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Agrophysical condition of chernozem as a criterion for its readiness for soil tillage minimization

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Abstract. The objective of this study was to develop an agrophysical criterion for assessing the condition of leached chernozem under systematic shallow tillage for six years, using differential porosity, crop productivity, and energy efficiency as indicators. The results were compared to those obtained under conventional ploughing, with the goal of evaluating the feasibility of further tillage minimization in a short-rotation grain crop rotation system. The study employed standard research methods, including field observations, laboratory analysis, mathematical statistics, and comparative-calculative approaches. Under shallow tillage, the median bulk density in the 0–30 cm soil layer was higher by 0.03 g cm^{-3} compared to ploughing, while the standardized density range remained similar across tillage systems. However, both the upper and lower typical values increased by 0.02 g cm^{-3} under shallow tillage. The coefficient of variation for bulk density was 1.85 times higher under ploughing than under shallow tillage. Differential porosity measurements across five crops in the sixth year of the trial revealed that in spring, shallow tillage resulted in higher bulk density (by 0.06 g cm^{-3}), lower total porosity (by 3%), and a 6.0% reduction in air-filled pore volume compared to ploughing. At the same time, the ratio of water-filled to air-filled pores approached an optimal 1:1 balance under shallow tillage, whereas ploughed soils showed a dominance of air-filled pores. Systematic use of both ploughing and conservation-oriented shallow tillage over five years in a five-field grain-row crop rotation produced similar levels of productivity in terms of yield, energy efficiency, and output of grain and feed units. While productivity indicators under ploughing remained stable relative to the mean, shallow tillage demonstrated a positive trend. This trend is associated with the completion

of the transition period following the cessation of deep ploughing and the shift toward preliminary deep chisel tillage, followed by systematic shallow tillage at a depth of 10–12 cm.

Key words: leached chernozem, bulk density, soil moisture, ploughing, shallow tillage.

INTRODUCTION

The global trend toward the minimization of soil tillage is driven, on the one hand, by the effort to reduce material and labor inputs for cultivation and, on the other hand, by the potential to manage soil-forming processes and achieve the expanded reproduction of soil fertility – something that remains unattainable under continuous conventional plowing. Permanent minimal tillage promotes the development of self-regulation processes similar to those found in virgin soils. It contributes to the accumulation of organic matter, nutrients, and stored energy in the upper soil profile of chernozem, which, when combined with a rational anthropogenic impact, creates a foundation for sustainable enhancement of soil fertility (Sayko & Maliyenko, 2007).

The soil cover of the Cherkasy region is primarily composed of typical chernozems, heavily degraded dark gray podzolized and degraded soils, podzolized chernozems, and light and gray podzolized soils. In terms of texture, the soils range from light loam to medium and heavy loam. Typical and heavily degraded chernozems dominate the soil cover of the region, accounting for over 50%.

Tillage itself does not enrich the soil environment with energy materials necessary for restoring the fertility of chernozem soils. However, it directly affects the agrophysical parameters of the soil, which determine the air and thermal conditions of the soil climate, the degree and depth of plant residue incorporation, and consequently influence the dynamics and balance between the synthesis and mineralization of humus, the formation of available nutrient forms, and their uptake by agricultural crops (Bardgett et al., 2014; Tonkha et al., 2017).

Chernozems, as the main productive resource of agriculture, have long been subjected to conditions that differ significantly from the optimal ones formed in their natural state, making them increasingly prone to degradation processes (Krupenikov, 2008). The primary cause is the inconsistency of applied technologies with the natural principles underlying chernozem formation (Bulgakov et al., 2024b). One such inconsistency is conventional tillage, which disrupts the sod layer and litter, leading to progressive agrophysical degradation of chernozems within agrocenoses (Demydenko, 2013; Philippot et al., 2013; Zhang et al., 2015).

The choice of a tillage system for chernozem soils has always been one of the most controversial and pressing issues in agricultural practice within the Forest-Steppe zone of Ukraine. Ongoing debates concerning the necessity of deep tillage with soil inversion have led to a growing need to minimize tillage. This trend increasingly favors reducing both the depth and frequency of tillage operations (Demydenko & Velychko, 2015).

In recent decades, the most balanced approach to chernozem management has been the differentiated tillage system, which combines various ploughing and non-inversion tillage techniques (Tomnytskyi et al., 2024). Issues related to the deterioration of agrophysical properties following the abandonment of intensive tillage are addressed through the periodic application of ploughing for the most demanding crops (Gordienko, 2004; Bulgakov et al., 2020a). At the same time, substantiated evidence is emerging in support of tillage minimization on chernozems with naturally high agrophysical properties, which are relatively close to optimal for the cultivation of most crops (Bulgakov et al., 2024a).

