










Regulation of productive soil moisture reserves in different links of short-rotation cereal-sugar beet crop rotations in the forest-steppe zone

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ABSTRACT

The study focuses on quantifying the contribution of precipitation during the period between harvest of the preceding crop and sowing of the subsequent crop to the formation of initial soil moisture reserves, evaluating crop-specific patterns of vertical moisture extraction within the 0–150 cm soil profile, and determining how different crop rotation models influence the efficiency of soil moisture utilization and stabilization of agroecosystem productivity under rainfed conditions. A multi-year field experiment (2020–2025) was conducted to assess precipitation distribution, soil moisture dynamics within the 0–150 cm layer, total crop water consumption, yield performance, and the water consumption coefficient (WCC) under different fertilization systems. The highest depletion of productive soil moisture was recorded under clover (205–212 mm) and sugar beet (up to 132 mm under 40 t ha⁻¹ manure + N₁₀₀P₉₀K₉₀), reflecting intensive moisture extraction from deeper soil horizons (50–150 cm). In contrast, winter wheat primarily utilized moisture from the 0–30 cm layer, and soil moisture reserves at harvest exceeded sowing values by 3–50 mm. Total crop water consumption ranged from 2193 to 5487 m³ ha⁻¹. Sugar beet demonstrated the highest productivity and water use efficiency: root yield reached 42.8 t ha⁻¹, total biomass 62.6 t ha⁻¹, with a WCC of 90 m³ t⁻¹ under organo-mineral fertilization. Sunflower consumed 4220–4400 m³ ha⁻¹ with grain WCC values of 1137–1491 m³ t⁻¹. Leguminous crops showed elevated WCC values under unfertilized conditions, reaching 3027 m³ t⁻¹ for spring vetch grain. Mineral (N₅₃P₄₂K₄₂) and organo-mineral (6.7 t ha⁻¹ manure + N₅₃P₄₂K₄₂) increased crop yields and reduced WCC across the crop rotations. The cereal–fodder–tilled crop rotation demonstrated the most efficient water use WCC (118 m³ t⁻¹ for total biomass and 160 m³ t⁻¹ for grain), whereas the tilled rotation exhibited the highest soil moisture depletion (up to 107 mm). Precipitation during the period between harvest of the preceding crop and sowing of the subsequent crop (48–394 mm) significantly influenced initial soil moisture reserves and subsequent crop performance, confirming its critical role in agroecosystem water balance formation.

Keywords: soil water content, yield, weather conditions, water use efficiency, water consumption coefficient, sugar beet, barley, winter wheat, soybean, sunflower, clover, spring vetch.

INTRODUCTION

Under conditions of unstable moisture supply in the forest-steppe zone of Ukraine, the principal limiting factors affecting field crop productivity

are precipitation deficits during the active growing season and elevated air and soil temperatures. These factors intensify physical evaporation and plant transpiration, reduce productive soil moisture reserves in the arable layer, and deteriorate

soil water potential. Their combined effect leads to suppression of photosynthetic activity, disrupts transpiration processes, and ultimately leads to a significant decline in crop yields (Bhattacharya, 2021; Luan et al., 2024; Ousayd et al., 2024).

In the context of global climate change, characterized by an increasing frequency of drought periods and temperature extremes, understanding hydrothermal conditions and their influence on the accumulation and utilization of productive soil moisture is increasingly important. Soil moisture reserves, together with atmospheric precipitation patterns, determine crop water consumption, photosynthetic efficiency, and yield formation under moisture-deficit conditions (Mei et al., 2024; Fries et al., 2020; Tarariko et al., 2025; Fu et al., 2024).

