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The effect of soil moisture reserves on the productivity of soybean and sunflower under different fertilization systems and residual effects of fertilizers

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ABSTRACT

Detailed analyses have been conducted on productive moisture reserves, water consumption, and water use efficiency (WUE) coefficients of soybean and sunflower crops depending on the immediate and residual effects of mineral and organic fertilizers, as well as their influence on yield. The study was conducted in the Central Forest-Steppe of Ukraine on leached typical chernozem. It was found that soybean plants consume the largest portion of available soil moisture from the 0–20 cm and 0–50 cm layers during the growing season. Sunflower, due to its well-developed root system, utilizes the moisture reserves most effectively from the entire 0–100 cm soil profile. Moreover, in the 101–150 cm soil layer, sunflower extracted an additional 51–58 mm of moisture compared to the initial reserves. This physiological trait allows sunflower to be efficiently placed after row crops such as soybean in crop rotation systems. The application of $N_{40}P_{40}K_{40}$ fertilizers under soybean improved root system development and enabled better use of moisture from deeper soil layers, resulting in yields of 3.39 and 3.45 t ha^{-1}. Sunflower yields under fertilized conditions ranged from 3.38 to 3.81 t ha^{-1}. The residual effect of previously applied fertilizers remained stable (2.73–3.18 t ha^{-1}), confirming the long-term efficiency of fertilization and the high adaptability of sunflower to residual soil nutrient supply. The findings justify the placement of sunflower after row crops, particularly soybean, in crop rotations and support the development of adaptive fertilization and rotation strategies under unstable water availability conditions. These results provide important insights for improving the management of available soil moisture reserves from different soil layers and optimizing the WUE coefficient in soybean and sunflower crops under the application of mineral fertilizers and their residual effects.

Keywords: soybean, sunflower, soil moisture, productive moisture reserves, yield, weather conditions, water use efficiency.

INTRODUCTION

Under current agricultural practices in the forest-steppe zone of Ukraine, it is advisable to incorporate high-margin row crops such as soybean and sunflower into crop rotations. At the same time, it is necessary to consider the saturation of crop rotations with sunflower in terms of minimizing soil degradation and adapting technological elements to limited resource availability. A key direction for sustainable agricultural development remains the implementation of short-rotation cropping systems with a high proportion of row crops, combined with the application of crop residues as fertilizer, along with mineral and organic fertilizers.

There is a growing need for research into crop rotations characterized by a high concentration of high-yielding row crops and the use of various fertilization systems tailored for short rotations. Particular scientific relevance is attributed to studying the soil water regime in soybean and sunflower crops under conditions of climate transformation, which is accompanied by a decrease in precipitation and disruptions in its seasonal distribution. This will enable the rational integration of organic and mineral fertilizer applications, their residual effects, and the use of crop by-products (such as cereal and legume straw, and sunflower stalks), as well as green manure crops, in combination with other intensification measures (Miroshnychenko et al., 2023; Sokolovska and Mashchenko, 2023; Kussul et al., 2022; Le Gall et al., 2022).

The dynamics of agroclimatic resources in the forest-steppe zone have had a positive impact on the productivity of many agricultural crops. An average temperature increase of +180–200 °C in accumulated growing degree days, a rise in mean annual air temperature (> +1.8 °C), more frequent summer heat extremes (+4.0–5.0 °C), an extension of the summer season to up to five months, and a reduction in snow cover intensity and its duration have contributed to higher yields of thermophilic crops. On the other hand, in this zone of unstable moisture availability, the primary limiting factor remains the reserves of productive moisture in the soil. In typical chernozem soils of the forest-steppe zone, the water regime corresponds to a periodically leached type. However, the temporal pattern of moisture dynamics increasingly exhibits features of a non-leaching regime, indicating a trend toward soil aridization under ongoing global climate change (Demydenko et al., 2021; Demydenko, 2025). The accumulation and efficient use of atmospheric precipitation is a key factor in shaping and enhancing crop yields. It is also one of the most significant uncontrollable abiotic factors limiting productivity. Soil moisture deficit during the growing season of field crops not only adversely affects growth processes but also reduces the efficiency of certain cultivation technologies, particularly the performance of mineral fertilizers and crop protection systems (Wang et al., 2024; Rahmati et al., 2024).

Climate change has led to the expansion of effective sunflower cultivation zones within the forest-steppe region, including areas previously considered marginal or less suitable. Today, sunflower is the primary oilseed crop and a strategically important agricultural commodity, with sown areas steadily increasing (Vasylkovska et al., 2024; Geletukha et al., 2020). In addition to its economic significance, sunflower exhibits high drought tolerance, as confirmed by numerous studies (Jocković et al., 2024; Miladinović et al., 2019; Earley et al., 2024).

However, sunflower plants are particularly sensitive to drought and heat stress during the critical period from the onset of flowering to seed development, primarily due to limited regulation of leaf growth and a high transpiration rate, especially under conditions of insufficient soil moisture (Hussain et al., 2018). Prolonged drought significantly reduces both seed yield and oil content. For instance, in the Republic of Moldova between 2001 and 2020, average sunflower yields ranged from 1.2 to 2.3 t ha^{-1}; however, in years with severe drought (2007, 2012, and 2020), yields dropped to 0.7, 1.0, and 1.03 t ha^{-1}, respectively (Duca et al., 2022).

There is well-documented evidence on the negative effects of drought on key agromorphological and physiological traits of sunflower, including head and stem diameter, plant height, root-to-shoot ratio, leaf water potential, leaf area index, total chlorophyll content, and a significant reduction in seed yield due to lower seed weight and oil output during the seed filling stage (Harsányi et al., 2021; Ashraf and Siddiqi, 2024). Drought stress has been shown to substantially reduce growth, yield, and (WUE) (Saudy et al., 2023).

Sunflower plants develop a strong root system that can reach depths of 150–300 cm, enabling them to extract moisture from deep soil layers inaccessible to many other crops. As a result, plants utilize approximately 30–40% of moisture from soil reserves and 60–70% from atmospheric precipitation during the growing season (Baranskyi, 2024). Sunflower has demonstrated superior (WUE) due to the improved ability of its root system to absorb water from deeper layers–specifically from 50–70 cm and 70–90 cm soil depths (He et al., 2024). This trait has become a strategic basis for growing sunflower after row crops such as soybean under Ukrainian conditions, where irrigation is not widely available. Furthermore, sunflower is capable of producing stable yields on fertile soils with minimal fertilizer input (Bola Adelabu et al., 2021). According to Sarker et al. (2023), sunflower requires no more than 90–120 kg ha^{-1} of nitrogen in active ingredient form, while higher rates may negatively impact yield. In the Steppe zone, sunflower crops respond more significantly to sowing dates and seeding rates than to mineral fertilizer application (Gordeyeva et al., 2024; Kirchev et al., 2024). Although seed yield tends to increase with higher nitrogen rates, a notable improvement was observed when 225 kg ha^{-1} of fertilizer (in physical weight) was applied, compared to 135 kg ha^{-1}. However, increasing the rate to 315 kg ha^{-1} did not result in a statistically significant yield increase over the 225 kg ha^{-1} rate (Ren et al., 2025). Economic analyses indicate that the optimal nitrogen rate was 60 kg ha^{-1} (active ingredient), while the application of 90 kg ha^{-1} was the least economically efficient, given the yield response and the cost of nitrogen fertilizers (Jarecki, 2022).