One of the most practical approaches to addressing the issue of chernozem degradation is the further improvement of soil tillage technologies through the reduction of production costs. As a result, resource-saving technologies of primary tillage are becoming increasingly widespread (Matyukha & Semenov, 2024). These practices contribute to the improved adaptation of agricultural crops to the challenging modern natural and climatic conditions, helping to maintain agroecological balance within agrocenoses (Dolia & Shevchenko, 2024).

Changes in the depth of primary tillage significantly affect the fertility of chernozem. Generally, less cultivated chernozems require deeper tillage (Shevchenko et al., 2024), whereas as the degree of cultivation and improvement of agrophysical properties increases, the sensitivity of chernozem to intensive tillage decreases. In such cases, fertility under tillage minimization may exceed that achieved through conventional deep tillage (Shykula, 2001; Torma et al., 2017; Vozhegova et al., 2021).

In modern agricultural production, resource-saving technologies – such as combined, minimum, and zero tillage systems – are widely used. Under these systems, agrophysical factors of chernozem fertility require particular attention. Soil bulk density is the key indicator of the physical state of chernozem for successful crop cultivation (Samofalova et al., 2013; Hirte et al., 2017; Bulgakov et al., 2021; Yermakov et al., 2021). Favorable physical properties are the foundation and an essential condition for realizing the potential fertility of chernozem and achieving high crop yields (Jordan et al., 2010; Copec et al., 2015; Nandan et al., 2019; Modak et al., 2020). Creating and maintaining an optimal structure of the arable layer through various tillage systems is a critical task in contemporary agriculture (Lampurlanes et al., 2016; Castellini et al., 2019; Adamchuk et al., 2021).

The current global trend toward soil tillage minimization is driven by two major objectives: reducing energy and labor costs and ensuring sustainable soil fertility reproduction. In Ukraine's Central Forest-Steppe, long-term systematic ploughing of podzolic chernozems has led to severe agrophysical degradation, expressed in excessive compaction, reduced porosity, and disruption of the soil's structural organization. Such conditions significantly limit the potential for effective implementation of minimal or zero tillage systems.

Many long-term studies and meta-analyses have shown that reduction of tillage intensity often results in changes to bulk density, pore size distribution, and aggregate stability, although the magnitude and direction of such changes depend strongly on soil type, climate, and transition period. For example, a global meta-analysis reported that no-tillage generally improves soil structure and porosity, particularly in the upper soil layers, although effects on bulk density are modest and variable (Mondal & Chakraborty, 2022).

Similarly, in a long-term trial, Dam et al. (2005) observed how changes in tillage affected soil bulk density, seedling emergence, and yield in continuous maize systems under differing tillage regimes. These findings underscore that transitions in tillage systems must be examined over multi-year periods, especially in degraded soils, to detect stable trends in soil physical indices.

The scientific problem lies in the absence of clear criteria for assessing when degraded chernozems become agrophysically ready for minimization of tillage. Without this, the transition to reduced tillage depth often leads to unstable soil responses and yield fluctuations, resulting in the discrediting of the concept of tillage minimization in crop rotations. Therefore, there is a need to substantiate agrophysical indicators that can serve as reliable criteria for determining the readiness of podzolic chernozem to shift from conventional ploughing to shallow and, subsequently, zero tillage systems.

Additionally, several works emphasize that soil structural recovery under reduced disturbance is not instantaneous. For instance, short-term investigations suggest that a considerable period (often more than 3–5 years) is needed to develop improved pore continuity and stability (Jensen et al., 2020). This supports our choice of a 6-year trial period and justifies monitoring temporal dynamics of bulk density and porosity during this critical transition window.

However, despite the wealth of such studies, there is still a lack of clearly defined agrophysical readiness criteria for degraded podzolized chernozems in the initial 5–6 years of transition to shallow tillage in temperate Forest-Steppe zones. In many published works, the discussion of bulk density, porosity, and yield is descriptive, and rarely linked to a criterion by which a degraded chernozem can be judged fit for further minimization of tillage.

The dynamic nature of soil processes influenced by tillage, along with their impact on fertility, necessitates the systematic study of changes in the agrophysical parameters of chernozems in the Forest-Steppe zone of Ukraine – both in the short and long term.

This study aims to identify the agrophysical criterion that determine the soil's readiness for tillage minimization based on long-term field observations of bulk density, differential porosity, and productivity under systematic ploughing and surface tillage in a five-field grain-row crop rotation.

