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The impact of sustainable tillage systems when growing corn for grain on the agrophysical condition of typical black soil and agroecological efficiency

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ABSTRACT

The relevance of this study stems from the need to optimize primary soil tillage techniques for grain maize cultivation, as they have a substantial impact on agrophysical soil properties. This issue becomes particularly critical under conditions of unstable and insufficient moisture supply. Enhancing these soil properties is expected to improve the water regime and reduce weed pressure, thereby enabling stable and high yields. Consequently, there is an urgent need to develop effective tillage strategies for row crops, especially maize. The research was conducted in 2023 and 2024 in the left-bank forest-steppe of Ukraine, on low-humus typical chernozem. The study found that the highest reserves of productive moisture in the arable layer at the time of maize sowing were observed under plowing to a depth of 20–22 cm (18.4 mm), while the lowest moisture reserves were recorded under shallow disk tillage without soil inversion (16.0 mm). By the time of harvest, soil moisture reserves had dropped to critical levels in the arable horizon (0.6–1.2 mm), while the meter-deep layer retained 28.3–32.1 mm. At the maize emergence stage, soil bulk density remained within the optimal range across all tillage methods: plowing – 1.13–1.22g/cm^3, deep loosening – 1.16–1.26 g/cm^3, heavy cultivator tillage (12–14 cm) – 1.18–1.26 g/cm^3, disk tillage (12–14 cm) – 1.17–1.25 g/cm^3. However, from emergence to harvest, soil compaction increased more under plowing than under no-till methods. The highest maize grain yield – 7.98 t ha^{-1} – was achieved with plowing to 20–22 cm. In contrast, deep loosening without soil turnover and no-till methods at 12–14 cm resulted in a significant yield reduction of 1.20–1.32 t ha^{-1}. In terms of energy efficiency, the lowest energy efficiency ratio (2.4) was recorded under plowing. With reduced energy inputs in no-till systems without inversion, this ratio increased to 2.7–2.9.

Keywords: soil agrophysical parameters, energy intensity of technologies, yield structure, bulk soil density, water-physical properties, ecosystem resilience, ecological risk assessment, maximum permissible load.

INTRODUCTION

Soil is the fundamental and irreplaceable natural resource upon which agricultural productivity depends. Under current conditions, there is an urgent need to adopt innovative primary tillage practices for row crops that improve and regulate key agrophysical properties of the soil. Purposeful management of the soil's physical condition particularly its moisture, air, temperature, and nutrient regimes – is essential to create favorable conditions for crop growth and development [Stępień-Warda, 2020; Datsko et al., 2025].

In recent years, significant shifts in weather and climate patterns have been observed, marked by a growing number of extreme and drought-prone seasons. As a result, crop productivity and quality have become increasingly dependent on these climatic factors, especially in Ukraine's forest-steppe zone [Kabanets and Sobko, 2023].

To ensure high and stable yields in modern agricultural systems, it is critical to execute a full range of technological operations within defined timeframes and in strict compliance with agrotechnical standards [Mishchenko et al., 2025].

Among all agrotechnical measures designed to boost crop productivity, primary tillage plays a central role. It directly enhances the agrophysical conditions of the arable layer and regulates essential biochemical processes within the soil environment. Only through mechanical intervention enabled by tillage tools can optimal conditions for root system development, efficient use of soil amendments, fertilizers, and other treatments be achieved [Datsko et al., 2024].

Scientific studies have confirmed that insufficient soil moisture negatively impacts plant development and significantly reduces the effectiveness of individual agrotechnical practices [Wang et al., 2019; Butenko et al., 2025]. Well-moisturized soils support higher seed yields, while precipitation during autumn, winter, and early vegetation stages has been identified as especially critical [Datsko and Zakharchenko, 2022].

When choosing a primary tillage strategy for row crops such as maize, several factors must be considered: soil type, climatic conditions, crop biology, and crop rotation requirements. The effectiveness of mechanical tillage increases when tillage depth, method, and sequencing follow a scientifically grounded system and are integrated into the broader agricultural management plan. However, excessive or poorly executed tillage can harm soil structure, reduce fertility, and increase energy costs. As a result, tillage systems must be continuously adapted alongside improvements in local crop production technologies [Partal et al., 2023].

Maize, in particular, develops a vigorous root system that spreads laterally and vertically, with the bulk concentrated in the 30–60 cm soil layer. Therefore, deep tillage is beneficial where soil and conditions permit.

