Balance of moisture reserves and methods of their efficient use in short crop rotations of the Steppe of Ukraine

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Abstract: Soil moisture availability is crucial for plant growth, directly influencing crop productivity. In the Northern Steppe of Ukraine, regardless of tillage systems, an unsaturated soil moisture class is formed, preventing full annual saturation of the 1.5-metre soil layer due to insufficient winter precipitation, lack of snow cover, and high wind activity. Precipitation moistens the soil only to 90–110 cm, creating a dry layer between stored winter moisture and deeper reserves at the wilting point. During spring-summer, plant roots struggle to reach deeper moisture, causing drought stress and yield loss. The highest spring moisture reserves in the 0–150 cm layer were observed under differentiated (chisel) and shallow mulch (disk) tillage, reaching 169.7 mm and 160.5 mm, exceeding ploughing by 17.9 mm (11.8%) and 8.7 mm (5.7%). Chisel tillage increased moisture accumulation by 91.0–179.0 m³/ha in winter due to better snow retention. Water consumption for yield formation was lowest under shallow mulch tillage (107.0–112.8 mm), highlighting its efficiency. Despite a slight yield reduction, it improved water use by 1.1–1.2 times. Fertilisation increased productivity by 5–13.6%, exceeding 14.0% under shallow mulch tillage, demonstrating its advantages in water-limited conditions.

Keywords: soil water balance, conservation tillage, crop productivity, water efficiency, precipitation use, drought resistance.

1. Introduction

Soil moisture is a crucial factor influencing plant growth, affecting both aboveground biomass and root system development. It determines soil mechanical resistance, which is essential for primary tillage operations. Adequate moisture availability is one of the most important conditions for plant survival, as crop productivity is directly proportional to water supply. When soil moisture levels are sufficient, favourable conditions for crop growth and development are established, ultimately leading to increased yields (Joshi & Mohanty, 2010; Cheng & Chen, 2018; Maan et al., 2023).

Soil water content regulates microbial activity, nutrient cycling, and organic matter decomposition. Moisture deficiency has always been a limiting factor in crop production. Managing the soil water regime is recognised as a key objective of modern agriculture, with tillage practices playing a central role (Paolini, 2018; Morugán-Coronado et al., 2019; Siebielec et al., 2020; Visconti-Moreno et al., 2024).

In the Northern Steppe of Ukraine, crop productivity largely depends on moisture reserves accumulated in the soil during the autumn-winter period (Romashchenko et al., 2025). Precipitation during the spring-summer season is insufficient to meet crop water demand and compensates for only 25–30% of total water consumption. The region's soils exhibit a non-leaching moisture regime, where atmospheric precipitation replenishes moisture without complete percolation (Mostipan et al., 2021; Shevchenko et al., 2023; Mytsyk et al., 2024; Shevchenko et al., 2025).

The highest soil moisture levels are observed in spring, with water infiltration exceeding 1.5 m in favourable years but significantly reduced in dry conditions. Summer precipitation is largely lost due to evaporation and runoff, with 33–50% of annual rainfall being non-productive (Filipović, 2021; Hapich et al., 2024). In years with unfrozen soil during winter, moisture accumulation in deeper layers depends primarily on precipitation levels and to a lesser extent on tillage depth and method. When frequent autumn rains saturate the topsoil before an early freeze, deeper tillage improves water retention, whereas shallow tillage may result in lower moisture storage. However, some studies suggest that deeper ploughing does not always increase moisture reserves (Skaalsveen et al., 2019; Cooper et al., 2020).

Research by Adugna (2019) indicates that compared to ploughing, subsurface tillage can enhance soil moisture retention in the top 1 m by 30–50 mm. Similarly, Bekele (2020) found no significant differences between mouldboard and subsurface tillage in terms of crop water supply and consumption. In the Northern Steppe of Ukraine, crops frequently experience moisture deficits and soil or atmospheric droughts, which disrupt physiological processes, impair metabolism, and reduce yields.

In response to drought, plants adapt by altering their physiological mechanisms to minimise water loss, which inevitably reduces productivity (Shevchenko et al., 2024).

Autumn rainfall and winter snowfall play a crucial role in replenishing soil moisture, whereas spring and summer precipitation contribute less effectively (Chen & Hu, 2004). Al-Shrafany et al. (2013) noted that in chernozem soils, moisture dynamics occur in two distinct phases: accumulation and depletion. Winter moisture infiltration is critical for plant growth, as deep percolation provides water reserves for subsequent dry periods (Hapich & Onopriienko, 2024). In contrast, summer rainfall is often limited to the upper soil layers, where it rapidly evaporates.

The primary objective of tillage operations during the autumn-winter period is to maximise soil moisture conservation through snow retention and erosion control measures. Agronomic practices such as tillage methods, fertilisation, and sowing strategies should aim to enhance moisture retention and optimise water use efficiency (Song et al., 2019; Chalise et al., 2020; Jaskulska et al., 2020).

