmelnytsky 2(8), 30-44. https://doi.org/10.7905/bbmspu.v0i3(6).543
5. Bolenius E, Rogstrand G, Arvidsson J (2006): On-the-go measurements of soil penetration resistance on a Swedish Eutric Cambisol. Proceedings of the 17th ISTRO Triennial Conference, 867-870.
6. Busscher WJ, Frederick JR, Bauer PJ (2000): Timing effects of deep tillage on penetration resistance and wheat and soybean yield. Soil Science Society of America Journal 64(3), 999-1003. https://doi.org/10.2136/sssaj2000.643999x
7. Castrignanò A, De Giorgio D, Fornaro F, Vonella AV (2004): 3D spatial variation of soil impedance as affected by soil tillage. Proceedings of the 13th ISCO Conference, Brisbane, 1-5. https://topsoil.nserl.purdue.edu/isco/isco13/PAPERS%20A-E/CASTRIGNANO.pdf
8. Dehtiar'ov Y, Havva D, Kovalzhy N, Rieznik S (2021): Transformation of physical indicators of soil fertility in typical chernozem of the eastern forest-steppe of Ukraine. In: Soils Under Stress. Springer, Cham, 105-110. https://doi.org/10.1007/978-3-030-68394-8_11
9. Demidov AA, Kobets AS, Gritsan YuI, Zhukov AV (2013): Spatial Agroecology and Land Recultivation. Svidler A.L. Publishing House, 560 pp.
10. Gao W, Whalley R, Tian Z, Liu J, Ren T (2016): A simple model to predict soil penetrometer resistance as a function of density, drying and depth in the field. Soil and Tillage Research 155, 190-198. https://doi.org/10.1016/j.still.2015.08.004
11. Godefroid S, Koedam N (2004): Interspecific variation in soil compaction sensitivity among forest floor species. Biological Conservation 119(2), 207-217. https://doi.org/10.1016/j.biocon.2003.11.009
12. Grunwald S, Barak P, McSweeney K, Lowery B (2000): Soil landscape models at different scales portrayed in virtual reality modeling language. Soil Science 165(8), 598-615. https://doi.org/10.1097/00010694-200008000-00002
13. Grunwald S, McSweeney K, Rooney DJ, Lowery B (2001): Soil layer models created with profile cone penetrometer data. Geoderma 103(1–2), 181-201. https://doi.org/10.1016/s0016-7061(01)00076-3
14. Grunwald S, Rooney DJ, McSweeney K, Lowery B (2001): Development of pedotransfer functions for a profile cone penetrometer. Geoderma 100(1–2), 25-47. https://doi.org/10.1016/s0016-7061(00)00079-3
15. Grzesiak S, Grzesiak MT, Filek W, Hura T, Stabryła J (2002): The impact of different soil moisture and soil compaction on the growth of triticale root system. Acta Physiologiae Plantarum 24(3), 331-342. https://doi.org/10.1007/s11738-002-0059-8
16. Håkansson I, Lipiec J (2000): A review of the usefulness of relative bulk density values in studies of soil structure and compaction. Soil and Tillage Research 53(2), 71-85. https://doi.org/10.1016/s0167-1987(99)00095-1
17. Herrick JE, Jones TL (2002): A dynamic cone penetrometer for measuring soil penetration resistance. Soil Science Society of America Journal 66(4), 1320-1324. https://doi.org/10.2136/sssaj2002.1320
18. Komisar YeO, Zubko VN (2021): Soil hardness – description of modern methods and devices. Bulletin of Sumy National Agrarian University. Series: Mechanization and Automation of Production Processes 42(4), 26-31. https://doi.org/10.32845/msnau.2020.4.6
19. Langmaack M, Schrader S, Rapp-Bernhardt U, Kotzke K (2002): Soil structure rehabilitation of arable soil degraded by compaction. Geoderma 105(1-2), 141-152. https://doi.org/10.1016/S0016-7061(01)00097-0
20. Medvedev VV (2007): Heterogeneity of Soils and Precision Agriculture. Part 1. Introduction to the Problem. Kharkiv: 13 Tipografiya (in Ukrainian).
