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Dynamics of productive moisture reserves, and water consumption use in short-rotation grain-sugar beet crop rotations in the forest-steppe depending on the fertilization system and soil potential fertility

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ABSTRACT

The research is based on a database of meteorological observations conducted by the Bila Tserkva research and breeding station, where the balance of productive moisture in short-rotation grain-sugar beet crop rotations is studied depending on the vegetation period, plant usage according to crop rotation characteristics, fertilization systems, and climatic conditions. It was found that crop rotation plants used productive moisture reserves unevenly across soil layers, which is associated with crop characteristics (root system development), vegetation period duration, and precipitation deficiency. The greatest decrease in productive moisture reserves was observed in the 50–100 cm soil layer for sugar beets, spring barley, and spring vetch, while winter wheat mainly utilized moisture from the 0–20 cm layer, sunflower, soybean, and clover for green fodder consumed moisture from the entire soil profile. The highest total water consumption was recorded in sugar beet fields with the application of $N_{100}P_{90}K_{90}$ (3980–4096 m³ ha⁻¹), 40 t ha⁻¹ of manure + $N_{100}P_{90}K_{90}$ (4147–4330 m³ ha⁻¹), and in winter wheat fields with $N_{90}P_{60}K_{60}$ (4600–5130 m³ ha⁻¹), regardless of crop rotation links. Under these conditions, the water consumption coefficient (WUE) for sugar beet crops remained at 67–86 m³ t⁻¹, while in winter wheat crops, it increased to 253–317 m³ t⁻¹. In cereal-fodder-tilled crop rotation, moisture was used most efficiently in clover fields due to its well-developed root system, with a WUE of 81–91 m³ t⁻¹ when applying $N_{40}P_{40}K_{40}$. In tilled crop rotation, sunflower with $N_{90}P_{60}K_{60}$ and soybean with $N_{40}P_{40}K_{40}$ had the highest WUE of 362–416 and 336–375 m³ t⁻¹, respectively, while spring vetch with $N_{40}P_{40}K_{40}$ showed 777–784 m³ t⁻¹.

Keywords: *Beta vulgaris*, *Hordeum vulgare*, winter wheat, soybean, sunflower, clover, vetch spring, soil water content, yield, weather conditions, water use efficiency.

INTRODUCTION

Under the conditions of unstable moisture supply in the forest-steppe of Ukraine, the most significant negative impact on crop yield formation is caused by insufficient precipitation during the plant vegetation period and rising air and soil temperatures. An important and relevant issue, not only in the context of modern agricultural development but also in the framework of global climate change, is the study of the accumulation of productive moisture in the soil, considering the climatic conditions of the region, the biological characteristics of crops, and their water consumption. This research will help determine rational methods for utilizing soil moisture and precipitation during crop cultivation [Steduto et al., 2012].

The soil water balance accounts for the stochastic characteristics of precipitation, as well as water balance components that interact with transpiration, runoff, and infiltration. This approach provides a probability distribution of soil saturation during the vegetation period, allowing for an assessment of the long-term average water uptake by plants and its utilization efficiency [Bassiouni et al., 2023].

This is particularly relevant in arid and semi-arid ecosystems, where the heterogeneity and deficit of precipitation prevent soil moisture from penetrating deeper than 10 cm, thereby reducing water movement to lower soil layers [Zhang et al., 2022; Ran et al., 2025]. Precipitation characteristics, such as amount, frequency, and intensity, as well as soil properties, are key factors influencing the spatio-temporal heterogeneity of soil moisture [Li et al., 2020]. A direct relationship has been identified between moisture reserves in the 0–50 cm layer and the increase in average daily air temperature during the autumn-winter period [Rucins et al., 2024].

The reserves of productive moisture in the soil at the time of crop sowing depend on the influence of preceding and pre-preceding crops, soil-climatic conditions, the amount and distribution of precipitation during the vegetation period, soil water properties, and initial moisture reserves. Sugar beet crops utilize water more efficiently than other rotation crops due to their deep root system, which develops intensively and reaches depths of over 2.5 m, allowing them to access groundwater [Gong et al., 2023]. Under drought conditions, sugar beets develop their root system in deeper soil layers where moisture is available [Bodner and Alsalem, 2023; Fitters et al., 2018; Wolfgang et al., 2023]. At the same time, the peak water consumption of sugar beet crops occurs at the end of July and the beginning of august, when the moisture content in the upper soil layer is at its minimum [Bastaubayeva et al., 2022]. Research findings indicate that the application of mineral and organic fertilizers under sugar beets, combined with deep moldboard plowing, enhances moisture infiltration into lower soil layers. This creates better conditions for full-fledged plant development during the early stages of vegetation [Syromyatnikov, 2023; Hlushchenko et al., 2020].

At the time of sowing, winter crops experience the greatest moisture deficit. They are the most widespread in both long- and short-rotation crop rotations, where they are sown in sequences with black and occupied fallow, perennial grasses, and grain crops. Under these conditions, the influence of preceding crops, soil tillage systems, and moisture availability for winter wheat is most pronounced in areas with insufficient moisture supply [Rucins et al., 2024]. According to research conducted on low-humus, heavy loam typical chernozem in the left-bank Forest-Steppe of Ukraine, winter wheat crops utilize soil moisture and precipitation most intensively for the formation of vegetative and generative organs during the period from spring vegetation renewal to heading. This growth stage is the most sensitive to soil moisture deficits, and moisture reserves determine the crop's productivity potential [Kaminsky and Hangur, 2018; Kyryliuk et al., 2020]. A significant issue in winter wheat cultivation remains the active water consumption, particularly in May, but only from the soil layer up to 80 cm, which directly affects plant yield [Turebayeva et al., 2022]. Recent studies have shown that under moisture deficits and uneven precipitation distribution throughout the growing season, plants tend to use more moisture from the deeper soil layers. However, this depends largely on root system development and soil tillage practices [Engels et al., 2025; Demydenko et al., 2021; Prymak et al., 2021].

Under the conditions of regenerative agriculture, the assessment of agroecosystems in terms of soil moisture availability during the crop vegetation period allows for forecasting yield levels. Studying the balance of productive moisture in agroecosystems and its utilization by plants, depending on crop rotation characteristics, fertilization systems, and climatic conditions, will enable the development of the most effective and rational model for regulating the moisture balance. This model will consider soil-climatic conditions, preceding crops, and fertilization systems, contributing to increased productivity and stability of agroecosystems.

The aim of the study is to analyze the formation of productive moisture reserves in the soil, its consumption by plants during the vegetation period, and the water use efficiency coefficients in grain-sugar beet crop rotations, depending on the fertilization system and crop placement.