MATERIALS AND METHODS

The research was conducted from 2016 to 2021 in a long-term field experiment at the Cherkasy State Agricultural Experimental Station of the National Scientific Center 'Institute of Agriculture of the NAAS'. The soil type is strongly degraded, low-humus, medium-loamy leached chernozem, developed on calcareous loess-like loam according to the national classification (Polupan et al., 2005) or Chernic Phaeozems (Hyperhumic, Siltic, Calcaric, Cutanic, Episiltic, Sodic) according to WRB 2022 (coordinates 49°56'42"N, 32°06'54"E).

In the arable layer, the humus content ranged from 2.76% to 3.03% (by method developed by Tyurin I.V., modified by Symakov V.M. (State standard of Ukraine, DSTU 4289:2004)), the sum of absorbed bases ranged from 24.5 to 28.1 meq per 100 g of soil, hydrolytic acidity ranged from 1.99 to 2.19 meq per 100 g of soil, and the pH of the salt extract ranged from 5.56 to 6.31. The base saturation degree was 92.8–93.3%, the content of available phosphorus (by Chirikov method (State Standard of Ukraine DSTU 4115:2002)) was 9.0 mg per 100 g of soil, and exchangeable potassium (by Brovkina method (State Standard of Ukraine DSTU 4405:2005)) was 12 mg per 100 g of soil.

The study was carried out within a stationary field experiment focused on evaluating the productivity of a five-field grain-row crop rotation system, which included the following crops: maize (Zea mays), barley (Hordeum vulgare), soybean (Glycine max), sunflower (Helianthus annuus) and sugar beet (Beta vulgaris). The tillage system consisted of:

1. Differential tillage based on ploughing.
2. Differential tillage using deep chiseling (applied in 2015), followed by shallow tillage at a depth of 10–12 cm for all crops in the rotation.

The fertilization system included the application of $N_{75}P_{75}K_{82}$ along with 6 tons per hectare of crop residues.

Soil sample analyses, records, and calculations were conducted according to standard procedures. Soil moisture was determined using the thermogravimetric method during the key crop growth stages (State standard of Ukraine, DSTU ISO 11465:2001). Soil bulk density was measured using the cutting ring method in the modification by N.A. Kachynsky during the periods of intensive crop growth and yield formation (State standard of Ukraine, DSTU ISO 11272:2001). When determining bulk density using metal cylinders with a height of 10 cm and a volume of 275 cm^3, the measurements were carried out layer by layer (0–10 cm, 10–20 cm, and 20–30 cm), followed by calculating the average value for the 0–30 cm soil layer. Soil moisture samples were simultaneously collected by layers (0–10 cm, 10–20 cm, and 20–30 cm) and later analyzed in the laboratory by weighing the soil samples before and after drying. Measurements were taken three to four times during the growing season across the five fields of the crop rotation over a five-year period. Soil sampling for bulk density and moisture determination was conducted within the same experimental plots (fields). Sampling was performed in five replicates.

To calculate the differential porosity, the main agrophysical characteristics of the podzolized chernozem were used: the particle density, bulk density, maximum hygroscopic moisture, wilting point moisture, and total moisture capacity:

1. Total porosity, defined as the total volume of voids between solid particles as a percentage of the total soil volume (TP, %): $TP = \left(d - d_v\right) \cdot 100\%$, where d – is the particle density of the soil, g cm^{-3}; d_v – is the bulk density of the soil, g cm^{-3}.

2. Volume of pores occupied by tightly bound (maximum hygroscopic) water (P_{mh}, %): $P_{mh} = (W_{mh} \cdot d_v) / 1.5$, where W_{mh} – is the maximum hygroscopic moisture (% of oven-dry soil weight); 1.5 is the density of water at W_{mh}, g cm^{-3}.

3. Volume of pores occupied by loosely bound water (P_{lb}, %): $P_{lb} = (W_{wp} - W_{mh}) / 1.25$, where W_{wp} – is the wilting point moisture (% of oven-dry soil weight); 1.25 is the density of loosely bound water, g cm^{-3}.

4. Volume of pores occupied by capillary water (CP, %): $CP = (W_{fc} - W_{wp}) \cdot d_v$, where W_{fc} – is the field (total) moisture capacity (%).

5. Volume of pores occupied by water of all categories (WP, %); $WP = P_{mh} + P_{lb} + CP$;

6. Aeration porosity (AP, %): $AP = TP - WP$.

For modeling and calculations, a total of 355 paired determinations of bulk density and soil moisture were used.