Due to its extensive root system, sunflower exhibits a relatively high level of water consumption. To achieve high yields, sunflower requires 1650–1850 m^3 ha^{-1} of moisture within the 0–150 cm soil layer, along with sufficient rainfall throughout the growing season (Dehtiarova, 2023). The crop's peak water uptake occurs in June–July during the stages of head formation and flowering. Adequate water availability during this period has a decisive influence on sunflower productivity.

During the growing season, sunflower plants extracted 525–617 m^3 ha^{-1} of productive moisture from the soil, which, together with rainfall, resulted in a total water use of 7349–7436 m^3 ha^{-1}. The (WUE) per 1 tonne of main and by-products ranged from 1182 to 1293 m^3 (Kvasnitska and Voitova, 2023). In the forest-steppe zone, total water consumption by sunflower ranges between 2923 and 3065 m^3 ha^{-1} (Borysenko, 2024). According to Harbar et al. (2025), over the years of research, total water use on typical low-humus chernozem soils averaged 3095 m^3 ha^{-1}, with a WUE coefficient ranging from 716 to 1796 m^3 t^{-1}. Among all factors studied, fertilization system had the most significant effect on reducing the water use coefficient. The saturation level of crop rotations with sunflower can vary from 20% to 60% of the total sown area. However, the (WUE) coefficient increases significantly under higher saturation: in crop rotations with 60% sunflower, reached 2969 m^3 ha^{-1}, compared to 2824 m^3 ha^{-1} and 2713 m^3 ha^{-1} under 20% and 40% saturation, respectively (Dehtiarova, 2023).

According to data from the Institute of Oil Crops of the NAAS of Ukraine, on ordinary chernozem soils, sunflower yield without fertilization was 2.43 t ha^{-1}. The application of mineral fertilizers at a rate of $N_{40}P_{60}$ increased yield to 2.80 t ha^{-1}, while the combination of $N_{20}P_{30}$ with organo-mineral fertilizers resulted in 3.10 t ha^{-1} (Polyakov and Shcherbak, 2023). The highest increase in yield was recorded under the mineral fertilization system $N_{40}P_{40}K_{40}$ – 2.39 t ha^{-1} compared to 1.93 t ha^{-1} without fertilization (Mashchenko and Sokolovska, 2023). In the Forest-Steppe of Ukraine, the highest yields of sunflower hybrids (2.81–3.02 t ha^{-1}) were obtained with the application of $N_{32}P_{32}K_{32}$ as a base fertilizer during primary soil tillage (Hanhur et al., 2022). Sunflower yield levels of up to 5.5 t ha^{-1} can be achieved when the crop consumes 331 mm and 297 mm of water over the growing season (Inzunza-Ibarra et al., 2022).

Under moisture-deficient conditions during critical growth stages of soybean – particularly during budding and flowering – the crop's physiological genetic potential is not fully realized. This leads to a reduction in plant height, fewer pods formed, and a decrease in thousand seed weight (Shcherba et al., 2022; Fedoruk et al., 2020). Drought stress induces water deficit in plants, resulting in cellular dehydration and disruption of normal cellular functions. Under such conditions, soybean plants reduce their water content, leading to wilting and leaf abscission (Hoffmann et al., 2021; Sanusi et al., 2025). To cope with potential damage, soybean plants have evolved adaptive mechanisms to withstand unfavorable environmental conditions. They undergo morphological, physiological, and biochemical changes that help them adapt to stress and complete their life cycle successfully (Zhang et al., 2019; Basal and Szabó, 2020). In response to drought, soybean leaves produce reactive oxygen species (ROS), accumulate osmotically active molecules, and enhance antioxidant activity to maintain cell membrane stability and minimize damage (Wang et al., 2022; Ryabukha et al., 2023). As a legume, soybean is capable of partially meeting its nitrogen requirements through biological nitrogen fixation. This process involves the activation and reduction of atmospheric nitrogen (N_2) to ammonia (NH_3), which is then assimilated into organic compounds within the plant. Through symbiosis with nitrogen-fixing bacteria, soybean plants can fulfill approximately 50–70% of their nitrogen demand (Staniak et al., 2024).

According to Kyryliuk et al. (2025) and Tymoshchuk et al. (2025), soil tillage systems had a significant effect – over 60% – on the reserves of productive soil moisture, whereas the influence of mineral fertilizers within the 0–40 cm soil layer accounted for only 24%. The application of mineral fertilizers at a rate of $N_{60}P_{60}K_{60}$ resulted in an average soybean grain yield of 2.25–2.49 t ha^{-1}. The highest available moisture reserves in the 0–40 cm layer were recorded under mineral fertilization combined with chisel or differentiated tillage systems. A moderate positive correlation (r = 0.66) was observed between soybean yield and the amount of productive soil moisture at the flowering stage under different tillage systems and mineral fertilizer variant Soybean yields ranged from 2.13 to 2.26 t ha^{-1}, reaching up to 2.60 t ha^{-1} with the use of top-dressing, inoculant application, and water-soluble fertilizers during critical growth stages (Trius et al., 2024). Other studies reported yield fluctuations from 2.15 to 2.73 t ha^{-1}, with an average of 2.41 t ha^{-1}, under total water use ranging from 2960 to 3800 m^3 ha^{-1}, and a mean value of 3340 m^3 ha^{-1} (Pendke et al., 2025).

Although low nitrogen availability limits soybean growth, higher nitrogen rates only slightly improve yields, while excessive nitrogen application may reduce both yield and (WUE). In the referenced study, maximum soybean yields of 4.096–4.404 t ha^{-1} were achieved with an application rate of 180 kg ha^{-1} of nitrogen (active ingredient), attributed to an increase in pod and seed numbers (Xu et al., 2025).