MATERIAL AND METHODS

The study on the water regime of grain-sugar beet short-rotation crop rotations was conducted within a long-term stationary experiment at the

Bila Tserkva research and breeding station (Kyiv region), located in the zone of unstable moisture supply in the central forest-steppe of Ukraine. The experiment included various six-field crop rotations. The soil of the experimental field is deep, leached, low-humus, silty medium loam typical chernozem, with a humus content of 3.6–3.8% in the 0–30 cm layer, mobile phosphorus content of 153–170 mg kg^{-1} (high), exchangeable potassium content of 64–78 mg kg^{-1} (medium) (according to DSTU 4115:2002), and alkaline hydrolysable nitrogen content of 120–140 mg kg^{-1} (low) (according to DSTU 7863:2015). The accounting plot area was 100 m², with a threefold replication. The crop cultivation technology followed the standard practices for the region. Crop rotation schemes: 1. cereal-fodder-tilled crop rotation: sugar beet – barley + clover – clover – winter wheat – vetch-oat mixture – winter wheat (the share of fodder crops 33%, tilled 17%, cereals 50%); 2. tilled crop rotation: sugar beet – barley – soybean – sunflower – vetch-oat mixture – winter wheat (the share of fodder crops 17%, tilled 50%, cereals 33%); 3. cereal-tilled crop rotation: sugar beet – barley – spring vetch – winter wheat – vetch-oat mixture – winter wheat (the share of fodder crops 17%, 17%, cereals 66%). The fertilization system is given in the tables, fertilizers were applied to all crops of the crop rotation except for vetch-oats and barley, (NPK 16:16:16), ammonium nitrate (NH_4NO_3) and granulated superphosphate were used, by spreading method. Variants without fertilizers were not applied at all since 1976, formation was carried out only due to natural fertility. Varieties included in the register of varieties were sown: sugar beet – Constanta, barley – Odyssey, soybeans – Apollo, vetch – Yaroslava.

Soil moisture was determined layer-wise up to a depth of 0–150 cm before sowing and after harvesting of the studied crops using the thermostat-weight method (DSTU ISO 11465-2001). The soil moisture index was determined layer-wise: arable soil layer 0–20 cm, subsoil layer 0–50 cm, meter-deep soil layer 0–100 cm, and one and a half meter soil layer 0–150 cm.

Soil moisture W in percentage was calculated using the formula:

$$W = 100 \times \frac{m_1 - m_0}{m_0 - m} \quad (1)$$

where: m_1 – mass of soil before drying with the container and lid, g; m_0 – mass of dried soil with the container and lid, g; m – mass of the empty container with the lid, g.

Total reserves of productive moisture in the soil W in mm were determined using the formula:

$$W = \frac{u \times \gamma \times h}{10} \quad (2)$$

where: u – moisture of absolutely dry soil, %; γ – soil bulk density, g cm^{-3}; h – soil layer depth, cm; 10 – conversion coefficient for expressing moisture content in mm.

Total water consumption was determined using the water balance method, which includes incoming and outgoing moisture components by determining moisture reserves at the beginning and end of the growing season, taking into account precipitation during the growing period and water supply from groundwater, as well as water losses due to runoff and infiltration into the soil (DSTU 7383:2013).

The water consumption coefficient – the ratio of total water consumption to the yield level of main and by-products in m^{-3} ha – was determined using the formula:

$$К = \frac{\text{Wn} - Wk + O}{\text{У}} \times 10 \quad (3)$$

where: Wn – initial reserves of productive moisture in the soil, mm; Wk – final reserves of productive moisture in the soil, mm; O – precipitation, mm; Y – yield of main and by-products, t ha^{-1}; 10 – conversion coefficient from mm to m^{-3}.

The yield of the main crop was determined by harvesting and weighing the yield from the entire plot, beet tops – based on samples of forty root crops, barley, wheat, vetch, sunflower, and soybean straw – based on sample sheaves. Statistical data processing was performed using the ANOVA program.

RESULTS AND DISCUSSION

According to the data from the Bila Tserkva meteorological station, the agroclimatic conditions during the study years were characterized by significant deviations from the long-term average indicators. This is primarily evident in the increasing air temperature, especially in winter and summer months. Each year, an abnormally warm winter was recorded, with air temperatures in January and February exceeding the long-term averages by +4.7 and +1.6 °C in 2020, +5.2 and +6.7 °C in 2022, +6.0 and +3.7 °C in 2023, and +3.7 and +7.7 °C in 2024 (Fig. 1, 2). The average annual precipitation sum is 526

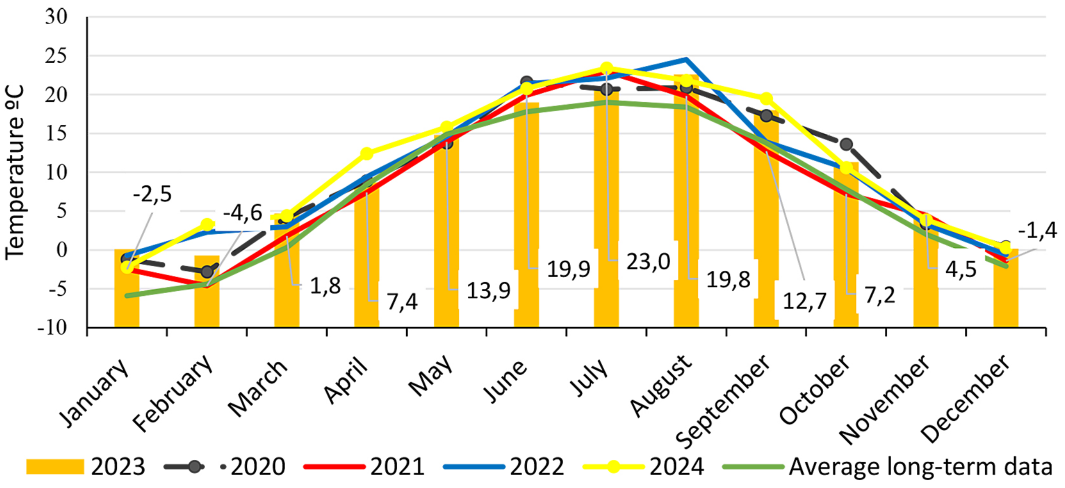

Figure 1. Air temperature, °C

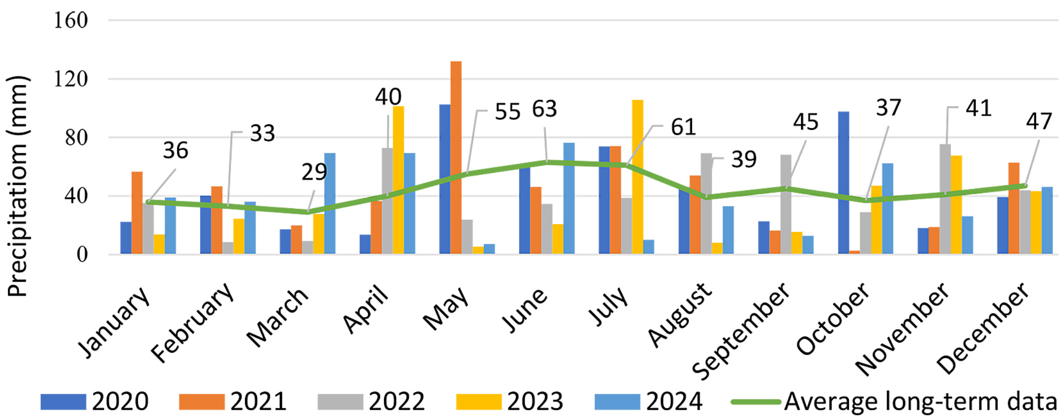

Figure 2. Precipitation amount, mm

mm; however, a clear trend of decreasing precipitation amounts over the years was observed: 554 mm 2020, 567 mm 2021, 509 mm 2022, 481 mm 2023, and 488 mm 2024.