Hydrothermal coefficient (HTC), determined by Selyaninov's method – is the sum of precipitation during the period when the average daily air temperature is above 10° C divided by the sum of active temperatures for the same period, reduced ten times. HTC < 0.4 – very severe drought, HTC from 0.4 to 0.5 – severe drought, HTC from 0.6 to 0.7 – moderate drought, HTC from 0.8 to 0.9 – mild drought, HTC from 1.0 to 1.5 – sufficiently moist, HTC > 1.5 – excessively moist.

Statistical data processing was performed using nonparametric statistical methods – that is, methods that do not require assumptions about the type of data distribution. Instead of operating with the raw values, these methods use their ranks or frequencies, which makes them flexible for analyzing data measured on different scales. For sample description, quartile analysis was applied – dividing an ordered data series into four equal parts. The following indicators were calculated during the analysis: mean value (Mean); minimum value (Min); maximum value (Max); median (Med) – the second quartile ($L_{0.50}$), which divides the data in half; amplitude range (Δ_a = Max – Min); lower quartile ($L_{0.25}$) – the value below which 25% of observations lie; upper quartile ($L_{0.75}$) – the value below which 75% of observations lie; quartile range ($\Delta n = L_{0.75} - L_{0.25}$) corresponding to the 50% probability level; probability deciles – lower ($L_{0.10}$) and upper ($L_{0.90}$); coefficient of variation (C_v, %) – characterizing the degree of relative variability of indicators.

The energy efficiency assessment was carried out using the methodology of Kalinichenko (2016). Statistical analysis of research results was performed using the 'Method of Analysis of Variance' with the STATISTICA software, employing nonparametric statistical methods, as well as correlation and factor analysis (Bulgakov et al., 2020b).

RESULTS

The impact of different tillage methods on the bulk density and soil moisture content of the 0–30 cm soil layer of leached chernozem was studied. It was established that the average bulk density, regardless of tillage method, was the same; however, the amplitude range of bulk density under ploughing was 1.75 times greater compared to shallow tillage. The median bulk density under shallow tillage was higher by 0.03 g cm^{-3}, while the standardized range of density was the same for both tillage methods, with an increase of 0.02 g cm^{-3} in both the upper and lower quantiles under shallow tillage. The coefficient of variation of bulk density under ploughing was 1.85 times higher than under shallow tillage (Table 1).

Under different tillage methods, the factor loading of soil moisture was mainly associated with the principal factor F1: $R = +0.94 \pm 0.03$; $R^2 = 0.88$, whereas bulk density showed a strong direct correlation along factor F2 ($R = +0.97 \pm 0.02$).

The amplitude range of chernozem bulk density was wider under ploughing (Δ = 0.51 g cm^{-3}) compared to shallow tillage (Δ = 0.41 g cm^{-3}). The shift in density under ploughing occurred within a moisture interval of Δ = 18.5%, whereas under shallow tillage, the interval was Δ = 17.8%. In the latter case, the minimum moisture level was 1.32 times higher compared to ploughing.

Regardless of the tillage method, the normalized range of bulk density was within 0.17–0.18 g cm^{-3} for a normalized moisture range of 11.5–12.4% to 21.0–22.0%.

Table 1. Normalized parameters of bulk density and soil moisture content in the 0–30 cm soil layer depending on the tillage system of degraded leached chernozem, 2016–2021

Soil moisture, % / Bulk density, g cm^{-3}				Soil moisture quantiles, % / Bulk density quantiles, g cm^{-3}			
Mean	Min / Max	Max / Min	Med., $L_{0.50}$	$L_{0.10}$ / $L_{0.90}$	$L_{0.25}$ / $L_{0.75}$	$L_{0.75}$ / $L_{0.25}$	$L_{0.90}$ / $L_{0.10}$
	Amplitude range: Δ_a = Max – Min			Normalized range: $\Delta_n(50\%) = L_{0.75} - L_{0.25}$; $\Delta_n(10\%) = L_{0.90} - L_{0.10}$			
Ploughing (22–25 cm)							
16.5	7.11	22.6	17.6	8.50	12.7	20.4	21.8
1.19	1.38	0.98	1.18	1.33	1.26	1.11	1.08
Shallow tillage (10–12 cm)							
15.6	6.9	22.5	16.7	9.25	11.1	19.7	20.9
1.19	1.39	1.05	1.22	1.35	1.27	1.13	1.10

The normalized range at a 10% significance level (Δ_n, 10%) for bulk density, regardless of the tillage method, was 0.25 g cm^{-3} under a normalized soil moisture range of 13.3% for ploughing and 11.4% for shallow tillage. In the first case, the minimum value of soil moisture was lower than the wilting point (WP = 8.85%), while in the second case it was higher than WP: 8.5% and 9.25%, respectively.