With the application of $N_{30}P_{60}K_{60}$ fertilizer and pre-sowing seed variant, the yield of the soybean variety Sandra reached 2.91 t ha^{-1}, while the early-maturing variety Legenda produced 2.51 t ha^{-1} (Mazur et al., 2023). Other studies report that soybean seed yield levels in the Forest-Steppe zone of Ukraine varied between 2.10 and 3.10 t ha^{-1}. The lowest yields (2.10–2.22 t ha^{-1}) were recorded in control variants without fertilizer application. In contrast, mineral fertilization at a rate of $N_{45}P_{45}K_{45}$ resulted in an additional yield increase of 0.42–0.48 t ha^{-1} compared to the control, or by 20–22% (Rasevich and Tetereshchenko, 2023). According to data from the Institute of Feed Research of the NAAS of Ukraine, only a few soybean cultivars – both domestic and foreign – exceeded 3.0 t ha^{-1} under the conditions of the Right-Bank Forest-Steppe of Ukraine, with 1000-seed weight above 180 g. However, the average yield across all varieties was 2.82 t ha^{-1} (Petrychenko et al., 2024; Didur et al., 2020).

In modern agricultural systems, biological factors are gaining increasing importance. Their effectiveness has been confirmed by studies involving the use of crop residues from previous crops (e.g., shredded cereal straw). On control plots (ploughing to a depth of 20–22 cm and the use of straw as fertilizer), soybean yield was 1.58 t ha^{-1} and increased by 0.23 t ha^{-1} in variants with spring chiseling. The application of mineral fertilizers and two foliar variants with an organic fertilizer-biostimulant also improved yields by 22.1% under ploughing with mineral fertilizers, and by 42.4% in other variants (Kunychak et al., 2024). Fertilization with crop residues alone contributed to increased soybean yields under different tillage systems – by 28.9% under moldboard ploughing, 29.9% under flat-cut tillage, and 13.9–20.3% under disk tillage – compared to the unfertilized control. This effect is associated with the soybean plant's ability to fix atmospheric nitrogen (average yield without fertilization was 2.08 t ha^{-1}; with crop residues – 2.52 t ha^{-1}; with $N_{40}P_{50}K_{60}$ and crop residues – 3.02 t ha^{-1}) (Ptashnik et al., 2025). Total water consumption by soybeans was the lowest under ploughing – ranging from 4800 to 4900 m^3 ha^{-1} – while it increased to 4896–5189 m^3 ha^{-1} under long-term no-tillage. Due to more intensive plant growth under post-harvest green manure (cover crop) variants, total water use by the crop increases. Under ploughing, the water requirement for producing 1 tonne of yield ranged from 1280 to 1480 m^3 (Hranovska and Reznichenko, 2023).

Improving (WUE) by plants depending on the fertilization system is one of the key factors in adapting agricultural technologies to contemporary climate changes. Conditions of water deficit, exacerbated by decreasing precipitation and increasing average annual temperatures, necessitate comprehensive studies on the impact of various fertilization systems on water consumption and (WUE) of soybean and sunflower (Hoover et al., 2022).

The scientific focus of this research lies in exploring the relationships between fertilization systems, residual effects of fertilizers combined with the use of crop residues, and the soil's capacity to accumulate and retain productive moisture. This knowledge enables optimization of the water regime of crops, enhancement of plant drought tolerance, and yield improvement by reducing the water consumption coefficient per unit of produced biomass. Detailed analyses have been conducted on productive moisture reserves, water consumption, and (WUE) coefficients of soybean and sunflower crops depending on the immediate and residual effects of mineral and organic fertilizers, as well as their influence on yield.

The hypothesis of this study is that in regions with unstable moisture supply, soybean and sunflower can be effectively cultivated in row crop rotations due to their ability to extract productive soil moisture from different soil layers, thereby ensuring high yields. Given the high natural fertility of typical chernozem soils, it is assumed that the residual effects of previously applied fertilizers can be utilized without significant yield reduction, since the primary limiting factor is the availability of productive moisture. The research is based on a stationary field experiment conducted during 2022–2024 within a row crop rotation system, where soybean and sunflower were grown under different fertilization systems and residual fertilizer effects. The study assessed productive soil moisture reserves at various depths (0–20, 21–50, 51–100, and 101–150 cm) at sowing and harvesting, total water consumption during the growing season, (WUE) coefficients, and yield performance.

METHODS

The study of the water regime of soybean and sunflower was conducted in a long-term stationary experiment at the Bila Tserkva State Research Station, Kyiv region, an area with unstable moisture supply in the Central Forest-Steppe zone of Ukraine, during the period 2022–2024. The soil of the experimental field is a deep, typical leached chernozem, low-humus, coarse-silty medium loam, with a humus content of 3.6–3.8% in the 0–30 cm layer; available phosphorus forms 153–170 mg kg^{-1} soil (high content) and exchangeable potassium 64–78 mg kg^{-1} soil (medium content) according to DSTU 4115:2002; hydrolyzable nitrogen 120–140 mg kg^{-1} soil (low content) according to DSTU 7863:2015. The plot size was 100 m² with three replications. The crop cultivation technology used was standard for the zone. The study was conducted within a row crop rotation: sugar beet – barley – soybean – sunflower – vetch-oats – winter wheat (forage crops – 17%, row crops – 50%, cereals – 33%). The crop rotation mineral fertilizer norm was $N_{320}P_{250}K_{250}$, organic fertilizers included 40 t ha^{-1} manure, straw, and tops; per 1 ha of rotation area, this corresponded to $N_{53}P_{42}K_{42}$ + 6.7 t ha^{-1} manure (Table 1).

Var. 5–10 investigated the residual effect of previously applied fertilizer rates in combination with the incorporation of crop residues from the crop rotation. Since 2006, no fertilizers have been applied to soybean and sunflower. Var. 5 – previous application (1976–2006) in the crop rotation of $N_{53}P_{42}K_{42}$ + 6.7 t ha^{-1} of manure (for soybean $N_{40}P_{40}K_{40}$; for sunflower $N_{50}P_{60}K_{60}$). Var. 6 – previous application (1976–2006) in the crop rotation of a double rate of both mineral and organic fertilizers: $N_{106}P_{84}K_{84}$ + 13.4 t ha^{-1} of manure (for soybean $N_{80}P_{80}K_{80}$; for sunflower $N_{100}P_{120}K_{120}$). Var. 7 – previous application (1976–2006) in the crop rotation of a double rate of mineral fertilizers with a single rate of manure: $N_{106}P_{84}K_{84}$ + 6.7 t ha^{-1} of manure (for soybean $N_{80}P_{80}K_{80}$; for sunflower $N_{100}P_{120}K_{120}$). Var. 8 – same as Var. 7 ($N_{106}P_{84}K_{84}$ + 6.7 t ha^{-1}), combined with soil liming (for soybean $N_{80}P_{80}K_{80}$; for sunflower $N_{100}P_{120}K_{120}$). Var. 9 – previous application (1976–2006) in the crop rotation of a triple fertilizer rate: $N_{159}P_{126}K_{126}$ + 6.7 t ha^{-1} of manure (for soybean $N_{120}P_{120}K_{120}$; for sunflower $N_{150}P_{180}K_{180}$). Var. 10 – previous application (1976–2006) in the crop rotation of a quadruple fertilizer rate: $N_{212}P_{168}K_{168}$ + 6.7 t ha^{-1}of manure (for soybean $N_{160}P_{160}K_{160}$; for sunflower: $N_{200}P_{240}K_{240}$). Nitroammophoska (16:16:16), ammonium nitrate, and granular superphosphate were applied by broadcast. The no fertilized variants have not received fertilizers since 1976, relying solely on natural soil fertility, while in the residual fertilizer effect variants with by-product