In forest-steppe regions characterized by unstable and limited moisture availability, the primary objectives of tillage include maximizing soil water retention and effective weed control. The choice of tillage method and its timing largely depend on the harvest date of the preceding crop [Kadhim, 2020].

In various soil-climatic regions of Ukraine, differentiated autumn tillage practices are commonly applied to maize, including plowing and multiple no-till techniques (such as chisel, flat-cut, and combined tillage). Each has its strengths, and the most suitable method is often determined by local conditions, soil characteristics, and the available machinery [Radchenko et al., 2022; Tykhonova et al., 2023].

Autumn tillage operations should aim to evenly distribute crop residues, level the field, and improve soil structure, all of which contribute to reducing springtime tillage needs and preserving moisture [Litvinov et al., 2020].

The relevance of this study lies in the development of soil tillage systems that substantially influence agrophysical properties a priority in regions with erratic and limited moisture. While there is no universal solution for selecting the optimal tillage method, the core objective remains: to enhance agrophysical conditions, balance soil moisture, and suppress weed growth, thereby enabling maximum yield potential. Hence, there is a growing necessity to develop effective primary tillage strategies for row crops, especially grain maize.

MATERIAL AND METHODS

The research was conducted in a stationary field experiment in the conditions of the natural and climatic zone of the left-bank forest-steppe of Ukraine in 2023 and 2024. Experimental experiments were conducted on the basis of the Institute of Agriculture of the north-east of the NAAS (geolocation: 50°53'22.3"N latitude, 34°42'34.1"E longitude, 137.7 m above sea level; Map data ©2025 Google).

The soils of the experimental plots are typical low-humus black soils (humus content 3.8%; Ph – 6.2; P_2O_5 – 21.4 mg/100 g; K_2O – 10.2 mg/100 g). The average daily temperatures in these years were 1.6 °C and 1.8 °C higher than the long-term average of 7.4 °C, respectively. The absolute maximum temperature in 2023 was 36 °C in the first decade of August and 34 °C in the second decade of July in 2024; the minimum temperature in 2023 was -18.0 °C in the second decade of January, and in 2024 – minus 19 °C in the first decade of January; the minimum temperature in 2023 was minus 19 °C in the first decade of January; rainfall in 2023–24 was 634 mm, which is 41 mm more than the long-term average (593 mm).

The experiment included four main methods of soil cultivation for growing corn for grain:
- plowing to a depth of 20–22 cm (control),
- deep loosening to a depth of 35–40 cm,
- zero tillage with a heavy cultivator to a depth of 12–14 cm,
- disk cultivation without tillage to a depth of 12–14 cm.

The experiment was set up in a four-field crop rotation: soybean-winter wheat-corn for grain-barley. Treatments and replications were organized in a system design with three replications. With the exception of the main tillage, crop management followed standard regional practices. The following research methods were used in the experiments: field, laboratory, analytical and statistical. In the laboratories, agrophysical properties of the soil were determined: soil bulk density (soil density), total porosity, and soil moisture. The bulk soil mass (soil compaction) was determined by the cutting ring method by Kachinsky [1965]. The actual soil moisture was determined by the thermostatic-gravimetric method, which meets the requirements of DSTU B V.2.1-17:2009 [Altukhova et al., 2010]

The field experiments were established in accordance with the methodological recommendations for conducting field research and were planned and conducted taking into account the stages of corn development [Malienko et al., 2017, 2020]. Statistical processing of the experimental results was carried out using the Statistica 6.0 program.

RESULTS AND DISCUSSION

Moisture is a fundamental factor for all living organisms and plays a vital role in plant growth and development. The size of the crop yield largely depends on the availability of moisture. However, both excess and deficiency of soil moisture can have a detrimental impact on plants. In either scenario, plants are unable to efficiently use thermal energy, which impairs biomass accumulation and prevents the formation of optimal yields [Krestianinov et al., 2019; Resul et al., 2022].

Soil moisture reserves depend on various factors, especially on water permeability and evaporation from the soil surface. These properties are directly influenced by soil structure, which can be modified through tillage methods [Zakharchenko et al., 2023].

At the time of maize sowing, soil moisture reserves were primarily influenced by weather conditions and tillage techniques, which played a decisive role in achieving uniform germination and subsequent plant development. Spring precipitation contributed to soil moisture replenishment in all treatments. However, plant water availability in the early growing season showed substantial differences between tillage variants (Table 1).