The bulk density value at the median under ploughing was 0.01 g cm^{-3} lower than the mean, whereas under shallow tillage, it was 0.03 g cm^{-3} higher than the mean. This indicates a stable trend toward increasing bulk density in the latter case, though still within optimal values, optimizing both total and differential porosity.

The coefficient of variation for bulk density under ploughing was 1.15 times higher compared to shallow tillage (Table 1).

According to the general model for different tillage systems, each unit increase in bulk density corresponded to a 0.019% decrease in soil moisture, indicating a consistent pattern in the change of bulk density depending on soil moisture content. However, under shallow tillage, each unit increase or decrease in bulk density corresponded to a 0.018% change in soil moisture (Table 2). Under systematic ploughing, for each unit increase in total porosity, there was a decrease in the volume of pores filled with capillary water and air in a ratio of 1.7 to 1, whereas under shallow tillage, this ratio was 0.25 to 1. Shallow tillage led to the stabilization of capillary water-filled pore volume while maintaining an adequate amount of air-filled pore volume.

Table 2. Influence of the tillage system on changes in bulk density as a function of soil moisture in the 0–30 cm layer of leached, degraded chernozem (2016–2021)

Regression equation	Correlation coefficient, r	Determination coefficient, r^2
Ploughing		
$y = 1.52 - 0.019 \cdot x$	r = –0.87	0.75
Shallow tillage		
$y = 1.50 - 0.018 \cdot x$	r = –0.78	0.61
Overall model		
$y = 1.51 - 0.019 \cdot x$	r = –0.77	0.60

The determination of bulk density and calculation of differential porosity under different tillage methods for five crops in a row-crop grain rotation, in the sixth year of the experiment, showed that in spring, bulk density under systematic shallow tillage was 0.06 g cm^{-3} higher than under ploughing. The average total porosity under shallow tillage was 3 to 4 percentage points lower. The volume of pores filled with water was higher compared to systematic ploughing, which influenced the ratio of pore types: under shallow tillage, the ratio was close to the lower optimal threshold (~1:1), while under ploughing, it favored air-filled pores.

A similar trend was observed in the amplitude and normalized range of porosity categories. The stabilization of differential porosity under systematic shallow tillage was confirmed by a lower coefficient of variation (C_V) for all porosity parameters compared to ploughing (Table 3).

Table 3. Normalized parameters of differential porosity in the 0–30 cm soil layer depending on the tillage system of leached, degraded chernozem, 2016–2021

Agrophysical indicators	Mean	Median	Min	Max	Quantile: $L_{0.25}$	$L_{0.75}$	C_V, %
			Amplitude range: Δ_a=Max – Min		Normalized range: $\Delta_n(50\%)=L_{0.75}-L_{0.25}$		
Systematic ploughing (22–25 cm)							
	1.09	1.08	-	-	-	-	7.75
TP, %	58.0	58.0	53.0	64.0	56.0	64.0	5.52
WP, %	24.0	25.	19.0	29.0	21.0	27.0	12.0
CP, %	18.0	18.0	13.0	21.0	15.0	20.0	14.5
AP, %	33.0	33.0	24.0	35.0	35.0	37.0	17.6
WP to AP	0.77	0.77	0.42	0.82	0.60	0.73	27.9
Systematic shallow tillage (10–12 cm)							
	1.14	1.15	-	-	-	-	8.61
TP, %	56.0	55.0	55.0	61.0	52.0	59.0	6.42
WP, %	26.0	27.0	20.0	29.0	24.0	29.0	10.0
CP, %	18.0	18.0	14.0	20.0	17.0	19.0	10.0
AP, %	27.0	28.0	35.0	32.0	28.0	30.0	15.8
WP to AP	~1.0	~1.0	0.57	0.91	0.77	~1.0	21.5

Note: TP – total porosity, %; WP – water-filled pores, %; CP – capillary pores, %; AP – aeration pores, %; C_V – coefficient of variation, %.

Under systematic ploughing, crop yields in the 5-field crop rotation demonstrated a steady upward trend compared to shallow tillage, although the differences were not statistically significant. A significant increase in yield was recorded for maize and sugar beet. The grain unit output per rotation under both systematic ploughing and shallow tillage ranged from 34.4 to 35.1 tonnes, or 6.88 to 7.02 tonnes per hectare. The largest contributions to the total grain unit output came from maize, sunflower, and sugar beet.

The feed unit output was nearly the same regardless of the tillage method, amounting to 34.5–34.6 tonnes, or 6.90–6.91 tonnes per hectare. In terms of feed-protein units, ploughing slightly outperformed shallow tillage: 37.0 tonnes vs. 33.9 tonnes, or 7.40 t ha^{-1} vs. 6.79 t ha^{-1}. The highest contribution to total feed-protein output came from maize (23.3–24.9%) and sunflower (22.6–23.6%) (see Table 4).