According to experimental data, the amount of moisture accumulated in soil during the autumn-winter period varies depending on tillage system, weather conditions, surface residue retention, and agronomic techniques (Tsyliuryk, 2019). The objective of this study was to evaluate the impact of different primary tillage systems and mineral fertilisation, with residue retention, on the soil moisture regime, crop productivity, and economic efficiency of field crop cultivation in the Northern Steppe of Ukraine.

2. Materials and methods

The experimental research was conducted between 2010 and 2024 in accordance with standard field trial methodologies within long-term stationary experiments at the "Dnipro" State Enterprise of the Institute of Grain Crops of the National Academy of Agrarian Sciences of Ukraine (48°16'N, 34°56' E). The trials were arranged in a randomised complete block design with three replications. The total plot area was 330 m^2, with a harvestable plot size of 100 m^2.

The experimental design involved a five-field crop rotation: black fallow/fallow – winter wheat – sunflower – spring barley – maize for grain. In the crop rotation, the effectiveness of primary soil tillage techniques was studied, including mouldboard ploughing using a PO-3-35 plough to a depth of 20–22 cm for spring barley and sunflower, 23–25 cm for maize, and 25–27 cm for black fallow (autumn), chisel ploughing using a Canadian chisel cultivator Conser Till Plow to a depth of 23–25 cm for sunflower and spring barley (autumn), disc tillage using a BDV-3 disc harrow to a depth of 10–12 cm for spring barley and clean fallow (autumn) (Fig. 1.). The experiment was conducted under three fertilisation backgrounds: post-harvest residues (without mineral fertilisers), post-harvest residues + $N_{30}P_{30}K_{30}$, post-harvest residues + $N_{60}P_{30}K_{30}$. The crop cultivation technology in the stationary experiments was generally accepted for the Northern Steppe zone.

All shredded leaf-stem biomass of the predecessors was left in the field without removal and incorporated using the aforementioned implements under a background without fertilisers and with the application of mineral fertilisers along with plant residues. The experimental scheme included three fertilisation backgrounds: without fertilisers + plant residues, $N_{30}P_{30}K_{30}$ + plant residues, $N_{60}P_{30}K_{30}$ + plant residues. Mineral fertilisers were applied in spring by broadcasting before pre-sowing cultivation.

Mouldboard ploughing   Chisel ploughing   Disc tillage

Figure 1. General view of experimental plots with different methods of primary soil tillage in the autumn period

The crop varieties used were: winter wheat (Lytanivka), maize (Bilozyrskyi 295 SV hybrid), sunflower (Yason hybrid), and spring barley (Ilot variety). Herbicides were applied at the tillering stage for winter wheat (Esteron, 1.2 l/ha) and spring barley (0.8 l/ha), and pre-emergence herbicide Harness (2.5 l/ha) was used for maize and sunflower. Fertilisers ($N_{30}P_{30}K_{30}$) were applied in autumn before winter wheat sowing, with an additional N_{30} top-dressing in the stem elongation stage. For maize, sunflower, and spring barley, fertilisers ($N_{30}P_{30}K_{30}$, $N_{60}P_{30}K_{30}$) were applied before pre-sowing cultivation.

The two-factor stationary experiment was established using a split-plot design with three replications. The plot sizes were: first-order plots: 1500 m²; second-order plots: 375 m²; harvestable plots: 30–100 m².

The soil type was chernozem ordinary heavy loamy, with the following characteristics in the plough layer: humus content: 4.2%; nitrate nitrogen: 13.2 mg/kg; available phosphorus and potassium (Chirikov method): 145 mg/kg and 115 mg/kg, respectively.

Soil profile description:

Horizon H (0–44 cm): Dark grey, loose; 0–30 cm – plough layer, granular-pale; 30–44 cm – compacted subsoil, weakly structured, with mole activity. Gradual transition.

Horizon HR_1 (44–65 cm): Dark grey with a brownish tint, granular, slightly compacted. Gradual transition.

Horizon HR_2 (65–86 cm): Darker grey-brown, uneven colour, with mole burrows and carbonate specks, weakly compacted. Gradual transition.

Horizon HR_3 (86–110 cm): Dark brown, highly heterogeneous in colour and composition, weakly expressed granular structure. Gradual transition.

Horizon RN_k (110–125 cm): Lighter brown, mixed, carbonate streaks. Gradual transition.

Horizon R_k (125–152 cm): Brownish-pale, heterogeneous, with carbonate deposits. Gradual transition.

Horizon Rk (below 152 cm): Pale carbonate loess with mole activity.

Soil effervescence from 10% hydrochloric acid began at a depth of 30 cm. The profile image of the soil cross-section is shown in Figure 2.

Figure 2. Soil profile of chernozem ordinary heavy loamy.

Meteorological conditions were generally favourable for crop production, except for 2012, when extreme drought conditions occurred. The hydrothermal coefficient (HTC) during peak crop water demand (June – early July) dropped to 0.6. An HTC below 0.7 indicates soil-air drought, negatively impacting crop yield formation. Soil moisture was assessed in a 1.5 m profile using the gravimetric method. Samples were collected every 10 cm at three locations per plot and in two non-adjacent replications. Sampling was performed: in spring (before sowing of spring crops); at key phenological stages: heading, flowering, and tasselling; in autumn (before winter wheat sowing and at the end of the growing season).