Moisture calculations in the 0–100 cm layer at sowing time revealed the highest moisture content (56.7 mm in the 0–50 cm layer) under plowing to 20–22 cm. Shallower no-till methods (12–14 cm), such as heavy cultivator and disk tillage, reduced soil moisture by 1.3 mm and 1.7 mm, respectively, compared to plowing.

At the maize field during sowing, the highest reserves of available moisture in the one-meter soil layer were recorded in the plot with plowing to a depth of 20–22 cm – 118.2 mm. After deep loosening with Delta NT shanks, the moisture content remained at the same level as the control (plowing). In the variant with no-till cultivation using a heavy cultivator, moisture reserves in the one-meter soil layer decreased by 6.2 mm compared to plowing. The lowest moisture reserves were recorded under

Table 1. The impact of main tillage methods on available moisture reserves in a corn field for grain, mm (2023–2024)

Variant	Sampling time											
	Sowing						Harvesting					
	Horizon, cm											
	0–20	To control	0–50	To control	0–100	To control	0–20	To control	0–50	To control	0–100	To control
Plowing 20–22 cm (control)	18.4	-	56.7	-	118.2	-	1.2	-	12.8	-	32.1	-
Deep loosening 35–40 cm	16.8	-1.6	56.0	-0.7	117.6	-0.6	1.0	-0.2	12.5	-0.3	30.5	-1.6
Heavy cultivator 12–14 cm	16.2	-2.2	55.4	-1.3	112.0	-6.2	0.9	-0.3	12.0	-0.8	28.8	-3.3
Disk tillage 12–14 cm	16.0	-2.4	55.0	-1.7	111.4	-6.8	0.6	-0.6	12.4	-0.4	28.3	-3.8

disk tillage at 12–14 cm – 111.4 mm, which is 6.8 mm less than the control.

At harvest, there was a general trend of decreasing productive moisture reserves. Disk tillage showed the lowest level of available moisture compared to the control. The total amount of available moisture in the one-meter soil layer under plowing was 32.1 mm, which was 3.8 mm more than under disk cultivation.

Soil bulk density is a critical indicator of its agrophysical condition and serves as a key agronomic parameter, reflecting soil structure, water-physical properties, and biological activity [Silver et al., 2021; Zakharchenko et al., 2023]. The functionality of soil water, air, thermal, and nutrient regimes, along with the biological activity of soil flora and fauna, directly depends on bulk density levels [Zinati et al., 2025].

One of the primary goals of soil tillage is to regulate soil bulk density. Achieving high and stable crop yields largely relies on maintaining optimal bulk density in the arable layer – an outcome that depends significantly on the type and intensity of mechanical tillage [Singh et al., 2020; Mishchenko et al., 2025].

Table 2 presents the bulk density data in maize fields under different primary tillage practices. During the maize emergence stage, the bulk density of the arable soil layer remained within the optimal range across all tillage variants: plowing: 1.13–1.22 g/cm³, deep loosening: 1.16–1.26 g/cm³, no-till with heavy cultivator (12–14 cm): 1.18–1.26 g/cm³, disk tillage (12–14 cm): 1.17–1.25 g/cm³. In no-till treatments using a heavy cultivator and disk harrow, higher compaction was observed in the 10–20cm soil layer compared to plowing by 0.07 and 0.06 g/cm³, respectively. Regardless of the tillage method used, the least compacted soil layer was consistently the top 0–10 cm, as all tillage approaches provided sufficient surface loosening.

Importantly, all studied tillage methods maintained soil bulk density within the recommended threshold of 1.3 g/cm³, ensuring favorable agrophysical conditions for maize cultivation.

During the maize growing season, soil bulk density increased across all primary tillage variants and soil layers, from the emergence stage to harvest. A shallower tillage depth led to increased compaction in the underlying untreated layers. By the end of the season, the highest bulk

Table 2. Effect of tillage methods on soil agrophysical indicators under maize (2023–2024)