Table 1. Fertilization systems for soybean and sunflower in the row crop rotation

Var.	Soybean	Sunflower	Per 1 ha of crop rotation area
1	No fertilizers since 1976; only natural fertility of typical chernozem		No fertilizers
2	$N_{40}P_{40}K_{40}$	$N_{50}P_{60}K_{60}$	$N_{53}P_{42}K_{42}$
3	$N_{40}P_{40}K_{40}$	$N_{90}P_{60}K_{60}$	$N_{53}P_{42}K_{42}$ + 6.7 t of manure
4	No fertilizers	No fertilizers	6.7 t of manure
5–10	Incorporation of crop residues from the rotation		

use, fertilizers have not been applied since 2006. Soybean and sunflower varieties sown were those listed in the official variety registry: Apollo (soybean) and Tunka (sunflower).

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; $m0$ – 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 WUE – the ratio of total water consumption to the yield level of main and by-products in m^{-3} ha – was determined using the formula:

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

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 products was determined by harvesting and weighing the entire plot, while straw yield was measured using sample sheaves. Statistical data processing was performed using ANOVA software. According to the results of ANOVA (comparison between data groups) the number of replications was n = 6. Significant differences between group means were determined using Tukey's honest significant difference (HSD) test at the 5% probability level (Tukey HSD (B), $p < 0.05$. Grain and straw yields were analyzed separately as main and by-products (n = 3). Standard deviation (SD) is provided. Statistical differences between treatment means were evaluated using Tukey's HSD test ($p < 0.05$).

RESULTS AND DISCUSSION

The reserves of available soil moisture in the arable layer at the time of soybean emergence were sufficient for plant growth and development, depending on the fertilization system. This can be attributed to the later sowing dates and precipitation that occurred in April (72.8 mm in 2022, 101.3 mm in 2023, 69.34 mm in 2024, compared to the long-term average of 40 mm). The available moisture reserves in the 0–20 cm and 0–50 cm soil layers ranged from 24 to 28 mm and 68 to 72 mm, respectively (Figure 1a). In the 0–100 cm layer, the available moisture reserve under the no fertilized variant was 160 mm, while in the fertilized variants it increased to 167 and 164 mm. However, in the 0–150 cm layer, the difference was insignificant, ranging from 242 to 256 mm.

At the time of harvest, despite 146 mm of precipitation during the growing season, available soil moisture reserves in soybean crops were virtually absent in the 0–20 cm soil layer, amounting to only 2–3 mm. This was primarily due to the complete lack of rainfall during the second and third ten-day periods of August and the first ten-day period of September (2023–2024), accompanied by air temperatures exceeding the long-term average by +3.4 to +6.1 °C. In the 0–50 cm soil layer, only residual moisture reserves of 10–14 mm were recorded, which can be attributed to their full utilization by the plants and the delayed harvesting period. Minor available moisture reserves of 20–22 mm (Var. 2, 3) were observed in the 51–100 cm layer under fertilizer application, and 20–24 mm in variants with residual effects of organic and mineral fertilizers (Figure 1b). A significant increase in available

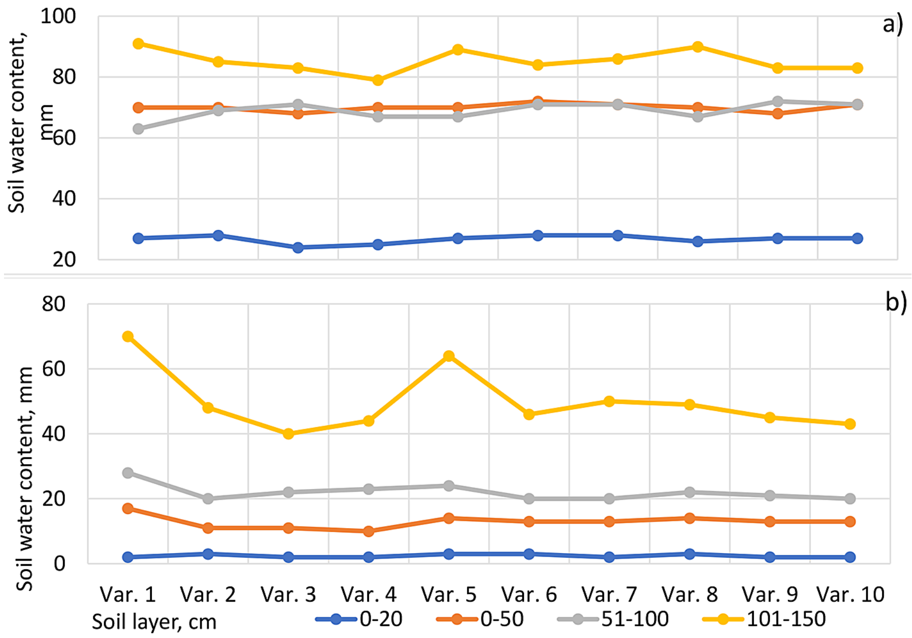

Figure 1. Distribution of available soil moisture reserves across soil layers at the time of sowing (a) and harvesting (b) of soybean, depending on the fertilization system and residual effects of applied fertilizers

soil moisture was recorded only in the no fertilized variant – 47 mm in the 0–100 cm layer and 117 mm in the 0–150 cm layer, which exceeded the control variant 3 by 12 mm and 42 mm, respectively. This can be explained by the considerably lower yield of the crop. Overall, across the soil profile, a clear trend was observed: available soil moisture reserves decreased in variants where higher soybean yields were obtained.

According to research, the greatest moisture deficit in soybean crops occurs during the flowering to grain-filling stages, which may lead to a shortened growing season and reduced yield (Shcherba et al., 2022; Fedoruk et al., 2020; Sanusi et al., 2025; Kyryliuk et al., 2025). In our study, the intensive growth and development of plants required mineral nutrients, which led to a reduction in soil moisture reserves in the 0–150 cm layer to 72–82 mm under the application of $N_{40}P_{40}K_{40}$. Under the residual effect of fertilizers (Var. 5–10), the moisture reserves ranged from 78 to 106 mm, which was sufficient for yield formation depending on the fertilization system.

Overall, during the growing season, soybean plants consumed the largest amount of moisture from the 0–50 cm soil layer (excluding the 0–20 cm layer, where available moisture reserves were minimal or entirely absent in 2024), amounting to 53–60 mm, or 81.4% of the initial reserves. In the 51–100 cm soil layer, moisture consumption was 35–51 mm, or 31.9%, and only 21–43 mm, or 58.8% of the initial reserves, was used from the 101–150 cm layer.