The distribution of precipitation throughout the year is uneven: a higher amount falls during the warm period of the year, while a lower amount occurs in winter. In 2020, an early and warm spring was observed, with precipitation over two months amounting to only 44% of the norm, but in May, double the normal amount fell. The summer was hot, with air temperatures exceeding the long-term average by +2.7 °C, and precipitation reaching 110% of the norm. The autumn was warm with a sufficient amount of precipitation. In the spring of 2021, 152% of the normal precipitation was recorded, and air temperatures did not exceed long-term averages. The summer was hot (air temperature exceeded the long-term norm by +2.5 °C), with precipitation within normal limits. The autumn was extremely dry across all months, with only 31% of the normal precipitation. The drought lasted until the end of October, leading to the complete drying of the arable soil layer, preventing the emergence of winter crop seedlings. March 2022 was quite dry and warm, with precipitation at 32% of the norm. April was warm and humid, while May was cool and dry. The summer was abnormally hot: June +3.6 °C, July +3.1 °C, August +5.9 °C, with precipitation at 87% of the norm (occurring as heavy showers on only a few days per month). The autumn was close to long-term temperature averages, with precipitation at 128% of the norm.

In 2023, the amount of precipitation during the winter period was 70% of the norm, at the same time, the rainy April (101 mm) contributed to the accumulation of productive moisture in the soil, but May was dry. During the summer months, precipitation amounted to 83% of the norm, and air temperature exceeded the long-term average by +2.3 °C, the autumn was warm and rainy, and overall, there was a shortage of 45 mm of precipitation for the year. In 2024, a significant increase in air temperature was observed during the winter and spring periods, particularly in February (+7.7 °C), March (+4.3 °C), and April (+4.0 °C) above the long-term average, while precipitation remained within the norm. The summer was the hottest on record, with temperatures exceeding the long-term average by +3.6 °C and precipitation at 73% of the norm (July was particularly dry). The autumn period was characterized by high air temperatures (+3.5 °C) and precipitation at 89% of the norm. Overall, insufficient precipitation during the years of study, especially in May and June, had the most negative impact on winter wheat yields, as confirmed by recent research [Barabolia and Doronin, 2023; Chourghal et al., 2023; Knight et al., 2024].

During the sowing period of sugar beets, productive moisture reserves ranged between 24–27 mm (Fig. 3). In the lower soil layers, a decreasing trend in productive moisture was observed in the tilled crop rotation, with differences of 10–12 mm in the 0–100 cm layer and 6–14 mm in the 0–150 cm layer compared to other crop rotations. Overall, productive moisture reserves remained high, reaching 153–165 mm in the 0–100 cm soil layer and 209–229 mm in the 0–150 cm layer. The distribution of productive moisture reserves among soil layers (0–20, 20–50, 50–100, and 100–150 cm) was 12%, 24%, 37%, and 26%, respectively.

By the time of sugar beet harvesting, productive moisture reserves had decreased to 36–39 mm in the 0–50 cm soil layer, 67–76 mm in the 0–100 cm layer, and 91–101 mm in the 0–150 cm layer due to plant uptake. At the same time, in the 0–20 cm layer, productive moisture reserves remained at the same level as during the emergence period due to the 300 mm of precipitation received during the growing season. The most significant decrease in moisture reserves was observed in the 50–100 cm layer, depending on crop rotation sequences, with a reduction of 45–47 mm. Overall, productive moisture reserves decreased by 39–44 mm (53%) in the 0–50 cm layer, 86–91 mm (55%) in the 0–100 cm layer, and 118–132 mm (56%) in the 0–150 cm layer compared to the initial reserves.

During the sowing period of spring barley, productive moisture reserves in the 0–20 cm soil layer were nearly identical across crop rotations, ranging from 31–36 mm (Fig. 4). In deeper soil layers, a clear linear increase in moisture reserves was observed: in the 0–50 cm layer, reserves reached 85–89 mm, in the 0–100 cm layer—169–171 mm, and only in the 0–150 cm layer within the cereal-tilled crop rotation did reserves reach 237 mm, while in other crop rotations, they increased to 243–244 mm. The distribution of productive moisture reserves among the soil layers (0–20, 20–50, 50–100, and 100–150 cm) in percentage terms was 14%, 22%, 34%, and 29%, respectively.

A sufficient amount of precipitation (an average of 169 mm during the barley growing season in 2021–2023) contributed to the preservation of productive moisture reserves at the time of harvest, but only in the 0–20 cm soil layer, where they remained at 23–28 mm. Starting from the 0–50 cm soil layer, a decrease in productive moisture reserves was observed: by 38 mm (1.8 times) in the tilled crop rotation, by 45 mm (2.1 times) in

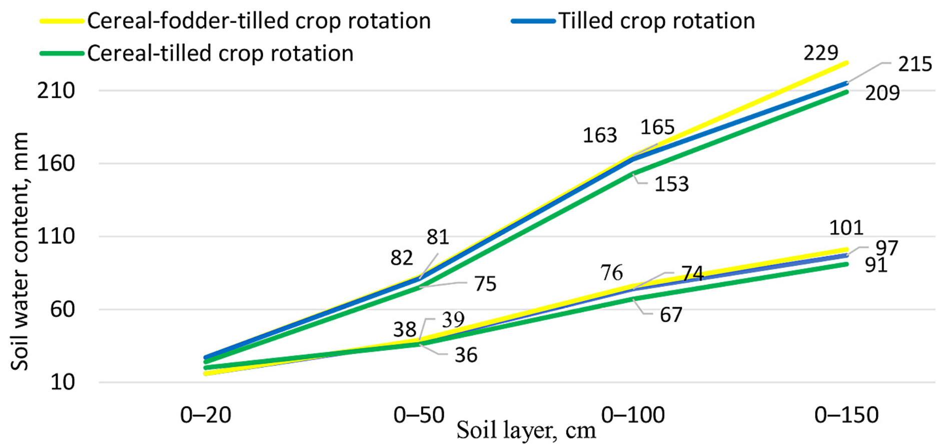

Figure 3. Productive moisture reserves in sugar beet crops during the emergence and harvesting period, average for 2020–2022