Soil layer	Soil density, g/cm³			Total porosity, %		
	Emergence	Harvest	Seasonal average	Emergence	Harvest	Seasonal average
Plowing to a depth of 20–22 cm						
0–10	1.13	1.19	1.16	56.8	54.2	55.5
10–20	1.18	1.22	1.20	54.3	53.8	54.1
20–30	1.22	1.26	1.24	53.6	52.3	53.0
30–40	1.16	1.24	1.20	54.0	53.4	53.7
Deep loosening to a depth of 35–40 cm						
0–10	1.16	1.20	1.18	54.6	53.6	54.1
10–20	1.22	1.24	1.23	53.8	52.1	53.0
20–30	1.24	1.27	1.26	52.4	51.7	52.1
30–40	1.26	1.28	1.27	51.8	50.9	51.2
Non-inversion tillage using a heavy cultivator at a depth of 12–14 cm						
0–10	1.18	1.22	1.20	54.2	53.3	53.8
10–20	1.25	1.28	1.27	52.3	51.6	52.0
20–30	1.26	1.29	1.28	51.6	50.9	51.3
30–40	1.23	1.27	1.25	52.8	51.4	52.1
Disk tillage without soil inversion to a depth of 12–14 cm						
0–10	1.17	1.22	1.20	54.4	53.4	53.9
10–20	1.24	1.26	1.25	52.8	52.5	52.7
20–30	1.25	1.28	1.27	52.3	51.8	52.1
30–40	1.22	1.26	1.24	53.0	52.1	52.6

density in the 20–30 cm layer was recorded after non-inversion tillage using a heavy cultivator at 12–14 cm, reaching 1.29–1.30 g/cm³. In contrast, the lowest bulk density in the 0–10 cm topsoil layer 1.19 g/cm³ was observed under plowing to 20–22 cm.

In the deeper 30–40 cm soil layer, a general declining trend in bulk density was noted. On average, throughout the growing season, bulk density in the arable layer increased more under non-inversion tillage with a heavy cultivator and disk implements than under traditional plowing.

Based on these findings, it can be concluded that bulk density in maize fields increased from plant emergence to harvest under all tillage systems, but the values remained within acceptable agrophysical limits.

Soil total porosity was calculated using the method of Kachinsky [1965], and the values were consistent with the bulk density data. Under plowing to 20–22 cm, porosity in the 0–10 cm soil layer was measured at 55.8% at the beginning of vegetation and 54.2% before harvest. The lowest porosity was found in the 10–20 cm layer under non-inversion tillage with a heavy cultivator and disks at a depth of 12–14 cm.

Maize plants, like other annual crops, have a determinate growth pattern, ceasing linear growth during maturation regardless of the combination of agrotechnical and meteorological conditions.

Among the many economically valuable traits of maize hybrids that significantly influence yield formation, two stand out: the number of kernel rows per cob and the number of kernels per row.

The highest kernel set per cob – 477.2 kernels – was recorded under plowing, while the lowest – 438.0 kernels – was observed under non-inversion disk tillage to a depth of 12–14 cm. Grain weight per cob ranged from 152 to 153 g, which is a favorable result under severe moisture deficit conditions during the grain-filling and ripening phases (Table 3).

Both the weight of grain from one ear and the weight of 1000 grains varied little depending on the methods of main tillage. It ranged from 277.0 g to 299.1 g (Table 4).

The years of research were characterized by a moisture deficit in the second half of the plant vegetation, which affected the formation of the corn grain yield at the level of 6.66–7.98 t ha^{-1} (Table 5). It was greater in the control variant with plowing at 20–22 cm. Deep loosening of the soil without rotation of the furrows and no-till cultivations caused a slight decrease in yield by 1.20–1.32 t ha^{-1}. At the time of harvesting, only 46–47 mm of productive moisture remained in the meter-long soil horizon, which neutralized the influence of the main cultivation methods on the formation of the grain yield and its size.

Energy analysis is a critical tool for evaluating crop cultivation technologies, as it enables the assessment of the rational use of energy inputs both those consumed and those reproduced through biomass production. In this study, the tillage machinery and techniques used for primary soil cultivation in a 4-field crop rotation system differed significantly in terms of labor productivity and materialized non-renewable energy expenditures.

Accordingly, an evaluation of the energy intensity of various primary tillage methods for maize was conducted. Based on these calculations, the energy costs per hectare were determined (Table 6).

The assessment of energy intensity in grain maize cultivation, which was based on different tillage depths and methods, revealed that reducing energy inputs in primary tillage operations had only a minor influence on the overall energy intensity of the cultivation system.