At the time of sunflower sowing (following soybean as the preceding crop), the available soil moisture reserves were sufficient to ensure uniform seedling emergence, amounting to 24–28 mm in the 0–20 cm soil layer (Figure 2a). In the 0–50 cm layer, moisture reserves increased to 68–82 mm, and in the 0–100 cm layer—to 163–176 mm. According to the results of ANOVA (comparison between data groups), a significant difference in available soil moisture in the 0–100 cm layer was observed only between variant 1 (no fertilizers applied since 1976) and variants 2 and 3 with the application of mineral fertilizers at $N_{50}P_{60}K_{60}$ and $N_{90}P_{60}K_{60}$ rates. Other fertilization variants and residual effects of fertilizers showed no statistically significant deviations. Compared to soybean crops, higher moisture reserves were recorded in the 101–150 cm soil layer under the residual effects of different fertilizer rates, amounting to 86–89 mm (Var. 4–10), while under $N_{90}P_{60}K_{60}$ application they reached 84 mm, and in the no fertilizers variant since 1976 – 106 mm. A similar trend was observed in the entire 0–150 cm soil profile: under $N_{90}P_{60}K_{60}$ application, the available moisture reserve was 243 mm, while in the no fertilizers variant it was 26 mm higher, which is explained by the higher yield of sunflower.

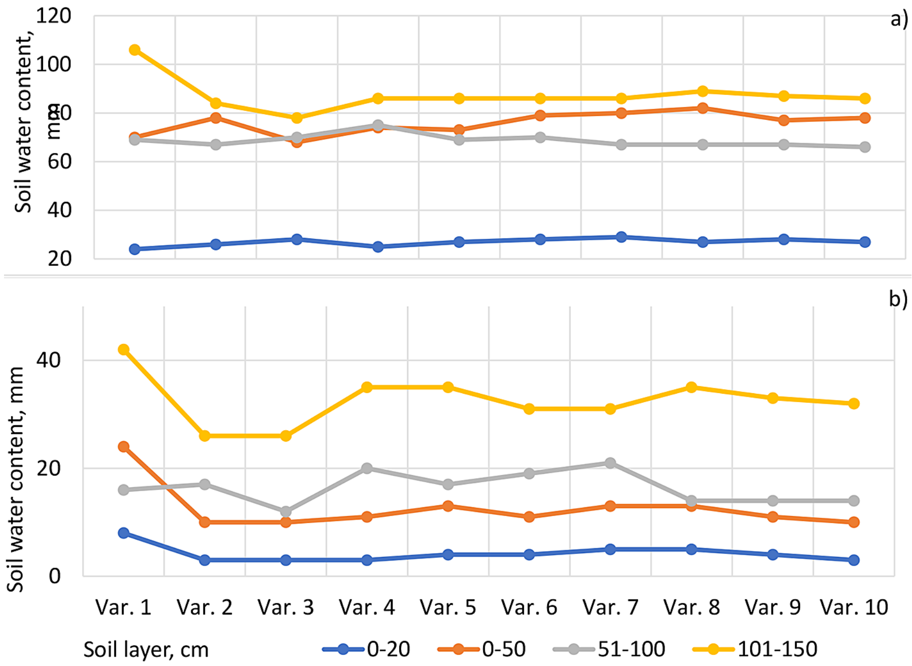

Figure 2. Distribution of available soil moisture reserves across soil layers at the time of sowing (a) and harvesting (b) of sunflower, depending on the fertilization system and the residual effects of applied fertilizers

At the time of harvest, sunflower plants had utilized the available soil moisture reserves from both the 0–20 cm layer (3–5 mm) and the 0–50 cm layer (10–13 mm), with higher values observed only in the no fertilized variant – 8 mm and 24 mm, respectively. Considering the well-developed root system of sunflower, a substantial reduction in available soil moisture was observed in the 51–100 cm soil layer, where reserves decreased to 12–21 mm. In the 0–100 cm soil layer, the difference in available moisture between the no fertilized variant since 1976 (Var. 1) and those with $N_{50}P_{60}K_{60}$ and $N_{90}P_{60}K_{60}$ applications (Var. 2, 3) amounted to 19 and 23 mm, respectively (48 mm in var. 1 vs. 29 mm and 25 mm in var. 2, 3). In variants with the residual effect of fertilizers, available moisture reserves in the 0–100 cm soil layer also remained at a relatively low level – only 28–39 mm.

Overall, during the growing season, sunflower plants consumed the largest amount of moisture from the 0–100 cm soil layer – 135–144 mm, or 80.8% of the initial reserves, taking into account 177 mm of precipitation during the vegetation period. By soil layers, this amounted to 22–25 mm (or 85.1%) in the 0–20 cm layer, 58–69 mm (82.9%) in the 0–50 cm layer, and 46–58 mm (46.8%) in the 51–100 cm layer. Even in the 101–150 cm layer, sunflower plants extracted 51–58 mm of moisture, which corresponds to 36.5% of the initial reserves. Moreover, when comparing available moisture reserves at harvest time with those under soybean, sunflower plants utilized on average 15 to 37 mm more in the 0–150 cm soil profile.

A detailed analysis of weather conditions during the study years revealed an increase in air temperature, particularly in the winter and summer months. For instance, air temperatures in July and August exceeded the long-term averages by +4.3 °C and +6.7 °C in 2022, +2.8 °C and +4.8 °C in 2023, and +5.6 °C and +4.0 °C in 2024, respectively (Figure 3). The average annual precipitation totals 526 mm; however, there was a clear variation in its distribution across the years: 504 mm in 2022, 488 mm in 2023, and 521 mm in 2024 (Figure 4).

The distribution of precipitation throughout the year is uneven: a higher amount falls during the warm period of the year, and a lower amount during the winter. March 2022 was quite dry and warm, with precipitation amounting to only 32% of the norm. April was warm and wet, while May was cool and dry. The summer was abnormally hot: June was +3.6 °C, July +3.1 °C, and August +5.9 °C above average, with precipitation at 87% of the norm (falling over just a few days in the form of heavy showers). Autumn temperatures