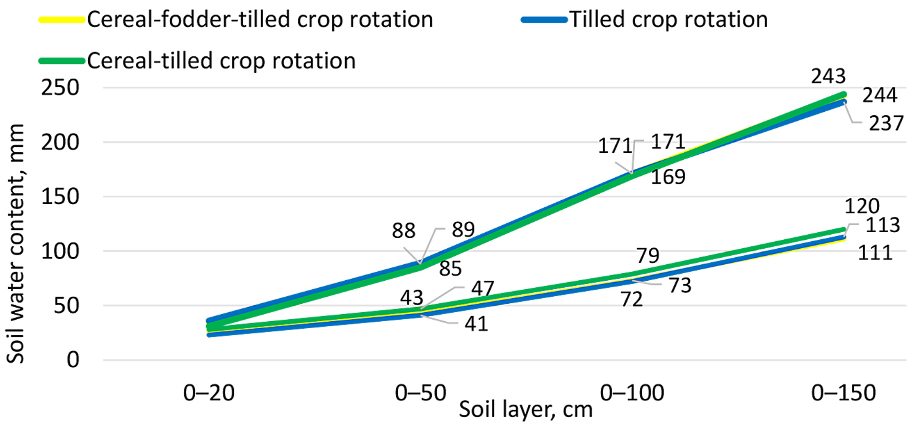

Figure 4. Distribution of productive moisture reserves in barley crops during the emergence and harvesting period, average for 2021–2023.

cereal-fodder-tilled crop rotation, and by 48 mm (2.2 times) in the cereal-tilled crop rotation. In the 1-meter and 1.5-meter soil layers, the greatest reduction in productive moisture reserves was noted in the cereal-fodder-tilled crop rotation 98 mm and 132 mm, respectively. By the time of spring barley harvesting, productive moisture reserves in the 0–150 cm soil layer amounted to 120 mm in the talled crop rotation, while in other crop rotations, they were 111–113 mm. It was established that barley plants primarily utilized productive moisture from the 50–100 cm soil layer (51–53 mm), followed by the 20–50 cm layer (35–38 mm), while the least amount was used from the 100–150 cm layer (25–34 mm), as confirmed by multiple studies [Hanhur et al., 2021; Shevchenko et al., 2020].

During the regrowth period of clover in the cereal-fodder-tilled crop rotation, productive moisture reserves were sufficient in the 0–20 cm and 0–50 cm soil layers, reaching 36 mm and 88 mm, respectively. This can be explained by plant emergence in the fall, which led to greater moisture accumulation. However, in deeper soil layers, the difference was neutralized, and a decreasing trend in productive moisture reserves of 11–14 mm was observed in the 0–150 cm layer compared to other crop rotations (Fig. 5). Soybeans, as a late-sown crop, had lower productive moisture reserves compared to spring vetch, with 24 mm in the 0–20 cm layer, 67 mm in the 0–50 cm layer, and 158 mm in the 0–100 cm layer. The distribution of productive moisture reserves during the germination period in clover crops (crop rotation) between soil layers 0–20, 20–50, 50–100 and 100–150 cm was 12, 24, 37 and 26%, in spring vetch crops 12, 22, 35 and 30%, in soybean crops 10, 17, 37, 36%, respectively.

By the time of legume crop harvesting, there was an almost complete depletion of productive

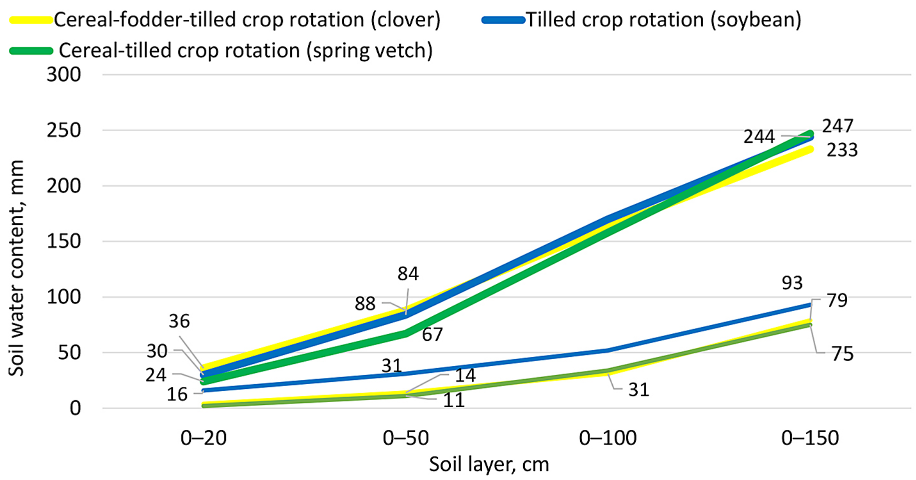

Figure 5. Distribution of productive moisture reserves in legume crops during the emergence and harvesting period, average for 2022–2024

moisture reserves in the upper 0–20 cm soil layer, particularly in clover and soybeans, where only 2 mm and 4 mm remained, respectively. In clover grown for green fodder, productive moisture reserves decreased by 74 mm (6.3 times) in the 0–50 cm layer, by 132 mm (5.3 times) in the 0–100 cm layer, and by 154 mm (2.9 times) in the 0–150 cm layer due to plant uptake and high productivity. As observed, clover plants utilized the maximum available moisture from the entire soil profile, which aligns with previous studies [Barbour et al., 1996]. Another contributing factor to this high moisture consumption was the insufficient precipitation – only 90 mm fell during the growing season (average for 2022–2024) – and the short vegetation period of clover for green fodder. Spring vetch plants consumed moisture more efficiently, but their yield did not exceed 2.2 t/ha. By the time of harvesting, productive moisture reserves in the 0–20 cm layer were 16 mm, decreasing by only 14 mm, which can be explained by the 155 mm of precipitation received during the growing season. Meanwhile, in the 0–50 cm layer, productive moisture reserves decreased by 53 mm (5.3 times), in the 0–100 cm layer by 118 mm (3.3 times), and in the 0–150 cm layer by 151 mm (2.6 times) due to plant consumption. Soybeans were harvested the latest, despite receiving 146 mm of precipitation during the growing season. As a result, productive moisture reserves decreased to 2 mm in the 0–20 cm layer, 11 mm in the 0–50 cm layer, 34 mm in the 0–100 cm layer, and 75 mm in the 0–150 cm soil layer. Overall, in soybean crops, productive moisture reserves declined by 56 mm (6.1 times) in the 0–50 cm soil layer, by 124 mm (4.6 times) in the 0–100 cm layer, and by 172 mm (3.3 times) in the 0–150 cm layer due to plant uptake.

It was established that soybean plants utilized the most productive moisture reserves from the 50–100 cm soil layer (68 mm) and the 100–150 cm layer (48 mm), while only 34 mm was used from the 20–50 cm layer. Clover crops grown for green fodder used the most productive moisture reserves from the 50–100 cm soil layer (58 mm), followed by the 20–50 cm layer (42 mm), the 0–20 cm layer (32 mm), and only 22 mm from the 0–150 cm layer. Spring barley crops primarily utilized productive moisture reserves from the 50–100 cm soil layer (65 mm), followed by the 20–50 cm layer (39 mm), and only 33 mm from the 0–150 cm layer.