All labor, material, and financial resources used in maize grain production share a common

Table 3. Average maize cob kernel set depending on primary tillage method, 2023–2024

№ п/п	Tillage Method	Average per cob, pcs.		Kernel set per cob, kernels/cob	Grain weight per cob, g	Number of cobs, thousand pcs.
		Number of kernel rows	Number of kernels per row			
1	Plowing to a depth of 20–22 cm	15.1	31.6	477.2	153.0	66
2	Deep loosening to a depth of 35–40 cm	16.1	27.6	444.4	146.0	59
3	Non-inversion tillage with heavy cultivator (12–14 cm)	15.2	30.2	459.0	152.0	61
4	Non-inversion disk tillage to a depth of 12–14 cm	15.7	27.9	438.0	153.7	51

Table 4. Grain yield per cob and weight of 1000 grains depending on the methods of main tillage for corn, 2023–2024

№ п/п	Tillage method	Grain output, %	1000 Kernel weight, g
1	Plowing to a depth of 20–22 cm	83.8	281.1
2	Deep loosening to a depth of 35–40 cm	83.5	277.0
3	Non-inversion tillage with heavy cultivator (12–14 cm)	84.7	299.1
4	Non-inversion disk tillage to a depth of 12–14 cm	82.7	287.3

Table 5. Maize grain yield by tillage method (2023–2024)

№ п/п	Tillage method	Yield, t ha^{-1}	Difference from control
1	Plowing to a depth of 20–22 cm	7.98	-
2	Deep loosening to a depth of 35–40 cm	6.78	-1.20
3	Non-inversion tillage with heavy cultivator (12–14 cm)	6.66	-1.32
4	Non-inversion disk tillage to a depth of 12–14 cm	6.78	-1.20
LSD_{05}, t ha^{-1}		2.13	

Table 6. Energy assessment of the efficiency of growing corn for grain depending on the methods of main tillage, 2023–2024

Tillage method	Yield, t ha^{-1}	Energy Output, MJ ha^{-1}	Energy Input, MJ ha^{-1}	EEC*
Plowing to a depth of 20–22 cm	7.98	12079	29284	2.4
Deep loosening to a depth of 35–40 cm	6.78	10262	29288	2.9
Non-inversion tillage with heavy cultivator (12–14 cm)	6.66	10081	28132	2.8
Non-inversion disk tillage to a depth of 12–14 cm	6.78	10262	27911	2.7

Note: *Energy efficiency coefficient.

energy equivalent, making energy analysis a suitable and integrative approach for comparing and optimizing cultivation technologies.

Calculations of the energy efficiency of growing maize for grain using different methods of basic soil cultivation showed that the reduction in energy consumption compared to the control – plowing occurred when using disk cultivation to a depth of 12–14 cm – by 1374 MJ ha^{-1} and a heavy cultivator to the same depth – by 1152 MJ ha^{-1}. There was an increase in energy consumption during deep loosening to a depth of 35–40 cm by 4 MJ ha^{-1} compared to plowing.

The highest energy efficiency occurred in the variant of cultivation with a delta HT stand – deep loosening to a depth of 35–40 cm with a coefficient of 2.9.

The coefficient of energy efficiency was lower when plowing under corn – 2.4. As the energy intensity of the crop decreased during no-till tillage without crop rotation, it increased to 2.7–2.9 when growing maize.

CONCLUSIONS

Based on the results of our research, the following conclusions can be drawn:

The highest reserves of productive moisture in the arable soil layer at the time of maize sowing were recorded under plowing to a depth of 20–22 cm (18.4 mm), while the lowest values were observed under no-till disk cultivation (16.0 mm). By harvest time, soil moisture had decreased significantly, reaching critical levels: 0.6–1.2 mm in the arable horizon and 28.3–32.1 mm in the 1-meter soil layer.

At the maize emergence stage, the bulk density of the arable soil layer remained within optimal limits across all tillage methods: plowing: 1.13–1.22 g/cm^3, deep loosening: 1.16–1.26 g/cm^3, heavy cultivator (12–14 cm): 1.18–1.26 g/cm^3, disk tillage (12–14 cm): 1.17–1.25 g/cm^3.

In the 20–40 cm soil layer, bulk density tended to increase, especially under shallow no-till methods (1.24–1.29 g/cm^3), compared to plowing (1.22–1.26 g/cm^3). Overall, from emergence to harvest, soil compaction increased more under plowing than under no-till treatments.

The influence of tillage methods on maize yield components showed relatively small variations in kernel weight per cob (146.0–153.7 g) and thousand-kernel weight (277.0–299.1 g). However, the highest maize grain yield 7.98 t ha^{-1} was obtained under plowing to 20–22 cm. In contrast, deep loosening and shallow no-till methods (12–14 cm) resulted in a significant yield reduction of 1.20–1.32 t ha^{-1}.

The lowest energy efficiency ratio 2.4 was recorded under plowing. As energy input decreased under no-till methods without soil inversion, the energy efficiency ratio increased, reaching 2.7–2.9.

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