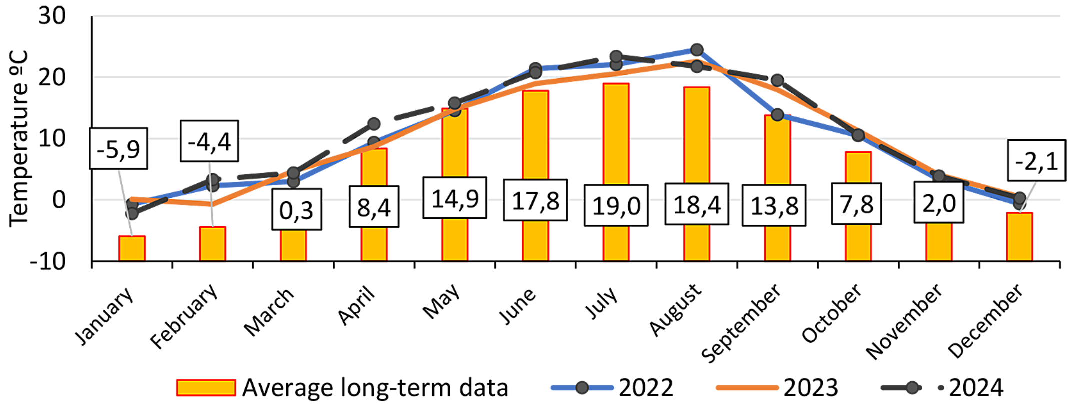

Figure 3. Air temperature, °C

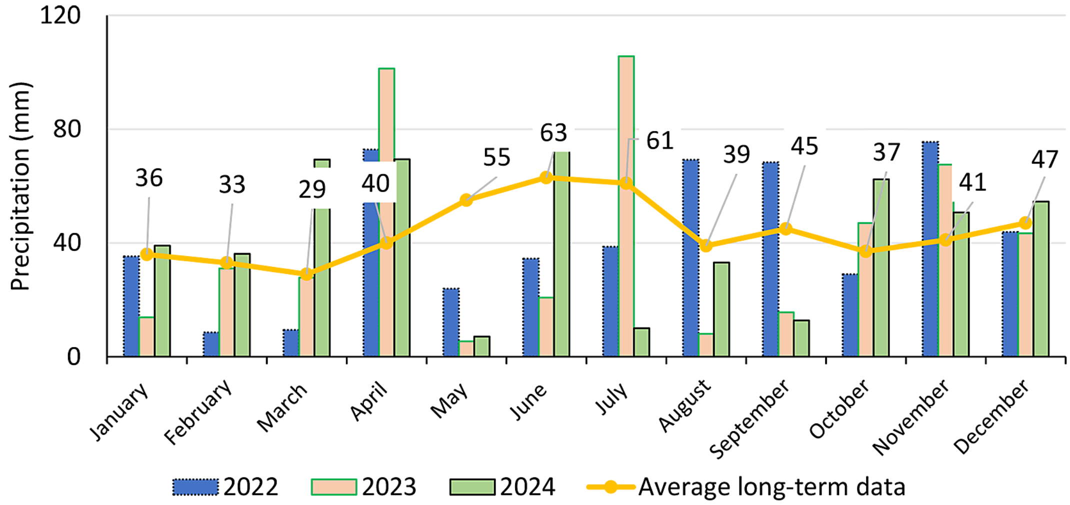

Figure 4. Precipitation amount, mm

were close to the long-term average, with precipitation reaching 128% of the norm.

In 2023, the amount of precipitation during the winter period was 70% of the norm. At the same time, a rainy April (101 mm) contributed to the accumulation of productive soil moisture, although May was dry. During the summer months, precipitation reached 83% of the norm, while air temperature exceeded the long-term average by +2.3 °C. Autumn was warm and rainy. Overall, there was a shortfall of 45 mm of precipitation for the year. In 2024, a significant increase in air temperature was observed during the winter and spring periods, especially in February (+7.7 °C), March (+4.3 °C), and April (+4.0 °C) compared to the long-term average, while precipitation remained within the normal range. The summer was the hottest on record, with temperatures exceeding the average by +3.6 °C and precipitation amounting to only 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.

At the beginning of the soybean growing season, during the period of intensive root system development, vegetative growth is slow, and water uptake by the plants is minimal. In the variant no fertilizers since 1976, the reserves of productive moisture in the 0–150 cm soil layer decreased by 134 mm, and total water consumption during the growing season amounted to 2800 m^3 ha^{-1} (Table 2). With the application of $N_{40}P_{40}K_{40}$, water use increased (taking into account 146 mm of rainfall during the growing period) to 3150 and 3173 m^3 ha^{-1}. However, the yield of both main and by-products increased by 1.6–1.7 times compared to the no fertilized variant.

A rather high residual effect was observed from a single application of manure at a rate of

40 t ha^{-1} under sugar beet (equivalent to 6.7 t ha^{-1} per hectare of crop rotation area). Soybean plants produced 8.40 t ha^{-1} of main and by-products, with a total water consumption of 3080 m^3 ha^{-1} and a (WUE) of 375 m^3 t^{-1}, which is close to the values observed in the fertilized variants.

Total water consumption in variants no fertilizer application since 2006 (under the residual effects of mineral and organic fertilizers applied in previous crop rotations at rates equivalent to 1–4 doses of NPK) did not increase significantly, ranging from 2923 to 3193 m^3 ha^{-1}. However, yield decreased to 5.94 t ha^{-1} under the residual effect of 1 NPK dose, resulting in an increased (WUE) ratio of 500 m^3 t^{-1}. With the residual effect of 2 NPK doses, yield increased slightly to 6.04–6.75 t ha^{-1}, but the (WUE) remained high, ranging from 499 to 516 m^3 t^{-1}. Only the residual effect of 3–4 NPK doses allowed soybeans to reach yields of 7.21 and 7.53 t ha^{-1}, with (WUE) of 442 and 452 m^3 t^{-1}, respectively; however, these values are still 106–110 m^3 t^{-1} higher compared to direct application of $N_{40}P_{40}K_{40}$.

Sunflower crops used the reserves of productive moisture in the 0–150 cm soil layer at levels ranging from 179 to 200 mm, including 177 mm of rainfall during the growing season (Table 3). In this case, water consumption by the plants in the no fertilized variant since 1976 amounted to 3557 m^3 ha^{-1}, while with the application of $N_{50}P_{60}K_{60}$ and $N_{90}P_{60}K_{60}$ it increased to 3773 and 3700 m^3 ha^{-1}, respectively. It should be noted that regardless of the dose (1–4 doses of NPK, Var. 5–10), the residual effects of fertilizers resulted in high water consumption levels – 3703 to 3760 m^3 ha^{-1} – most likely due to water use from the deeper soil layers. The highest yield of both main and by-products was observed in the variants with $N_{90}P_{60}K_{60}$, reaching 10.20 t ha^{-1}. A significant decrease in yield was observed only in the no fertilized variant from 1976, with 5.94 t ha^{-1}, and in the no fertilized variant from 2006, with 6.91 t ha^{-1}. In the fertilizer residual variants, especially after the residual effect of 2 NPK, manure + incorporation of by-products, and the residual effect of 4 NPK, manure + incorporation of by-products, sunflower

Table 2. Calculation of total water use in the 1.5-meter soil profile and (WUE) in soybean crops as affected by fertilizer application systems and their residual effects