During the sowing period of winter wheat, productive moisture reserves remained at 31 mm and 33 mm, respectively (Fig. 6). In deeper soil layers, a significant decrease was observed in the cereal-tilled crop rotation (previous crop: spring vetch), with reserves of 47 mm in the 0–50 cm layer, and 91 mm and 140 mm in the 0–100 cm and 0–150 cm layers, respectively, hese values were higher compared to the cereal-fodder-tilled crop rotation by 19 mm, 27 mm, and 52 mm, respectively. A different trend was observed in the tilled crop rotation with sunflower, where productive moisture reserves increased to 161 mm in the 0–100 cm layer and 248 mm in the 0–150 cm layer, which can be attributed to moisture accumulation during the autumn and winter periods. The distribution of productive moisture reserves among the soil layers in winter wheat crops was 28%, 21%, 18%, and 32% for the 0–20, 20–50, 50–100, and 100–150 cm layers, respectively,

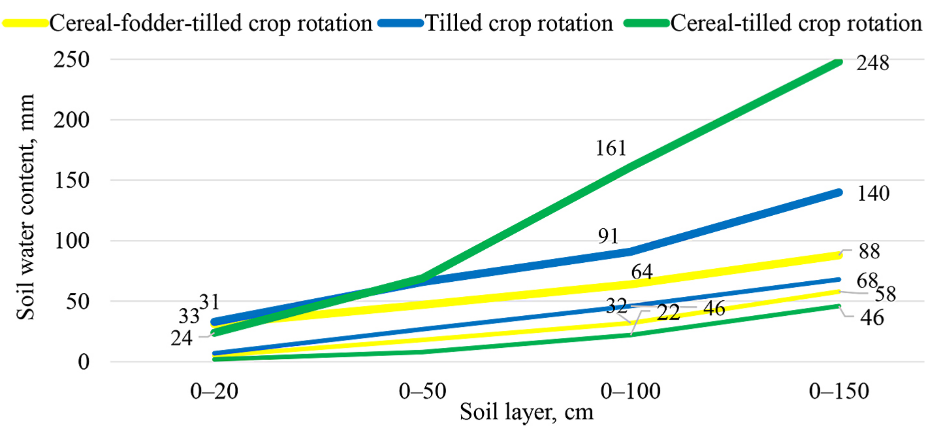

Figure 6. Distribution of productive moisture reserves in winter wheat (Cereal-fodder-tilled crop rotation and cereal-tilled crop rotation) and sunflower (tilled crop rotation) during the emergence and harvesting period, average for 2023–2024

while in sunflower crops, the corresponding percentages were 10%, 18%, 37%, and 35%. Therefore, during the sowing period of winter crops, the lowest moisture reserves were observed in the 50–100 cm soil layer.

By the time of harvesting winter wheat and sunflower, productive moisture reserves decreased to critical levels of 2–7 mm in the 0–20 cm soil layer due to insufficient rainfall and plant usage. During the growing season, winter wheat received 442 mm of precipitation, whereas sunflower only received 177 mm. In the 0–50 cm and 0–100 cm soil layers, winter wheat plants consumed more moisture in the cereal-fodder-tilled crop rotation compared to the cereal-tilled crop rotation, but overall, productive moisture reserves remained low, which is associated with the previous crop, clover for green fodder [Panchenko, 2024]. Specifically, productive moisture reserves decreased by 34 mm (1.7 times) in the 0–50 cm layer, 39 mm (2.0 times) in the 0–100 cm layer, and 51 mm (2.2 times) in the 0–150 cm layer. Sunflower consumed the most moisture, especially from the 50–100 cm and 100–150 cm soil layers. In these layers, productive moisture reserves decreased by 61 mm (8.6 times) in the 0–50 cm layer, 139 mm (7.3 times) in the 0–100 cm layer, and 202 mm (5.4 times) in the 0–150 cm layer.

It was established that sunflower plants utilized the most productive moisture reserves from the 50–100 cm soil layer (78 mm), followed by the 100–150 cm layer (63 mm), and the 20–50 cm layer (39 mm). Meanwhile, winter wheat plants primarily utilized the most productive moisture reserves from the 0–20 cm soil layer (26 mm), while from the 20–50 cm layer, only 3–13 mm were used, 3–6 mm from the 50–100 cm layer, and in the 100–150 cm layer, there was even a slight moisture accumulation of up to 2 mm in the cereal-fodder-tilled crop rotation, and a decrease to 27 mm in the cereal-tilled crop rotation.

A detailed analysis of the total moisture consumption by different crop rotations, depending on the fertilization system and crop rotation links, was conducted, with the calculation of moisture consumption coefficients. In the cereal-fodder-tilled crop rotation with sugar beets, when applying $N_{100}P_{90}K_{90}$ fertilizer, a decrease in moisture reserves of 109 mm was observed over the growing season. However, with the application of 40 $t \cdot ha^{-1}$ of manure + $N_{100}P_{90}K_{90}$, moisture reserves increased to 133 mm, which is associated with higher yields of both main and by-product production (Table 1). The moisture usage by the plants, considering the 300 mm of precipitation during the growing season, was 4093 and 4330 $m^3 \cdot ha^{-1}$ with fertilizer application, and 3883 $m^3 \cdot ha^{-1}$ due to natural fertility. In the sowing of spring barley, the decrease in productive moisture reserves from the aftereffects of organic-mineral fertilizers was similar to that of sugar beets, at 132 and 106 mm,

Table 1. Calculation of total moisture consumption in the one-and-a-half-meter soil layer and the moisture consumption coefficient in the cereal-fodder-tilled crop rotation

Crop	Fertilization system	Productive water reserves		Reduction of reserves during the growing season, mm	Water use by plants, $m^3 \cdot ha^{-1}$	*Crop yield, $t \cdot ha^{-1}$	Water use efficiency, $m^3 \cdot t^{-1}$
		At the time of sowing	At the time of harvest				
Sugar beet	Mineral, $N_{100}P_{90}K_{90}$	209	100	109	4093	52.57	78
	Zero fertilization	241	153	88	3883	24.00	162
	Organic-mineral, 40 $t \cdot ha^{-1}$ cattle manure + $N_{100}P_{90}K_{90}$	229	97	133	4330	64.23	67
Barley + clover	Residual effect of mineral fertilizers	237	131	106	2753	7.36	376
	Zero fertilization	259	158	101	2707	5.35	549
	Residual effect of organic-mineral fertilizers	243	111	132	3010	8.76	343
Clover	$N_{40}P_{40}K_{40}$	230	71	158	2480	27.33	91
	Zero fertilization	219	102	117	2067	13.90	148
	$N_{40}P_{40}K_{40}$	233	79	154	2437	29.73	81
Winter wheat	$N_{90}P_{60}K_{60}$	81	63	19	4600	16.14	289
	Zero fertilization	94	101	7	4345	11.86	374
	$N_{90}P_{60}K_{60}$	88	58	31	4720	18.96	253

Note: *Crop yield includes main and by-products.

respectively. Meanwhile, the moisture used by the plants decreased to 3010 and 2753 m³ ha^{-1}, which is linked to a lower amount of precipitation (169 mm) during the growing season.