21. Medvedev VV (2009): Soil Hardness. Kharkiv: Gorodskaya Tipographiya (in Ukrainian).

22. Medvedev VV (2010): Heterogeneity as natural display of horizontal structure of a soil cover. Soil Science 11(1-2), 6-15 (in Ukrainian).
23. Medvedev VV (2010): Soil hardness as a criterion for justifying technologies and technical means for its cultivation. Bulletin of Agricultural Science 4, 14-18 (in Ukrainian).
24. Medvedev VV (2013): Physical Degradation of Chernozems. Diagnostics. Reasons. Consequences. Warning. Kharkiv: Gorodskaya Tipographiya (in Ukrainian).
25. Medvedev VV (2013): Temporal and spatial heterogenisation of ploughed land. Soil Science 14(1-2), 5-22 (in Ukrainian).
26. Medvedev VV, Lyndina TE, Laktionova TN (2004): Soil Density (Genetic, Ecological and Agronomic Aspects). Kharkiv: 13 Tipografiya (in Ukrainian).
27. Montagu KD, Conroy JP, Atwell BJ (2001): The position of localized soil compaction determines root and subsequent shoot growth responses. Journal of Experimental Botany 52(364), 2127-2133. https://doi.org/10.1093/jexbot/52.364.2127
28. Plisko IV, Romanchuk KYu, Kutsova KM (2024): The influence of spatial heterogeneity of agrophysical soil properties on the yield of agricultural crops. Bulletin of Uman National University of Horticulture 1, 31-39. https://doi.org/10.32782/2310-0478-2024-1-31-39
29. Riedell WE, Osborne SL, Pikul JL, Schumacher TE (2006): Tillage and crop residue effects on soil physical properties and corn yield. Progress Report, Agricultural Experiment Station, South Dakota State University, 1-5. https://doi.org/10.17221/176/2018-SWR
30. Rooney D, Norman J, Stelford M (2001): Mapping soils with a multiple-sensor penetrometer. Proceedings of the W1 Fertilizer, Aglime and Pest Management Conference, Madison, 213-221.
31. Serafim ME, Vitorino ACT, Peixoto PPP, Souza CMA, Carvalho DF de (2008): Intervalo hídrico ótimo em um latossolo vermelho distroférrico sob diferentes sistemas de produção. Engenharia Agrícola 28(4), 654–665. https://doi.org/10.1590/s0100-69162008000400005
32. Shilina LI, Shapoval IE, Yermolaev MM (2006): Changes in the structural and aggregate state of typical chernozem under the influence of agricultural factors. AgroChemistry and Soil Science, Special Issue, Book 2, 188-190.
33. Topp GC, Lapen DR, Edwards MJ, Young GD (2003): Laboratory calibration, in-field validation and use of a soil penetrometer measuring cone resistance and water content. Vadose Zone Journal 2(4), 633. https://doi.org/10.2136/vzj2003.0633
34. Tsentylo LV, Tsiuk OA (2019): The dynamics of soil firmness change depending on its basic cultivation. Bulletin of Poltava State Agrarian Academy 1, 147-153. https://doi.org/10.31210/visnyk2019.01.19
35. Tsilyuryk A, Sudak V (2014): Effectiveness of moldboardless tillage under sunflower in the Northern Steppes of Ukraine. Bulletin of Lviv National Agrarian University. Series: Agronomy, 160-166. https://doi.org/10.31210/visnyk2014.01.06
36. Tsiz I, Holii V (2024): Soil hardness research results for "ELITA" fields. Agricultural Machines 50, 25-36. https://doi.org/10.36910/acm.vi50.1332
37. Tykhonenko DG, Degtiarov YuV (2016): Soil cover of experimental field "Rohanskyy stationary" of Kharkiv National Agrarian University named after V.V. Dokuchayev. Bulletin of Kharkiv National Agrarian University named after V.V. Dokuchayev 2(1), 5-13 (in Ukrainian).
38. Young GD, Adams BA, Topp GC (2000): A portable data collection system for simultaneous cone penetrometer force and volumetric soil water content measurements. Canadian Journal of Soil Science 80(1), 23-31. https://doi.org/10.4141/S99-025