The energy content of the harvest under systematic ploughing reached 416.0 MJ per crop rotation, or 83.3 MJ ha^{-1}. Under shallow tillage, the energy content of the harvest was lower by 9 MJ and 1.9 MJ ha^{-1}. The most energy-dense crops were maize and sugar beet, yielding 121–128 MJ ha^{-1}.

Table 4. Productivity of agricultural crops under different soil tillage methods in a five-field grain-row crop rotation during 2016–2021

Productivity indicators	Crops in the 5-field crop rotation system					
	Maize	Spring barley	Soybean	Sunflower	Sugar beet	Average
Shallow tillage						
$N_{75}P_{75}K_{82}$ + 6 t ha^{-1} crop residues						
Yield, t ha^{-1}	7.95	3.74	2.35	3.55	46.7	-
Energy content of yield, GJ ha^{-1}	120.3	61.5	42.6	63.3	119.4	81.4*/407.0
Grain units, tons	7.95*/23.1	2.99/8.69	4.25/12.4	7.10/20.6	12.10/35.2	6.88*/34.4
Feed units, tons	10.60/30.7	4.52/13.1	3.76/10.9	4.01/11.6	11.60/33.6	6.90*/34.5
Energy efficiency coefficient (EEC)	4.80	3.90	3.70	2.41	3.55	3.67
Ploughing						
$N_{75}P_{75}K_{82}$ + 6 t ha^{-1} crop residues						
Yield, t ha^{-1}	8.15	3.56	2.47	3.60	47.50	-
Energy content of yield, GJ ha^{-1}	128	58.5	44.8	64.0	121.4	83.3*/416.0
Grain units, tons	8.15/23.2	2.86/8.15	4.49/12.9	7.18/20.5	12.4/35.3	7.02*/35.1
Feed units, tons	10.7/30.9	4.35/12.6	3.44/9.94	4.06/11.7	12.0/34.7	6.91*/34.6
Energy efficiency coefficient (EEC)	5.71	5.39	5.05	3.01	4.58	4.75

Note: *Numerator – value per hectare (t ha^{-1}); Denominator – total output (t).

The output of crop residues was similar under both tillage systems, amounting to 40.7–41.3 tonnes per crop rotation (7–8 t ha^{-1}), with energy content in residues reaching 242–245 MJ, or 48–49 MJ ha^{-1}.

Analysis of the exponential regression equations ($y = a \cdot e^{-bx}$) reflecting the dynamics of changes in grain unit yield under different soil tillage treatments (Fig. 1) revealed that the rate of decline depends on the tillage method and fertilizer application. For the unfertilized variants, the decline coefficient under surface tillage (b = 0.061) was approximately 1.2 times higher compared to plowing (b = 0.051), indicating a more intensive decrease in grain unit yield under surface tillage. In contrast, for the fertilized variants, the opposite tendency was observed: the decline coefficient under plowing with fertilizers (b = 0.067) exceeded that under surface tillage with fertilizers (b = 0.061), which indicates a slower decline in crop yield under surface tillage toward the end of the observation period.

Thus, at the later stages of the experiment, surface tillage combined with fertilizer application provided more stable grain unit yield values compared to plowing. This effect may be attributed to the gradual recovery of the soil's natural fertility mechanisms: structure formation, accumulation of organic matter, and activation of soil biota, which become evident only after several years of implementing surface tillage technology.

The determination coefficients (R^2 = 0.32 – 0.39) indicate a moderate fit of the models to the experimental data; however, the obtained dependencies make it possible to assess general trends in yield changes depending on tillage practices and fertilization.