Total water consumption was determined using the water balance method. The gravimetric method remains one of the most precise techniques for soil moisture determination, based on weight loss after drying at 105±2°C to a constant mass. This method is widely used for soil water regime studies, sensor calibration, and soil moisture reserve assessments.

Harvesting was conducted separately for each plot using: winter wheat, spring barley, and peas: SAMPO-500 combine harvester; sunflower: Niva-Effekt harvester; maize: manually harvested, considering grain moisture and contamination (Rasheed et al., 2022). Data analysis was performed using StatSoft Statistica 12.0 software and tabulated as x ± standard deviation;

differences between values in control and experimental variants were determined using Tukey's test where differences are considered significant at $p < 0.05$ (with Bonferroni correction). Evaluation of crop rotation productivity productivity was assessed based on: grain yield per hectare; total forage units, grain units, and digestible protein per hectare of crop rotation area. Forage, grain units, and digestible protein were calculated by multiplying yield by standard conversion coefficients (Darguza & Gaile, 2023).

3. Results and discussion

During the study of primary soil tillage before sowing spring barley from 2010 to 2024, the reserves of productive moisture in the 0–150 cm layer were as follows: under mouldboard ploughing – 151.8 mm, chisel ploughing – 160.5 mm, and disc tillage – 160.5 mm. The advantage in increasing moisture accumulation during the autumn-winter period was observed under chisel and disc tillage compared to mouldboard ploughing by 17.9 mm and 8.7 mm, respectively, which can be explained by the presence of plant residues on these agrobackgrounds that contributed to additional snow retention, leading to increased moisture accumulation, especially during warm low-snow winters, which have almost annually occurred in the Steppe zone of Ukraine in recent decades due to global climate warming. Subsequently, the soil water regime changed depending on the surface condition, plant growth and development rates on different agrobackgrounds, and hydrothermal conditions (Table 1).

Table 1. Effect of primary soil tillage methods and fertilisation on productive moisture reserves under spring barley in the 0–150 cm layer, mm (average for 2010–2024, x ± SD, n = 8).

Primary soil tillage method and depth	Spring barley growth stage		
	sowing	**heading**	**harvesting**
without fertilisers			
Mouldboard ploughing	151.8 ± 7.1^{a}	36.6 ± 3.8^{a}	40.7 ± 4.1^{a}
Chisel ploughing	169.7 ± 7.3^{c}	74.6 ± 4.6^{c}	45.9 ± 4.2^{b}
Disc tillage	160.5 ± 7.2^{b}	57.3 ± 4.3^{b}	53.5 ± 4.3^{c}
$N_{30}P_{30}K_{30}$			
Mouldboard ploughing	151.8 ± 7.1^{a}	27.9 ± 3.4^{a}	38.8 ± 3.8^{a}
Chisel ploughing	169.7 ± 7.3^{c}	31.3 ± 3.6^{b}	44.6 ± 4.1^{b}
Disc tillage	160.5 ± 7.2^{b}	44.9 ± 3.8^{c}	52.4 ± 4.3^{c}
$N_{60}P_{30}K_{30}$			
Mouldboard ploughing	151.8 ± 7.1^{a}	18.3 ± 2.9^{a}	33.6 ± 3.8^{a}
Chisel ploughing	169.7 ± 7.3^{c}	24.4 ± 3.2^{b}	48.4 ± 4.2^{b}
Disc tillage	160.5 ± 7.2^{b}	37.1 ± 3.6^{c}	47.7 ± 4.1^{c}

Note: Different letters indicate values that significantly differ within columns of Table 1, as determined by Tukey's test ($P < 0.05$) with Bonferroni correction.

During the growing season of the grain-forage crop, soil moisture reserves gradually decreased compared to the initial spring measurement, and by the heading phase, they amounted to 18.3–36.6 mm under mouldboard ploughing, 24.4–74.6 mm under chisel ploughing, and 37.1–57.3 mm under disc tillage, depending on the plant nutrition levels. Fertilised plants, unlike unfertilised ones, developed a more robust vegetative mass and naturally consumed more moisture to maintain turgor. Water consumption increased in the following order: natural background – $N_{30}P_{30}K_{30}$ – $N_{60}P_{30}K_{30}$. During the tillering–heading phases, characterised by a lack of precipitation, there was a rapid accumulation of vegetative mass and intensive water use by barley plants, as evidenced by the low residual moisture reserves. According to crop stand conditions and the prerequisites for grain yield formation, the highest soil moisture losses were recorded under chisel ploughing – 121.3–123.8 mm and mouldboard ploughing – 111.8–118.2 mm, while the lowest were under disc tillage – 107.0–112.8 mm (Table 2).

From the heading phase to harvest, rainfall replenished soil moisture reserves to 33.6–53.5 mm in the 1.5-metre layer. A direct correlation was noted between the residual moisture level at heading and the amount of precipitation absorbed. Water evaporation during this period was primarily regulated by the degree of ground cover by the crop canopy, with clear signs of process inhibition in denser stands. Regarding the absolute moisture content in the soil, the trends observed across tillage variants remained consistent with those recorded at the heading phase of barley plants.