Fertilization system	Productive water reserves, mm		Reduction of reserves during the growing, mm season, mm	Water use by plants, m^3 ha^{-1}	**Crop yield, t ha^{-1}	(WUE), m^3 t^{-1}
	At the time of sowing	At the time of harvest				
1. No fertilizers applied since 1976	251	117	134	2800	$5.59^{\pm0.59}$	505
2. $N_{40}P_{40}K_{40}$ ($N_{53}P_{42}K_{42}$)*	252	82	169	3150	$9.19^{\pm1.89}$	348
3. $N_{40}P_{40}K_{40}$ ($N_{53}P_{42}K_{42}$ + 6.7 t ha^{-1} of manure)*	247	75	172	3173	$9.54^{\pm1.38}$	336
4. Residual effect of manure (6.7 t ha^{-1} of manure)*	242	80	162	3080	$8.40^{\pm1.76}$	375
5. No fertilizers applied since 2006 (residual effect fertilizers)*	252	106	147	2923	$5.94^{\pm0.73}$	500
6. No fertilizers applied since 2006 (residual effect fertilizers)*	255	81	174	3193	$6.75^{\pm1.23}$	483
7. No fertilizers applied since 2006 (residual effect fertilizers)*	256	85	171	3170	$6.47^{\pm1.14}$	499
8. No fertilizers applied since 2006 (residual effect fertilizers)*	252	89	163	3083	$6.04^{\pm0.92}$	516
9. No fertilizers applied since 2006 (residual effect fertilizers)*	251	81	170	3160	$7.21^{\pm1.67}$	452
10. No fertilizers applied since (residual effect fertilizers)*	252	78	173	3190	$7.53^{\pm2.07}$	442

Note: *Fertilizer application per 1 ha of crop rotation area, var. 5 – residual effect of a single NPK application + manure + incorporation of crop residues, var. 6 – residual effect of double NPK dose + double manure + incorporation of crop residues, var. 7 – residual effect of double NPK dose + manure + liming + incorporation of crop residues, var. 8 – residual effect of double NPK dose + manure + liming + incorporation of crop residues, var. 9 – residual effect of triple NPK dose + manure + incorporation of crop residues, var. 10 - residual effect of quadruple NPK dose + manure + incorporation of crop residues. **Crop yield includes main and by-products. Comparison was made using ANOVA between the fertilization system, where data are significant at p *<0.05, **p<0.01, ***p<0.001.

Table 3. Calculation of total water use in the 1.5-meter soil profile and (WUE) in sunflower crops as affected by fertilizer application systems and their residual effects

Fertilization system	Productive water reserves, mm		Reduction of reserves during the growing season, mm	Water use by plants, $m^3\ ha^{-1}$	*Crop yield, $t\ ha^{-1}$	(WUE), $m^3\ t^{-1}$
	At the time of sowing	At the time of harvest				
1. No fertilizers applied since 1976	269	90	179	3557	$5.94^{\pm0.89}$	597
2. $N_{50}P_{60}K_{60}$ ($N_{53}P_{42}K_{42}$)*	255	55	200	3773	$9.70^{\pm1.69}$	392
3. $N_{90}P_{60}K_{60}$ ($N_{53}P_{42}K_{42}$ + 6.7 t ha^{-1} of manure)*	243	50	193	3700	$10.20^{\pm1.86}$	366
4. Residual effect of manure (6.7 t ha^{-1} of manure)*	259	69	191	3677	$8.57^{\pm1.99}$	438
5. No fertilizers applied since 2006 (residual effect fertilizers)*	255	69	186	3630	$6.91^{\pm1.35}$	530
6. No fertilizers applied since 2006 (residual effect fertilizers)*	262	64	197	3743	$8.22^{\pm1.18}$	458
7. No fertilizers applied since 2006 (residual effect fertilizers)*	263	70	193	3703	$7.31^{\pm1.42}$	515
8. No fertilizers applied since 2006 (residual effect fertilizers)*	266	67	199	3760	$7.79^{\pm1.55}$	492
9. No fertilizers applied since 2006 (residual effect fertilizers)*	260	62	198	3753	$7.98^{\pm1.34}$	475
10. No fertilizers applied since (residual effect fertilizers)*	256	59	197	3737	$8.32^{\pm1.58}$	456

Note: *Fertilizer application per 1 ha of crop rotation area, Var. 5–10 (see Table 1 for details). **Crop yield includes main and by-products. Comparison was made using ANOVA between the fertilization system, where data are significant at p *<0.05, **p<0.01, ***p<0.001.

yield amounted to 8.22 and 8.32 t ha^{-1}, or 80.6 % and 81.6 % of the $N_{90}P_{60}K_{60}$ variant (Var. 3), respectively. High effectiveness of organic fertilizer residuals was also noted, with a yield of 8.57 t ha^{-1}, or 84% of the maximum. The (WUE) significantly increased in the no fertilized variants from 1976 and 2006 (Var. 1, 5) to 597 and 530 $m^3\ t^{-1}$, which exceeded the $N_{90}P_{60}K_{60}$ variant by 231 and 164 $m^3\ t^{-1}$. Among the fertilizer residual variants, those with Var. 6, 10 showed (WUE) of 456 and 458 $m^3\ t^{-1}$, while other variants showed increased values, with the difference from $N_{90}P_{60}K_{60}$ ranging from 90 to 92 $m^3\ t^{-1}$.

Thus, under the residual effect of fertilizers, sunflower plants, due to their ability to utilize productive moisture reserves from deeper soil layers (below 100 cm), are able to form yields of main and by-products in the range of 6.91–8.32 t ha^{-1}; however, this is accompanied by a significant increase in the (WUE).

In the Central Forest-Steppe of Ukraine, the potential soybean yield under $N_{40}P_{40}K_{40}$ fertilization was 3.39 and 3.45 t ha^{-1}, with a comparable value observed under the residual effect of manure applied in crop rotation – 3.16 t ha^{-1} (Table 4). In no fertilized variants since 1976 and 2006, a significant decrease in yield was noted – to 2.38 and 2.48 t ha^{-1}, respectively, or 69% and 72% of the maximum potential. A problematic aspect in soybean cultivation remains the residual effect of 2 NPK doses, where yields amounted to 2.49 and 2.64 t ha^{-1}, with a straw-to-grain ratio of 1.43 and 1.45, respectively, indicating substantial growth retardation in plants. Only with the residual effect of 3–4 NPK doses was an increase in soybean yield observed, reaching 2.83 and 2.90 t ha^{-1}, though with considerable annual variation (standard deviation of 0.36 and 0.43 t ha^{-1}). Both straw yield and the straw-to-grain ratio also increased under $N_{40}P_{40}K_{40}$ fertilization.