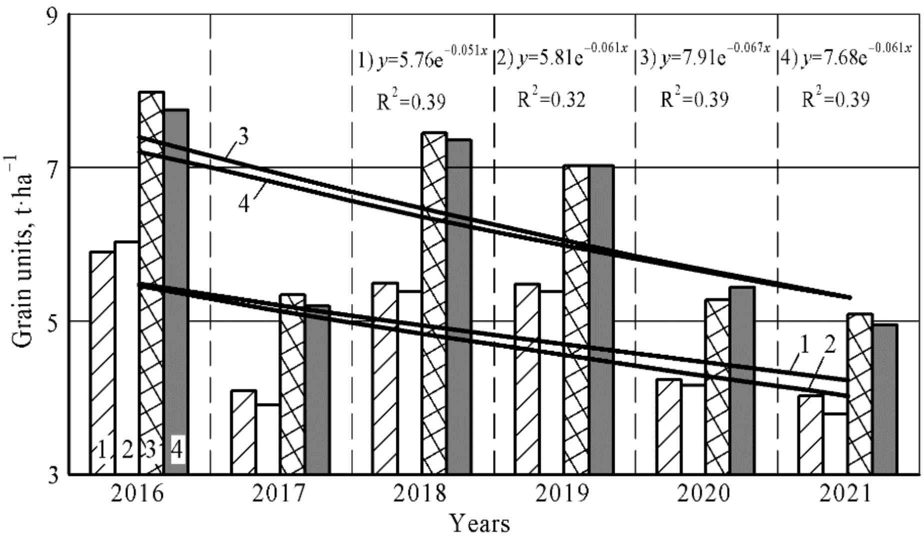

Figure 1. The effect of different tillage methods on the dynamics of grain unit yield in a five-field crop rotation during 2016–2021.

An agro-energy assessment of the input costs associated with the formation of productivity in a five-field crop rotation under different tillage systems showed that, regardless of the soil tillage method, a high level of production efficiency was ensured (energy efficiency coefficient, EEC > 2.5) for the main output. At the same time, energy profitability under shallow tillage increased by 1.45 times compared to plowing for the main produce and by 1.35 times for biological yield. The energy intensity of crop production within the rotation under average bulk density was found to be similar across tillage systems. However, the amplitude range of bulk density under plowing was 1.75 times greater compared to chisel tillage. The median bulk density in the 0–30 cm layer of chernozem was 0.03 g cm^{-3} higher, while the standardized density range remained the same regardless of tillage system, increasing by 0.02 g cm^{-3} under chisel tillage for both upper and lower typical values. The coefficient of variation of bulk density under plowing was 1.85 times higher compared to shallow tillage.

DISCUSSION

A key criterion for assessing the agroecological status of agricultural land is, first and foremost, the level of soil fertility, which serves as the foundation for the functioning of these land categories. Soil fertility determines land productivity, its economic significance, and value. It is defined as the soil's ability to meet plant needs for nutrients, water, air, and heat in sufficient quantities for normal growth and development – factors that together constitute the principal indicator of soil quality (Medvedev, 2013).

It is particularly important, under the conditions of the Central Forest-Steppe of Ukraine, to develop a criterion for assessing the agrophysical state of degraded podzolized chernozem during the initial years (five to six years) of transition to systematic shallow tillage. This is essential for preventing situations that could lead to the partial or complete discrediting of the core idea of tillage minimization in agrocenoses with diverse crop rotation systems. The need for such an approach is especially critical under sharply deteriorating weather and climate conditions, when the moisture coefficient (MC), calculated according to Shashko's method, decreases to values around 0.55, and the hydrothermal coefficient (HTC), determined by Selyaninov's method, drops to values between 0.5 and 0.61 or lower for a period of one to one and a half months during the growing season of field crops. Such conditions were observed during the years of research in the Central Forest-Steppe region.

Based on the conducted research, the nature of the potentially unstable response of chernozem as a system becomes clear during the initial years of systematic shallow non-moldboard tillage, particularly when the soil is in an advanced stage of agrophysical degradation and exposed to critical weather and climate conditions. During the first two years of transition, a temporary increase in bulk density and reduced air porosity were observed, reflecting the soil's structural inertia before self-regulation processes became dominant. Under conventional ploughing, the 0–30 cm layer of chernozem does not exhibit differentiation in bulk density or in the structure of the pore space. Partial humus depletion and agrophysical degradation lead to the formation of a cloddy and compacted structure in the horizon, whereas long-term non-moldboard tillage promotes the development of a fine-crumbly, loose soil structure. Following the discontinuation of systematic ploughing, a transition period of five to six years is required to achieve an optimal structure in the 0–30 cm soil layer, characterized by the following profile: loose (0–10 cm) – compacted (10–20 cm) – loose (20–30 cm). In our experiment, the median bulk density under surface tillage reached 1.33 g cm^{-3} compared to 1.30 g cm^{-3} under ploughing, while the coefficient of variation was 1.85 times lower, indicating structural stabilization. The qualitative restructuring of the pore system, aiming at an optimal ratio of pores filled with water and air, serves as a sufficient criterion for the feasibility of further tillage minimization, ultimately allowing the implementation of zero-tillage systems on medium-humus, medium-loam, podzolized chernozem.