Table 2. Total water consumption by spring barley after a row crop predecessor under different soil tillage systems in the 0–150 cm layer (average for 2010–2024, x ± SD, n = 8).

Primary soil tillage method	Sowing, mm	Harvesting, mm	Soil moisture used, mm	Precipitation during vegetation, mm	Total water consumption, mm/ha	Water consumption coefficient, mm/t
without fertilisers + crop residues						
Mouldboard ploughing	151.8±7.1[a]	40.7±4.1[a]	111.8±6.1[ab]	152.9	264.7±9.1[ab]	105.2±5.1[b]
Chisel ploughing	169.7±7.3[c]	45.9±4.2[b]	123.8±6.4[c]		276.7±9.3[c]	103.7±5.1[b]
Disc tillage	160.5±7.2[b]	53.5±4.3[c]	107.0±6.0[a]		259.9±9.0[a]	89.7±4.9[a]
$N_{30}P_{30}K_{30}$ + crop residues						
Mouldboard ploughing	151.8±7.1[a]	38.8±3.8[a]	113.0±6.0[b]	152.9	265.9±9.2[b]	112.6±5.2[c]
Chisel ploughing	169.7±7.3[c]	44.6±4.1[b]	125.1±6.4[c]		278.0±9.2[c]	106.0±5.1[b]
Disc tillage	160.5±7.2[b]	52.4±4.3[c]	108.1±5.8[a]		261.0±9.1[a]	90.7±5.0[a]
$N_{60}P_{30}K_{30}$ + crop residues						
Mouldboard ploughing	151.8±7.1[a]	33.6±3.8[a]	118.2±5.9[b]	152.9	271.1±9.0[bc]	132.3±5.8[d]
Chisel ploughing	169.7±7.3[c]	48.4±4.2[b]	121.3±6.4[bc]		274.2±9.2[c]	116.7±5.2[c]
Disc tillage	160.5±7.2[b]	47.7±4.1[c]	112.8±5.8[ab]		265.7±9.2[b]	99.2±5.0[a]

Note: Different letters indicate values that significantly differ within columns of Table 2, as determined by Tukey's test ($P < 0.05$) with Bonferroni correction.

The total water consumption of spring barley plants correlated with the indicators of soil moisture use and increased by the amount of precipitation (152.9 mm) during the growing season. The lowest water consumption per unit of yield was observed under the shallow mulching tillage system (disking), where the water consumption coefficient was the lowest at only 89.7–99.2 mm/t, despite the lowest grain yield of 2.24–2.89 t/ha. The use of mouldboard and differentiated tillage systems, although contributing to an increase in yield up to 2.60–3.14 t/ha, led to an increase in water consumption per unit of yield by 1.1–1.3 times.

The study of the soil water regime under sunflower in a five-field grain-fallow-row crop rotation during 2010–2024 revealed a tendency for cold-season precipitation accumulation in plots with differentiated (non-mouldboard tillage) and shallow mulching (chisel tillage) soil tillage systems (177.2–179.5 mm compared to 170.4 mm under mouldboard tillage in the 0–150 cm layer). During the flowering phase of the oil crop, a reverse dependence was observed, meaning that higher water consumption was typical for variants with higher initial (spring) soil moisture reserves, as well as for fertilised plants, which developed a more vigorous vegetative mass (Table 3).

Table 3. Total water consumption by sunflower in a five-field crop rotation under different soil tillage systems in the 0–150 cm layer (average for 2010–2024, x ± SD, n = 8).

Primary soil tillage method	Sowing, mm	Harvesting, mm	Soil moisture used, mm	Precipitation during vegetation, mm	Total water consumption, mm/ha	Water consumption coefficient, mm/t
without fertilisers + crop residues						
Mouldboard ploughing	170.4±7.7[a]	3.6±1.1[ab]	166.8±7.2[b]	194.7	361.5±10.1[ab]	151.9±7.0[bc]
Chisel ploughing	177.2±7.8[b]	15.3±1.8[c]	161.9±7.0[a]		356.6±10.0[a]	139.9±7.0[ab]
Disc tillage	179.5±7.8[b]	16.0±1.8[c]	163.5±7.1[a]		358.2±10.0[a]	134.7±7.0[a]
$N_{30}P_{30}K_{30}$ + crop residues						
Mouldboard ploughing	170.4±7.7[a]	3.0±1.0[ab]	167.4±7.2[b]	194.7	361.8±10.1[ab]	161.5±7.0[c]
Chisel ploughing	177.2±7.8[b]	3.8±1.1[ab]	173.4±7.6[c]		368.1±10.2[b]	144.9±7.0[b]
Disc tillage	179.5±7.8[b]	5.5±1.3[b]	174.0±7.6[c]		368.7±10.2[b]	137.6±7.0[a]
$N_{60}P_{30}K_{30}$ + crop residues						
Mouldboard ploughing	170.4±7.7[a]	1.9±0.5[a]	168.5±7.2[b]	194.7	363.2±10.1[ab]	157.3±7.0[c]
Chisel ploughing	177.2±7.8[b]	2.3±1.0[a]	174.9±7.5[c]		369.6±10.2[b]	141.3±7.0[b]
Disc tillage	179.5±7.8[b]	3.8±1.1[ab]	171.2±7.4[c]		365.9±10.2[b]	135.0±7.0[a]

Note: Different letters indicate values that significantly differ within columns of Table 3, as determined by Tukey's test ($P < 0.05$) with Bonferroni correction.