Sunflower yield depended more on the availability of productive soil moisture than on the fertilization system. Thus, considering the high natural fertility of typical chernozem, sunflower plants formed yields exceeding 3.0 t ha^{-1} both with fertilizer application rates of $N_{50}P_{60}K_{60}$ and $N_{90}P_{60}K_{60}$ – 3.38 and 3.81 t ha^{-1}, respectively – and under the residual effect of previously applied fertilizers: 2 doses of NPK + 2 manure – 3.10 t ha^{-1}, 3 doses of NPK – 3.03 t ha^{-1}, and 4 doses of NPK – 3.18 t ha^{-1}. The application of only organic fertilizers in the crop rotation also proved quite effective, providing a sunflower yield of 3.13 t ha^{-1}. In the no fertilized variants (since 1976 and 2006), the yield decreased to 2.34 and 2.43 t ha^{-1}, respectively. A significantly greater plant height was observed under $N_{50}P_{60}K_{60}$

Table 4. Soybean and sunflower yield depending on fertilizer application and its residual effect, average for 2022–2024

Var.	Soybean			Sunflower		
	Grain yield, t ha^{-1}	Straw		Grain yield, t ha^{-1}	Straw	
		Straw-to-grain ratio	Straw yield, t ha^{-1}		Straw-to-grain ratio	Straw yield, t ha^{-1}
1.	$2.38^{\pm 0.03*}$	1.35	$3.21^{\pm 0.56***}$	$2.34^{\pm 0.45**}$	1.54	$3.60^{\pm 0.53**}$
2.	$3.39^{\pm 0.24**}$	1.71	$5.81^{\pm 1.67**}$	$3.38^{\pm 0.33*}$	1.87	$6.32^{\pm 1.38***}$
3.	$3.45^{\pm 0.15***}$	1.77	$6.09^{\pm 1.27***}$	$3.81^{\pm 0.56*}$	1.68	$6.39^{\pm 1.85***}$
4.	$3.16^{\pm 0.24**}$	1.66	$5.24^{\pm 1.53*}$	$3.13^{\pm 0.39}$	1.74	$5.44^{\pm 1.65**}$
5.	$2.48^{\pm 0.16*}$	1.40	$3.46^{\pm 0.64**}$	$2.73^{\pm 0.45*}$	1.54	$4.19^{\pm 0.94***}$
6.	$2.70^{\pm 0.25**}$	1.50	$4.05^{\pm 1.02**}$	$3.10^{\pm 0.23**}$	1.65	$5.12^{\pm 1.04**}$
7.	$2.64^{\pm 0.23**}$	1.45	$3.83^{\pm 0.96***}$	$2.72^{\pm 0.48*}$	1.69	$4.59^{\pm 0.98*}$
8.	$2.49^{\pm 0.17**}$	1.43	$3.55^{\pm 0.80***}$	$2.81^{\pm 0.49*}$	1.77	$4.98^{\pm 1.13*}$
9.	$2.83^{\pm 0.36*}$	1.55	$4.38^{\pm 1.34*}$	$3.03^{\pm 0.48*}$	1.64	$4.95^{\pm 1.00**}$
10.	$2.90^{\pm 0.43*}$	1.60	$4.63^{\pm 1.67**}$	$3.18^{\pm 0.56*}$	1.62	$5.14^{\pm 1.18**}$

and $N_{90}P_{60}K_{60}$ application, which ensured green biomass yields of 6.32–6.39 t ha^{-1}, while in other variants it ranged from 5.12 to 5.44 t ha^{-1}, and in the no fertilized plots – 3.60 and 4.19 t ha^{1}.

CONCLUSIONS

According to our research on typical chernozems, the total water consumption in soybean crops did not significantly depend on the fertilization system or the residual effect of fertilizers, and ranged from 2923 to 3190 m^3 t^{-1}. Similarly, in sunflower crops, it ranged from 3557 to 3773 m^3 t^{-1}. The (WUE) per 1 ton of main and by-products in soybean crops under $N_{40}P_{40}K_{40}$ application was 336 and 348 m^3 t^{-1}, and 375 m^3 t^{-1} under the residual effect of organic fertilizer. In contrast, in no fertilized variants (since 1976 and 2006), the (WUE) to 500 and 505 m^3 t^{-1}. The residual effect of previously applied 3–4 doses of NPK + manure partially reduced it to 442 and 452 m^3 t^{-1}.

During the growing season, soybean plants consume the largest portion of productive soil moisture from the 0–20 cm and 0–50 cm soil layers. The application of fertilizers at a rate of $N_{40}P_{40}K_{40}$ promotes better root system development, allowing the plants to access moisture from deeper soil layers. Sunflower plants, due to their well-developed root systems, utilize productive moisture primarily from the entire 0–100 cm soil profile. Moreover, in the 101–150 cm soil layer, sunflower extracted 51–58 mm of water compared to initial reserves. When comparing productive moisture at harvest, sunflower plants extracted on average 15 to 37 mm more moisture from the 0–150 cm layer than soybean plants.

According to our research on typical chernozem soils, the total water consumption in soybean crops did not depend significantly on the fertilization system or the residual effect of fertilizers and ranged from 2923 to 3190 m^3 t^{-1}, sunflower crops – ranged from 3557 to 3773 m^3 t^{-1}. The (WUE) per ton of main and by-products in soybean under $N_{40}P_{40}K_{40}$ application was 336 and 348 m^3 t^{-1}, respectively, and 375 m^3 t^{-1} under the residual effect of previously applied organic fertilizers. In contrast, in unfertilized variant, the WUE increased to 500 m^3 t^{-1}. In sunflower crops, the (WUE) in no fertilized variants significantly increased to 597 and 530 m^3 t^{-1}, which exceeded that under $N_{90}P_{60}K_{60}$ fertilizer application by 231 and 164 m^3 t^{-1}, respectively.

Under the application of $N_{40}P_{40}K_{40}$, soybean plants achieved yields of 3.39 and 3.45 t ha^{-1}, whereas in unfertilized plots, a significant reduction to 2.38 t ha^{-1} was observed. It was established that soybean requires annual fertilization, as the absence of nutrient input leads to reduced plant height and lower yields. In dry years, soybean plants fully utilize the productive moisture reserves from the upper soil layers and partially from the lower layers, without substantial yield loss. Sunflower yield under fertilizer application ranged from 3.38 to 3.81 t ha^{-1}. Under the residual effect of fertilizers, yield remained relatively high (2.73–3.18 t ha^{-1}), confirming the feasibility of cultivating sunflower within row crop rotations in the forest-steppe zone of Ukraine.

The application of various fertilization systems, including mineral and organo-mineral fertilizers, as well as the incorporation of crop residues as organic amendments, enhances the soil's capacity to accumulate and retain productive moisture. This contributes to the optimization of the water regime in soybean and sunflower crops, increases their drought tolerance and (WUE), and reduces the water consumption coefficient per unit of yield under current climate change conditions.

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