Clover, due to its well-developed root system, utilized 154–158 mm of moisture with N40P40K40 application and 117 mm without fertilizers. Meanwhile, total plant water use, considering 90 mm of precipitation during the growing season, was the lowest in the crop rotation, amounting to 2437–2480 m³·ha^{-1} with fertilizers and 2060 m³·ha^{-1} without them. Winter wheat, having the longest growing period, minimally reduced soil moisture reserves under $N_{90}P_{60}K_{60}$ application by 19 and 31 mm. However, total water use, including 442 mm of precipitation, was the highest in the crop rotation, reaching 4600 and 4720 m³·ha^{-1}.

In tilled crop rotation, sugar beets utilized 4053 and 4183 m³ ha^{-1} of water with fertilizer application (Table 2). In barley fields, the reduction of soil moisture reserves due to fertilizer aftereffects was 124–127 mm, while total plant water use reached 2937–2963 m³·ha^{-1}. Soybeans grown after barley in tilled crop rotation, with $N_{40}P_{40}K_{40}$ application, consumed 162 and 172 mm of soil moisture during the growing season, considering 146 mm of precipitation, total water use amounted to 3080 and 3173 m³·ha^{-1}. Research findings indicate total water consumption of soybeans ranges from 4800 to 5000 m³·ha^{-1}, largely depending on yield, variety, and plant density [Hranovska and Reznichenko, 2023; Tanchyk et al., 2018].

In the cereal-tilled crop rotation, sugar beets showed the most optimal water consumption parameters. Moisture reduction during the growing season was 98 mm with mineral fertilization and 114 mm with organo-mineral fertilization, while total plant water use amounted to 3980 and 4147 m³ ha^{-1} (Table 3). For spring barley, plant water use was 2647 and 2897 m³·ha^{-1}, depending on the residual effect of fertilizers. This was 316 and 40 m³ ha^{-1} lower compared to tilled crop rotation and 100 and 113 m³·ha^{-1} lower than in cereal-fodder-tilled crop rotation. As observed, barley plants following sugar beets efficiently utilize productive moisture reserves, regardless of the fertilization system [Pavlova and Litvinov, 2024; Kyryliuk and Shemiakin, 2017].

Spring vetch in cereal-tilled crop rotation, with $N_{40}P_{40}K_{40}$ application, used 143 and 147 mm of productive moisture during the growing season, with total water consumption of 2980 and 3013 m³·ha^{-1}. Notably, spring vetch had the highest water use efficiency coefficients 777 and 784 m³·ha^{-1}, likely due to low yield under drought conditions. Spring vetch plants significantly reduce productivity even under short-term drought, as confirmed by research [Haffani et al., 2014; Tang et al., 2019; Antonets et al., 2024].

According to our research, the lowest WUE was recorded in sugar beet crops with

Table 2. Calculation of total water consumption in the 1.5-meter soil layer and water use efficiency coefficient in tilled crop rotation

Crop	Fertilization system	Productive water reserves		Reduction of reserves during the growing season, mm	Water use by plants. m³ ha^{-1}	*Crop yield. t ha^{-1}	Water use efficiency. m³ t^{-1}
		At the time of sowing	At the time of harvest				
Sugar beet	Mineral, $N_{100}P_{90}K_{90}$	212	107	105	4053	46.97	86
	Zero fertilization	244	159	85	3850	23.10	166
	Organic-mineral, 40 t ha^{-1} cattle manure + $N_{100}P_{90}K_{90}$	209	91	118	4183	55.37	76
Barley	Residual effect of mineral fertilizers	258	131	127	2963	7.24	412
	Zero fertilization	243	144	100	2690	5.27	520
	Residual effect of organic-mineral fertilizers	244	120	124	2937	9.57	308
Soyabean	$N_{40}P_{40}K_{40}$	242	80	162	3080	8.40	375
	Zero fertilization	251	117	134	2800	5.59	505
	$N_{40}P_{40}K_{40}$	247	75	172	3173	9.54	336
Sunflower	$N_{90}P_{60}K_{60}$	262	69	194	3700	9.09	416
	Zero fertilization	249	92	157	3330	5.53	598
	$N_{90}P_{60}K_{60}$	248	46	202	3785	10.61	362

Note: *Crop yield includes main and by-products.

Table 3. Calculation of total water consumption in the 1.5-meter soil layer and water use efficiency coefficient in cereal-tilled crop rotation

Crop	Fertilization system	Productive water reserves		Reduction of reserves during the growing season, mm	Water use by plants, $m^3\ ha^{-1}$	*Crop yield, $t\ ha^{-1}$	Water use efficiency, $m^3\ t^{-1}$
		At the time of sowing	At the time of harvest				
Sugar beet	Mineral, $N_{100}P_{90}K_{90}$	204	106	98	3980	45.97	87
	Zero fertilization	232	135	98	3980	25.03	159
	Organic-mineral, 40 t ha^{-1} cattle manure + $N_{100}P_{90}K_{90}$	215	101	114	4147	59.87	69
Barley	Residual effect of mineral fertilizers	220	125	95	2647	7.36	364
	Zero fertilization	245	150	95	2647	5.19	516
	Residual effect of organic-mineral fertilizers	237	116	120	2897	9.25	312
Spring vetch	$N_{40}P_{40}K_{40}$	253	106	147	3013	3.09	784
	Zero fertilization	262	104	158	3127	4.70	758
	$N_{40}P_{40}K_{40}$	233	90	143	2980	4.30	777
Winter wheat	$N_{90}P_{60}K_{60}$	122	76	46	4870	15.52	317
	Zero fertilization	151	118	33	4740	9.72	497
	$N_{90}P_{60}K_{60}$	140	68	72	5130	17.48	297

Note: *Crop yield includes main and by-products.

organo-mineral fertilization: 67 $m^3\ t^{-1}$ in cereal-fodder-tilled crop rotation, 69 m^3/t in cereal-tilled crop rotation, and 76 $m^3\ t^{-1}$ in tilled crop rotation. This can be explained by the well-developed root system, which allows plants to extract moisture from soil layers deeper than 150 cm, as well as the high productivity of the crop. Notably, under extensive sugar beet cultivation, the WUE increases to 159–166 $m^3\ t^{-1}$, while crop productivity declines to 23.10–25.03 t ha^{-1}, which is 2.4–2.7 times lower than with organo-mineral fertilization [Pysarenko et al., 2022; Syromyatnikov, 2023].