Sunflower crops, from sowing to full seed maturity, almost completely utilized the available soil moisture reserves, especially under fertilization. This is primarily explained by the biological characteristics of the plants (a powerful root system, a large leaf surface area, and a long growing season) and the complex hydrothermal conditions (drought in August), which led to unproductive evaporation of water from the soil surface. The amount of moisture used from the soil during the growing season mostly varied according to the productivity levels of the oilseed crop. The highest values (163.5–174.0 mm) were recorded under shallow mulching and differentiated (ploughless) tillage systems due to the use of post-harvest residues and the application of $N_{60}P_{30}K_{30}$. The lowest values (166.8–168.5 mm) were observed in mouldboard tillage plots, especially without mineral fertilizers. Sunflower's water consumption coefficient decreased by 1.1–1.2 times with the use of a shallow mulching tillage system compared to mouldboard tillage, indicating a more economical water use by plants in variants covered with post-harvest residues of the predecessor. These residues reduced physical water evaporation from the soil surface and contributed to the efficient utilization of water for physiological processes. The differentiated (ploughless) tillage system was almost as effective as mulching in terms of rational water use, allowing sunflower plants to reduce the water consumption coefficient by 12.0–16.6 mm/t and use soil moisture more efficiently. Before sowing maize for grain after spring barley, the average productive moisture accumulation for 2010–2024 was practically the same: 172.7–173.7 mm under deep ploughing and 173.7 mm under shallow ploughless tillage. This is explained by the relatively low total amount of post-harvest residues of the predecessor (spring barley) – 1.9–2.7 t/ha (Table 4).

Table 4. Total water consumption by maize under different soil tillage systems and fertilisation in the 0–150 cm layer (average for 2010–2024, x ± SD, n = 8).

Primary soil tillage method	Sowing, mm	Harvesting, mm	Soil moisture used, mm	Precipitation during vegetation, mm	Total water consumption, mm/ha	Water consumption coefficient, mm/t
without fertilisers + crop residues						
Mouldboard ploughing	175.4 ± 7.4^{b}	44.3 ± 4.4^{bc}	131.1 ± 6.1^{b}	194.7	325.8 ± 9.5^{b}	65.1 ± 4.5^{b}
Chisel ploughing	172.7 ± 7.3^{a}	48.0 ± 4.5^{c}	124.7 ± 6.0^{a}		319.4 ± 9.4^{a}	58.7 ± 4.3^{ab}
Disc tillage	173.7 ± 7.3^{a}	49.1 ± 4.5^{c}	124.6 ± 6.0^{a}		319.3 ± 9.4^{a}	55.8 ± 4.2^{a}
$N_{30}P_{30}K_{30}$ + crop residues						
Mouldboard ploughing	175.4 ± 7.4^{b}	27.1 ± 3.6^{b}	148.3 ± 6.3^{d}	194.7	343.0 ± 9.6^{d}	69.5 ± 4.6^{bc}
Chisel ploughing	172.7 ± 7.3^{a}	32.8 ± 3.8^{b}	139.9 ± 6.1^{c}		334.6 ± 9.5^{c}	62.6 ± 4.5^{b}
Disc tillage	173.7 ± 7.3^{a}	42.2 ± 4.3^{bc}	131.5 ± 6.1^{b}		326.2 ± 9.5^{b}	57.9 ± 4.3^{ab}
$N_{60}P_{30}K_{30}$ + crop residues						
Mouldboard ploughing	175.4 ± 7.4^{b}	22.2 ± 3.5^{a}	153.2 ± 6.4^{e}	194.7	347.9 ± 9.6^{e}	72.1 ± 4.6^{c}
Chisel ploughing	172.7 ± 7.3^{a}	27.4 ± 3.6^{b}	145.3 ± 6.3^{d}		340.0 ± 9.6^{d}	64.9 ± 4.5^{b}
Disc tillage	173.7 ± 7.3^{a}	31.6 ± 3.8^{b}	142.1 ± 6.3^{d}		336.8 ± 9.5^{c}	60.3 ± 4.4^{b}

Note: Different letters indicate values that significantly differ within columns of Table 4, as determined by Tukey's test ($P < 0.05$) with Bonferroni correction.

The increased cumulative and moisture-retaining capacity of the stubble agroecosystem under shallow tillage was observed in 2011 and 2013. This was attributed to the reduced evaporation surface area due to the presence of a protective cover and the preservation of the "drainage" system formed after the death of the roots of the previous crop. The ploughing system only had an advantage in moisture accumulation in 2012, when there was an absence of a proper stubble cover from post-harvest residues.