Comparison of the obtained results with the data from the literature sources indicates a general trend towards the necessity of minimizing traditional tillage of Chernozem soils. Thus, the findings of Baliuk et al. (2023) highlight a significant decrease in organic matter content and the need for the implementation of restorative practices, which fully aligns with our conclusions regarding the agrophysical degradation of Chernozems under intensive ploughing. The analysis by Lykhovyd (2024) confirmed the advantages of surface tillage over conventional ploughing in terms of soil biological activity, which also correlates with our findings on the improvement of soil physical properties under systematic minimal tillage. The study by Vilde et al. (2012) emphasized the importance of adapting tillage practices to specific soil properties to enhance yield and energy efficiency, supporting our recommendations for optimizing the structural parameters of working bodies to preserve soil porosity and prevent compaction. Therefore, the obtained results complement the overall scientific picture and confirm the relevance of transitioning to soil-conservation tillage technologies.

The stabilization of physical parameters coincided with yield and energy efficiency levels under surface tillage becoming comparable to those under ploughing after the fifth year of observation. Our observation that the median bulk density under systematic surface tillage was 0.03 g cm^{-3} higher than in ploughed soil, yet accompanied by a significantly reduced coefficient of variation, resonates with trends reported in other long-term trials. For example, Alam et al. (2014) found that zero and minimum tillage systems tended to stabilize bulk density with a smaller range of variation, while maintaining or improving porosity and yield over time.

In our study, the optimal 1:1 ratio of water-filled to air-filled pores under surface tillage aligns with the direction of structural shifts reported by Li et al. (2019), who documented that conservation tillage improved pore distribution and water retention while balancing aeration conditions.

The measurable trends only emerged after several years of surface tillage, illustrating a transitional soil response. This pattern is consistent with other findings that soil structural recovery and pore reorganization under reduced tillage require a temporal lag. Jensen et al. (2020) note that conversion from tillage to no-till often initially increases surface bulk density until soil reconfiguration stabilizes.

Moreover, meta-analytical evidence (Nunes et al., 2020) shows that while reductions in tillage intensity may not always lead to immediate gains in soil physical indicators, over a moderate timeframe (≥ 5 years) improvements in aggregate stability and porosity become discernible, reinforcing the general applicability of our 5–6 year findings.

Thus, our results suggest that the convergence toward stabilized bulk density plus a balanced water-air pore volume may function as a practical readiness threshold for degraded chernozems before further tillage minimization. This criterion is strengthened by the fact that yields and energy efficiency under surface tillage became comparable to those under ploughing over time. In this context, the literature supports the viability of such a threshold: authors often caution that until structural equilibrium is achieved, premature adoption of reduced tillage can provoke yield instability or structural setbacks (e.g., poor aeration in topsoil under long-term no-till, as noted by ten Damme et al., 2025).

In sum, our study demonstrates that in strongly degraded podzolized chernozems, a multi-year observation window is critical to identify when the soil's internal structure has shifted sufficiently to enable stable minimal tillage. The criterion we propose – stabilized bulk density combined with optimal differential porosity ratio can guide the timing of agronomic transitions from shallow to even zero tillage, minimizing risks of structural or yield failures.

CONCLUSIONS

Under shallow tillage, the median bulk density of the 0–30 cm layer of chernozem was higher by 0.03 g cm^{-3}, while the standardized range of density remained the same regardless of tillage method. However, under shallow tillage, both the upper and lower typical values of density increased by 0.02 g cm^{-3}. The coefficient of variation of bulk density under ploughing was 1.85 times higher compared to shallow tillage.

Differentiated porosity calculations for different tillage methods under five crops, conducted in the sixth year of the experiment, revealed that in the spring period, the bulk density under systematic shallow tillage was 0.06 g cm^{-3} higher than under ploughing. Total porosity was 3% higher, while the volume of air-filled pores was 6.0% lower. At the same time, the ratio of water-filled to air-filled pores reached an optimal level (1:1), whereas under ploughing, the ratio favored air-filled pores.

The influence of tillage method on the formation of differentiated porosity in the 0–30 cm soil layer demonstrated certain features. Under systematic ploughing, for every unit increase in total porosity, there was a reduction in the volume of both capillary water-filled pores and air-filled pores at a ratio of 1.7:1. In contrast, under shallow tillage, this ratio was 0.25:1, indicating the stabilization of capillary water-filled pore volume while maintaining a sufficient amount of air-filled pore volume. This provides grounds to argue for the possibility of further tillage minimization.

Systematic application (over five years) of both ploughing and conservation shallow tillage in a five-field grain-row crop rotation ensured comparable productivity in terms of yield, energy efficiency, and output of grain and fodder units. While productivity indicators under ploughing remained stable relative to the average, under conservation tillage they showed a better trend, which can be attributed to the completion of the transition period following the cessation of ploughing and the prior implementation of deep chiseling, followed by the adoption of systematic shallow tillage at a depth of 10–12 cm.

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