For spring barley, the WUE under the residual effect of organo-mineral fertilizers were 308–312 $m^3·t$ in row and cereal-tilled crop rotation, increasing to 343 $m^3·t^{-1}$ in the cereal-fodder-tilled crop rotation. Under the residual effect of mineral fertilizers, the coefficient rose further, regardless of crop rotation type, to 364–412 $m^3·t^{-1}$, in unfertilized conditions, it reached 516–549 $m^3·t^{-1}$, confirming earlier research [Makukh et al., 2023; Porodko, 2023]. In clover crops, due to autumn sowing and a strong root system, water was used most efficiently in the cereal-fodder-tilled crop rotatio. With $N_{40}P_{40}K_{40}$ application, the water use efficiency coefficient remained at 81–91 $m^3·t^{-1}$, with a yield of 27.33–29.73 $t·ha^{-1}$. In the tilled crop rotation, soybeans required significant moisture to produce 8.40–9.54 $t·ha^{-1}$ of main and by-products with $N_{40}P_{40}K_{40}$ fertilization. As a result, the water use coefficient increased to 336–375 $m^3·t^{-1}$, while in unfertilized conditions, it rose to 505 $m^3·t^{-1}$. Similarly, for sunflower crops, with $N_{90}P_{60}K_{60}$ fertilization, the highest water use coefficient in the rotation was recorded, reaching 362 and 416 $m^3·t^{-1}$.

For winter wheat, despite its long growing period, the WUE under $N_{90}P_{60}K_{60}$ fertilization ranged from 253–289 $m^3·t^{-1}$ in the cereal-fodder-tilled crop rotation and 297–317 $m^3·t^{-1}$ in cereal-tilled crop rotation. Thus, precipitation during the growing season accounted for the majority of wheat's total water consumption, as confirmed by multiple studies [Solodushko, 2024; Kyryliuk, 2018]. Meanwhile, research conducted in Romania indicates that wheat water consumption at yields of 6–7 $t·ha^{-1}$ reaches 6000–7500 $m^3·ha^{-1}$, approximately 1000 $m^3·t^{-1}$ [Berca et al., 2021].

In the central forest-steppe of Ukraine, the yield of sugar beet did not exceed 40–45 t ha^{-1} due to prolonged summer drought. A sufficient amount of rainfall in August and September did not facilitate the rapid accumulation of root mass. Research data on yield show that, without the use of fertilizers, the root crop yield was as follows: in the cereal-fodder-tilled crop rotatioon – 14.9–18.7 $t·ha^{-1}$, in the tilled crop rotation – 14.5–17.4 $t·ha^{-1}$, and in the cereal-tilled crop rotation – 15.8–19.1 $t·ha^{-1}$, depending on the year, which represents the lowest figures in the last two crop rotation cycles. In the cereal-fodder-tilled crop rotation, applying mineral fertilizers at a rate of

$N_{100}P_{90}K_{90}$ made it possible to obtain 32.1–39.2 t ha^{-1} of root crops, while the combination of manure and mineral fertilizers increased the yield to 39.1–45.4 t ha^{-1} (Table 4). In the tilled crop rotation, the most significant reduction in root crop yield was observed under the mineral fertilization system, decreasing to 29.8–32.4 t ha^{-1}. This was due to the saturation of the crop rotation with row crops and insufficient reserves of productive moisture [Tyshchenko et al., 2020; Pospelov et al., 2020].

In the cereal-tilled crop rotation, the application of mineral fertilizers ($N_{100}P_{90}K_{90}$) resulted in a yield of 29.8–34.1 t ha^{-1}, while adding 40 t ha^{-1} of manure + $N_{100}P_{90}K_{90}$ increased it to 38.6–43.0 t ha^{-1}, depending on the research year. Overall, with the continuous application of an organo-mineral fertilization system, depending on the crop rotation links, the average increase in root crop yield over the study years increased by 2.45–2.64 times, while the water consumption coefficient decreased by 2.18–2.42 times.

The yield of spring barley depended more on the reserves of productive moisture and the residual effects of mineral and organic fertilizers, while the crop rotation links did not significantly influence it. Thus, in the variants without fertilizers, the average yield over the study years was 2.35–2.53 t ha^{-1}, with the residual effects of mineral fertilizers – 3.16–3.25 t ha^{-1}, and with the residual effects of organo-mineral fertilizers – 3.74–4.01 t ha^{-1}. At the same time, spring barley plants used moisture most efficiently in the tilled crop rotation.

In the cereal-fodder-tilled crop rotation, the yield of clover increased to 28.0–32.6 t ha^{-1} with the application of $N_{40}P_{40}K_{40}$, whereas without fertilizers, it was 12.2–16.4 t ha^{-1}, or 2.13 times lower. Under these conditions, the WUE decreased to 81 m^3 t^{-1} in the fertilized variants. In the tilled crop rotation, the yield of soybean depended more on the weather conditions of the growing season. At the same time, a clear positive effect of the organo-mineral fertilization system on sugar beets was observed, leading to a soybean yield of 3.28–3.56 t ha^{-1}, while mineral fertilizers resulted in 2.93–3.41 t ha^{-1}. Without fertilizer application, the yield decreased to 2.35–2.41 t ha^{-1}. A persistent issue in soybean cultivation remains the significant use of productive moisture reserves and the relatively low yield of the main product. The yield of spring vetch in the cereal-tilled crop rotation remained the lowest among all crops and did not depend