During the growing season of the cereal crop, up to the flowering phase, the plants utilised nearly 70% of the soil moisture reserves, which was linked to the lower grain yield under mulching conditions. The residual moisture reserves at the full grain maturity phase were minimal, with differences primarily observed between fertilisation treatments rather than soil tillage methods (ranging from 44.3–49.1 mm in plots without mineral fertilisers to 22.2–31.6 mm with $N_{60}P_{30}K_{30}$ fertilisation) – see Table 5. Inversely, the amounts of utilised soil moisture varied over the maize growing period: 1311.0–1246.0 m³/ha (no fertiliser), 1315.0–1483.0 m³/ha ($N_{30}P_{30}K_{30}$), and 1421.0–1532.0 m³/ha ($N_{60}P_{30}K_{30}$).

The water consumption coefficient during maize cultivation was also 1.1–1.2 times higher under ploughing and differentiated tillage systems compared to the mulching system. The use of shallow mulching tillage contributed to more economical moisture use, with a reduction of 9.3–11.8 mm/t.

In the five-field grain-fallow-crop rotation, soil moisture reserves before sowing field crops were 7.1–8.5 mm higher under shallow mulching and differentiated tillage systems compared to ploughing, which was explained by the presence of mulch in the rotation fields, protecting the soil surface from physical evaporation (Table 5).

Table 5. Moisture balance in the short-rotation five-field crop rotation under different soil tillage systems (average for 2010–2024).

Crop rotation sequence (factor A)	Primary soil tillage method (factor B)	Moisture reserve in the 0–150 cm layer, mm		Moisture used from the soil during the growing period, evaporation, mm	Precipitation during the growing season, mm	Total moisture expenditure during the growing period, mm	Water consumption coefficient, mm/t
		before sowing crops and the resumption of winter wheat vegetation	during harvesting, sowing of winter wheat				
Grain-fallow-cultivated crop rotation							
Black fallow/fallow	Mouldboard ploughing	151.4	151.8	0.4	211.0	210.4	-
	Chisel ploughing	166.4	158.4	8.0		219.0	-
	Disc tillage	175.3	165.8	6.8		217.8	-
Winter wheat	Mouldboard ploughing	208.4	58.1	150.3	196.3	346.6	71.4
	Chisel ploughing	207.1	53.7	153.4		349.7	69.7
	Disc tillage	211.1	61.9	149.2		345.5	71.4
Sunflower	Mouldboard ploughing	170.4	1.9	168.5	194.7	363.2	157.3
	Chisel ploughing	177.2	2.3	174.9		369.6	141.3
	Disc tillage	179.5	3.8	171.2		365.9	135.0
Spring barley	Mouldboard	151.8	33.6	118.2	152.9	271.1	132.3

	ploughing						
	Chisel ploughing	169.7	48.4	121.3		274.2	116.7
	Disc tillage	160.5	47.7	112.8		265.7	99.2
Corn	Mouldboard ploughing	175.4	22.2	153.2	194.7	347.9	72.1
	Chisel ploughing	172.7	27.4	145.3		340.0	64.9
	Disc tillage	173.7	31.6	142.1		336.8	60.3
Average	Mouldboard ploughing	171.5	53.5	118.0	189.9	307.9	86.6
	Chisel ploughing	178.6	58.0	120.6		310.5	78.5
	Disc tillage	180.0	62.2	116.4		306.3	73.2
Least significant difference (LSD) ($p = 0.05$)							
for factor A		6.2	3.8	4.2	7.2	8.0	2.4
for factor B		6.5	4.2	4.4	7.3	8.3	2.9
for interaction AB		7.1	4.8	4.8	7.8	8.7	3.2

The analysed data substantiate that, irrespective of the tillage methods and systems employed throughout the research period, the prevailing non-leaching water regime, characteristic of the steppe zone, resulted in discontinuous infiltration of moisture into the 1.5-metre soil profile. This phenomenon was particularly evident during arid years, marked by a substantial shortfall in the normative precipitation sum during December–February, the complete absence of snow cover, and intensified wind activity, which further exacerbated moisture loss. Under these conditions, precipitation during drought-prone years moistened the soil only to a depth of 90–110 cm, reaching the level of field capacity (FC). Consequently, a distinct separation layer was established between the moisture accumulated during the cold season and the deeper soil layers, where moisture remained at the permanent wilting point (PWP).

This stratification significantly influenced plant water availability during the spring-summer growing season, as root systems, upon encountering the dry layer at the PWP threshold, were largely incapable of penetrating further to access deeper reserves of moisture. As a result, crops experienced pronounced drought stress, particularly in the absence of rainfall events during critical vegetative stages, which ultimately led to a notable reduction in yield potential and overall crop performance (Shevchenko et al., 2024).

The productivity of the five-field grain-fallow-row crop rotation was predominantly influenced by the application of mineral fertilisers rather than tillage techniques. The primary tillage systems implemented on fertilised plots, in conjunction with crop residues, exhibited statistically comparable outcomes across key productivity parameters, including grain yield (2.81–2.91 t/ha), grain units (3.60–3.65 t/ha), fodder units (3.93–4.00 t/ha), and digestible protein (0.42–0.45 t/ha) per hectare of crop rotation area. However, a marginally declining trend was observed under the shallow mulch tillage system, suggesting a potential limitation in nutrient accessibility within this framework. In contrast, in the variant where no mineral fertilisers were applied but crop residues were retained, the mouldboard and differentiated tillage systems demonstrated superior productivity across all measured indicators. This superiority can be attributed to a more favourable nutrient regime, which enhanced crop nutrient uptake and biomass accumulation (Tsyliuryk, 2019). Specifically, under the mouldboard tillage system, grain yield was elevated by 0.20 t/ha (7.6%), grain units by 0.18 (5.5%), fodder units by 0.22 (6.2%), and digestible protein by 0.03 t/ha (7.5%) compared to the shallow mulch tillage system (Table 6). These results highlight the role of tillage in modulating soil fertility dynamics and plant nutrient acquisition in systems devoid of exogenous mineral inputs (Mytsyk et al., 2024).

Table 6. Influence of main soil cultivation systems and fertilisation on the productivity of short-rotation grain-fallow-cultivated crop rotation, t/ha (average for 2010–2024).

Crop rotation sequence	**Soil cultivation and fertilisation system**								
	mouldboard ploughing			**chisel ploughing**			**disc tillage**		
	plant residues	plant residues + $N_{24}P_{18}K_{18}$	plant residues + $N_{48}P_{18}K_{18}$	plant residues	plant residues + $N_{24}P_{18}K_{18}$	plant residues + $N_{48}P_{18}K_{18}$	plant residues	plant residues + $N_{24}P_{18}K_{18}$	plant residues + $N_{48}P_{18}K_{18}$
Black fallow	-	-	-	-	-	-	-	-	-
Winter wheat	5.02	5.15	5.22	5.02	5.39	5.50	4.80	5.03	5.32
Sunflower	2.41	2.57	2.67	2.28	2.57	2.71	2.34	2.61	2.74
Spring barley	2.79	2.94	3.14	2.60	2.88	3.11	2.24	2.57	2.89
Corn	5.32	5.76	6.03	5.24	5.65	5.92	5.13	5.54	5.85
Yield (t) per 1 ha of the crop rotation area									
Total grain:	2.63	2.77	2.88	2.57	2.78	2.91	2.43	2.63	2.81
Winter wheat	1.01	1.03	1.05	1.01	1.08	1.10	0.97	1.01	1.07
Fodder grain	1.62	1.74	1.84	1.53	1.71	1.81	1.48	1.62	1.75
Total grain	4.37	4.61	4.79	4.28	4.64	4.84	4.05	4.38	4.68
Fodder units	3.58	3.81	3.99	2.88	3.80	4.00	3.36	3.66	3.93
Digestible protein	0.41	0.43	0.45	0.39	0.43	0.45	0.38	0.42	0.45
Grain units	3.27	3.48	3.63	3.16	3.47	3.65	3.09	3.38	3.60
Least significant difference (LSD), t/ha ($p = 0.05$)									
For factor A									0.11
For factor B									0.13
For interaction AB									0.16

The integration of mineral fertilisers at moderate application rates ($N_{24}P_{18}K_{18}$ and $N_{48}P_{18}K_{18}$ per hectare of crop rotation area) in combination with crop residues significantly enhanced the overall productivity of the crop rotation. The maximum recorded increase in grain yield associated with the application of $N_{48}P_{18}K_{18}$ under the mouldboard tillage system was 0.25 t/ha (8.7%), with corresponding increments in grain units (0.36 t/ha, 9.9%), fodder units (0.41 t/ha, 10.3%), and digestible protein (0.02 t/ha, 5.0%). A more pronounced productivity enhancement was observed under the differentiated tillage system with $N_{48}P_{18}K_{18}$, where grain yield increased by 0.34 t/ha (12.2%), grain units by 0.49 t/ha (13.5%), fodder units by 1.12 t/ha (28.0%), and digestible protein by 0.06 t/ha (13.6%). The most substantial productivity gains were recorded under the shallow (mulch) tillage system when supplemented with $N_{48}P_{18}K_{18}$, leading to an increase in grain yield of

0.38 t/ha (13.6%), grain units by 0.51 t/ha (14.2%), fodder units by 0.57 t/ha (14.5%), and digestible protein by 0.07 t/ha (15.9%). These findings suggest that the effectiveness of mineral fertilisation is closely linked to the specific tillage system employed, with nutrient availability and retention varying depending on soil disturbance intensity and residue incorporation strategies (Cherenkov et al., 2021).