Table 4. Yield of crops in grain-sugar beet crop rotations

Crops	$N_{100}P_{90}K_{90}$			Without fertilizers			40 t/ha of manure + $N_{100}P_{90}K_{90}$		
	2020	2021	2022	2020	2021	2022	2020	2021	2022
Sugar beet*	$32.1^{\pm1.11}$	$34.9^{\pm0.36}$	$39.2^{\pm1.14}$	$15.2^{\pm0.37}$	$18.7^{\pm0.36}$	$14.9^{\pm0.16}$	$39.1^{\pm0.85}$	$45.4^{\pm0.41}$	$44.1^{\pm0.41}$
Sugar beet**	$31.7^{\pm0.22}$	$29.8^{\pm0.45}$	$32.4^{\pm0.42}$	$14.9^{\pm0.43}$	$17.4^{\pm0.16}$	$14.5^{\pm0.22}$	$35.2^{\pm0.28}$	$38.3^{\pm0.51}$	$41.9^{\pm0.54}$
Sugar beet***	$29.4^{\pm0.62}$	$32.6^{\pm0.50}$	$34.1^{\pm0.29}$	$15.8^{\pm0.43}$	$19.0^{\pm0.45}$	$15.8^{\pm0.43}$	$38.6^{\pm0.29}$	$43.0^{\pm0.22}$	$42.5^{\pm0.43}$
	Residual effect of mineral fertilizers			Zero fertilization			Residual effect of organic-mineral fertilizers		
	2021	2022	2023	2021	2022	2023	2021	2022	2023
Barley*	$2.89^{\pm0.15}$	$3.37^{\pm0.09}$	$3.23^{\pm0.06}$	$2.18^{\pm0.12}$	$2.76^{\pm0.10}$	$2.10^{\pm0.12}$	$3.82^{\pm0.16}$	$3.57^{\pm0.21}$	$3.82^{\pm0.13}$
Barley**	$2.87^{\pm0.02}$	$3.41^{\pm0.08}$	$3.22^{\pm0.14}$	$2.40^{\pm0.15}$	$2.93^{\pm0.08}$	$2.77^{\pm0.10}$	$3.66^{\pm0.20}$	$4.23^{\pm0.15}$	$3.96^{\pm0.09}$
Barley***	$2.86^{\pm0.23}$	$3.61^{\pm0.14}$	$3.28^{\pm0.09}$	$2.23^{\pm0.13}$	$2.77^{\pm0.20}$	$2.27^{\pm0.04}$	$4.09^{\pm0.08}$	$3.83^{\pm0.23}$	$4.12^{\pm0.05}$
	$N_{40}P_{40}K_{40}$			Zero fertilization			$N_{40}P_{40}K_{40}$		
	2022	2023	2024	2022	2023	2024	2022	2023	2024
Clover*	$27.8^{\pm0.22}$	$28.2^{\pm0.94}$	$26.0^{\pm0.67}$	$12.2^{\pm0.16}$	$13.1^{\pm0.36}$	$16.4^{\pm0.73}$	$28.0^{\pm0.37}$	$28.6^{\pm0.28}$	$32.6^{\pm0.96}$
Soybean**	$3.41^{\pm0.11}$	$2.93^{\pm0.20}$	$3.15^{\pm0.12}$	$2.41^{\pm0.02}$	$2.35^{\pm0.06}$	$2.38^{\pm0.06}$	$3.56^{\pm0.25}$	$3.28^{\pm0.21}$	$3.51^{\pm0.12}$
Spring vetch***	$1.93^{\pm0.08}$	$1.27^{\pm0.11}$	$1.10^{\pm0.07}$	$2.18^{\pm0.08}$	$1.59^{\pm0.11}$	$1.38^{\pm0.06}$	$1.99^{\pm0.27}$	$1.41^{\pm0.06}$	$1.23^{\pm0.07}$
	$N_{90}P_{60}K_{60}$			Zero fertilization			$N_{90}P_{60}K_{60}$		
	2023	2024		2023	2024		2023	2024	
Winter wheat*	$6.71^{\pm0.09}$	$6.96^{\pm0.20}$		$5.17^{\pm0.17}$	$5.19^{\pm0.17}$		$7.51^{\pm0.10}$	$7.82^{\pm0.18}$	
Sunflower**	$2.76^{\pm0.06}$	$3.53^{\pm0.11}$		$2.01^{\pm0.09}$	$2.17^{\pm0.19}$		$3.24^{\pm0.11}$	$3.84^{\pm0.13}$	
Winter wheat***	$6.52^{\pm0.20}$	$6.78^{\pm0.18}$		$4.21^{\pm0.04}$	$4.63^{\pm0.17}$		$6.96^{\pm0.13}$	$7.28^{\pm0.16}$	

Note: *In the cereal-fodder-tilled crop rotation, **in tilled crop rotation, **in cereal-tilled crop rotation, ± standard deviation.

on the fertilization system. On average, over the study years, the yield of spring vetch without fertilizers was 1.72 t ha^{-1}, whereas with $N_{40}P_{40}K_{40}$ application, it decreased to 1.43–1.54 t·ha^{-1}.

The yield of winter wheat in the in the cereal-fodder-tilled crop rotation with the application of only mineral fertilizers at a rate of N90P60K60 was 6.84 t ha^{-1}, whereas in the cereal-tilled crop rotation, it decreased to 6.65 t ha^{-1}. Similarly, with the application of $N_{90}P_{60}K_{60}$ alongside the organo-mineral fertilization system for sugar beets, the yield increased to 7.82 and 7.12 t·ha^{-1}, respectively. In the variants without fertilizers, the yield of winter wheat decreased to 5.18 t·ha^{-1} in the cereal-fodder-tilled crop rotation and 4.42 t ha^{-1} in the cereal-tilled crop rotation, with the WUE increasing by 1.48–1.67 times compared to fertilized variants. The yield of sunflower in the tilled crop rotation was 3.15 t ha^{-1} with the application of $N_{90}P_{60}K_{60}$, while the use of the organo-mineral fertilization system in the crop rotation increased it to 3.54 t·ha^{-1}, without fertilizers, the yield was 20.9 t·ha^{-1}. At the same time, the WUE in sunflower crops increased to 362–416 m³·t^{-1} with fertilizers and 598 m³·t^{-1} without fertilizers.

CONCLUSIONS

It was established that crop rotation plants used productive moisture reserves unevenly across soil layers, which was related to crop characteristics (root system development), the length of the growing season, and the lack of precipitation. At the time of harvest, sugar beet utilized the most productive moisture reserves from the 20–50 cm soil layer (62%), followed by the 100–150 cm (58%), 50–100 cm (57%), and only 33% from the 0–20 cm layer. Spring barley plants extracted moisture as follows: 20–50 cm – 67%, 50–100 cm – 63%, 100–150 cm – 44%, and only 24% from the 0–20 cm layer. Sunflower plants in the tilled crop rotation reduced productive moisture reserves by 92% in the 0–20 cm layer, 87% in the 20–50 cm layer, 85% in the 50–100 cm layer, and 72% in the 100–150 cm layer. Winter wheat plants reduced moisture reserves by 81% in the 0–20 cm layer and by 21–34% in other soil layers. Clover grown for green fodder in the cereal-fodder-tilled crop rotation depleted soil moisture reserves as follows: 0–20 cm – 89%, 20–50 cm – 84%, 50–100 cm – 81%, and 100–150 cm – 66%. Soybean plants in the tilled crop rotation reduced moisture reserves by 92% in the 0–20 cm layer, 84% in the 20–50 cm layer, 78% in the 50–100 cm layer, and 70% in the 100–150 cm layer. Spring vetch plants in cereal-tilled crop rotation reduced moisture reserves by 69% in the 50–100 cm layer, 63% in the 20–50 cm layer, 62% in the 100–150 cm layer, and only 47% in the 0–20 cm layer.

The highest total water consumption was recorded in sugar beet crops with the application of $N_{100}P_{90}K_{90}$ (3.980–4.096 m³·ha^{-1}) and 40 t·ha^{-1} of manure + $N_{100}P_{90}K_{90}$ (4.147–4.330 m³·ha^{-1}), as well as in winter wheat with $N_{90}P_{60}K_{60}$ application (4.600–5.130 m³·ha^{-1}), regardless of crop rotation type. Under these conditions, the WUE in sugar beet crops remained at 67–86 m³·t^{-1}, while in winter wheat crops, it increased to 253–317 m³ t^{-1}. In the cereal-fodder-tilled crop rotation, moisture was used most efficiently in clover crops due to their well-developed root system, with a WUE of 81–91 m³·t^{-1} when $N_{40}P_{40}K_{40}$ was applied. In the tilled crop rotation, sunflower ($N_{90}P_{60}K_{60}$) and soybean ($N_{40}P_{40}K_{40}$) consumed the most water, with WUE of 362–416 m³·t^{-1} and 336–375 m³·t^{-1}, respectively. In contrast, spring vetch with $N_{40}P_{40}K_{40}$ had the highest water consumption coefficient of 777–784 m³·t^{-1}.

The highest sugar beet root yield was obtained in the cereal-fodder-tilled crop rotation under an organo-mineral fertilization system (40 t·ha^{-1} of manure + $N_{100}P_{90}K_{90}$), reaching 44.1·t·ha^{-1}.

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