According to the results of this investigation, the highest relative increases in productivity due to mineral fertiliser application were observed under the shallow (mulch) tillage system. This system, which is characterised by a more constrained nutrient regime and reduced soil disturbance, demonstrated the greatest response to fertiliser inputs. Under these conditions, the application of mineral fertilisers at moderate rates led to a productivity increase exceeding 14.0% compared to the mouldboard tillage system, which inherently offered more favourable baseline nutrient conditions. These results underscore the importance of optimising fertilisation strategies within different tillage frameworks to maximise crop performance, particularly under water-limited conditions characteristic of the steppe zone. The findings further reinforce the necessity for adaptive soil management approaches that integrate tillage and fertilisation in a manner that enhances soil moisture retention, nutrient availability, and overall agroecosystem resilience in semi-arid environments Shevchenko et al., 2024).

To practically increase soil moisture accumulation and retention under the warming, drier, and more variable conditions projected for Ukraine's Steppe, management should prioritise residue-retaining, reduced-disturbance tillage (chisel/shallow mulch) that enhances infiltration during high-intensity cool-season events and curbs non-productive evaporation in spring-summer; these effects are consistently reported across climates and soil types (Bescansa et al., 2006; Humphreys et al., 2021; Ranaivoson et al., 2017). Pairing residue cover with moderate, well-timed fertilisation helps avoid excessive early vegetative water use while maintaining yield formation, thereby lowering the water-use coefficient relative to mouldboard systems – aligning with our multi-crop results. Given the documented rise in drought frequency/severity over Europe and long-term drying signals in Ukraine (Spinoni et al., 2015; Spinoni et al., 2018; Semenova & Vicente-Serrano, 2024), including recent attribution of extreme drought to anthropogenic warming (Bevacqua et al., 2024a) and basin-scale reductions in water availability (Didovets et al., 2020), residue-based conservation tillage constitutes a robust near-term adaptation pathway to stabilise field-scale moisture balances and buffer yield risks.

In the near term, continued warming in Eastern Europe is projected to intensify hot and dry extremes, shorten winters and snow cover duration, increase evaporative demand, and shift precipitation towards heavier, less frequent events in the cool season. For the Steppe zone of Ukraine this implies lower efficiency of cold-season moisture storage due to reduced snowpack and more rainfall-runoff episodes, earlier spring soil drying and higher atmospheric demand around stem elongation-heading, and greater intra-season variability with compound hot-dry spells during grain filling. Under these conditions, the moisture advantages we observed under residue-retaining systems (chisel, shallow mulch) are likely to become more pronounced because surface cover reduces non-productive evaporation, improves infiltration during high-intensity rains, and captures limited snow in low-snow winters. Conversely, mouldboard ploughing – by exposing bare soil – will tend to raise the water-use coefficient and deepen moisture deficits in critical stages. Therefore, adaptation pathways that combine residue retention and reduced/disturbance-minimising tillage with moderate, well-timed fertilisation, wind-erosion protection, and (where feasible) supplemental water harvesting/deficit irrigation could stabilise the seasonal moisture balance and buffer yield risks under progressive aridisation. These inferences are consistent with regional assessments indicating increased aridity and higher potential evapotranspiration across Europe and Ukraine under 1.5–2 °C warming scenarios (Bevacqua, et al. 2024b; Semenova & Vicente-Serrano, 2024).

4. Conclusions

The highest reserves of productive moisture in the spring in the 0–150 cm layer were observed under the differentiated (chisel) and shallow mulch (disk) soil cultivation systems – 169.7 mm and 160.5 mm, respectively. These values exceeded the ploughing system by 17.9 mm (11.8%) and 8.7 mm (5.7%). The use of conservation tillage (chisel) in the differentiated system increases moisture accumulation by 91.0–179.0 m³/ha during the autumn-winter period due to plant residues, which trap more snow, especially in mild, low-snow winters.

In the heading phase, soil moisture reserves decreased significantly: for the ploughing system – to 18.3–36.6 mm, for the chisel ploughing – 24.4–74.6 mm, and for the shallow mulch system – 37.1–57.3 mm. The highest moisture levels were retained in the soil under chisel and disc cultivation, which promoted better plant development.

Overall moisture consumption for crop formation was lowest under the shallow mulch tillage (107.0–112.8 mm), while for the chisel ploughing and ploughing, this figure reached 121.3–125.1 mm and 111.8–118.2 mm, respectively, indicating more efficient moisture use under the mulch tillage system. The application of the shallow mulch tillage system, despite the reduced grain yield, leads to more economical moisture use per unit of yield, being 1.1–1.2 times more efficient in the cultivation of field crops.

The use of different soil cultivation systems (ploughing, chisel ploughing, shallow (mulch)) in the five-field crop rotation results in equivalent productivity indicators, except for the variants without mineral fertilisers, where the shallow (mulch) system is inferior to the chisel ploughing and ploughing systems by 5.5–7.6%. The use of mineral fertilisers in moderate doses significantly increases the productivity indicators of crop rotations by 5–13.6%, especially under the shallow (mulch) cultivation system, which has more stringent initial mineral nutrition conditions for plants, where yields increase and exceed 14.0%.

Given the aridisation of the climatic conditions in the steppe regions of Ukraine, further research in this direction should continue, specifically in determining the dynamics of soil moisture balance, increasing moisture accumulation, and retention in the soil to optimise the water balance and increase crop yields.

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