Considering the biological characteristics of crops and regional soil–climatic conditions, crop rotation systems serve as an essential tool for regulating the water regime of agroecosystems. Optimization of crop structure, implementation of diversified crop rotations, rational fertilization systems, and adaptive agronomic practices improve water use efficiency and reduce the water consumption coefficient, thereby decreasing the risk of yield losses under drought stress (Wang et al., 2024; Cui et al., 2022; Sainju et al., 2021). Compared with monoculture systems, crop rotations ensure more efficient utilization of soil moisture, stabilization of the water balance, and improvement of soil physical properties (Cherenkov et al., 2021).

Productive soil moisture reserves constitute a key component of the soil–plant interaction system and determine conditions for uniform seedling emergence and subsequent crop ontogenesis. Moisture deficits during critical growth stages significantly reduce the effectiveness of fertilization, crop protection measures, and other technological components of crop production. At the same time, assessment of soil moisture availability with consideration of crop developmental stages enables yield forecasting and optimization of management decisions.

Rational selection of crops within short-rotation cereal–sugar beet systems, optimization of tillage practices (reduced intensity and minimized mechanical disturbance), implementation of resource-saving fertilization strategies, and the use of drought-adapted varieties and hybrids contribute to reduced moisture losses and enhanced ecological resilience of agroecosystems. Investigation of the productive soil moisture balance, its

accumulation during the period between harvest and sowing, and its expenditure for yield formation provides a basis for developing science-based models of water regime regulation (Wang et al., 2024; Fries et al., 2020).

The amount of precipitation occurring between the harvesting of the preceding crop and the sowing of the subsequent crop characterizes moisture input into the soil during the inter-cropping period. In combination with data on total crop water consumption, this makes it possible to determine the proportion of precipitation effectively accumulated in the soil and to evaluate the efficiency of different crop rotation links in conserving and utilizing soil moisture.

Despite the considerable number of studies devoted to soil water balance and crop water use efficiency, the role of different crop rotation structures in regulating productive soil moisture reserves under conditions of unstable moisture supply in the Forest-Steppe zone of Ukraine remains insufficiently studied.

The aim of the study was to identify the regulatory role of crop rotation structure and fertilization systems in the formation and redistribution of productive soil moisture under conditions of increasing intra-annual hydrothermal variability in the Forest-Steppe zone of Ukraine.

The study focuses on quantifying the contribution of precipitation during the period between harvest of the preceding crop and sowing of the subsequent crop to the formation of initial soil moisture reserves, evaluating crop-specific patterns of vertical moisture extraction within the 0–150 cm soil profile, and determining how different crop rotation models influence the efficiency of soil moisture utilization and stability of agroecosystem productivity under rainfed conditions.

MATERIAL AND METHODS

The study was conducted within an established stationary crop rotation experiment at the Bila Tserkva Research and Breeding Station (Kyiv region, Ukraine), located in the zone of unstable moisture supply in the central Forest-Steppe (49°48' N, 30°06' E). The analysis is based on a multi-year observation period (2020–2025), which made it possible to evaluate soil moisture dynamics, precipitation distribution, and crop water consumption within one complete crop rotation cycle. The region is characterized by a

temperate continental climate with pronounced interannual variability in precipitation. The long-term average annual precipitation is 526 mm, with a mean annual air temperature of 7.5 °C and an average growing season temperature of 15.4 °C. The experiment included several six-field short-rotation crop rotations designed to assess the effect of crop rotation structure on soil moisture use and crop productivity.

The soil of the experimental field is deep, leached, low-humus typical chernozem, developed on loess deposits. According to the World Reference Base for Soil Resources (WRB) classification, the soil corresponds to Haplic Chernozem, while according to the Ukrainian soil classification it is classified as typical low-humus chernozem. The soil texture of the arable layer is silty medium loam, determined according to the pipette method (ISO 11277). The main agrochemical characteristics of the 0–30 cm soil layer were as follows: humus content – 3.6–3.8%; mobile phosphorus – 153–170 mg kg⁻¹ (high supply level, according to DSTU 4115:2002); exchangeable potassium – 64–78 mg kg⁻¹ (medium supply level, according to DSTU 4115:2002); alkaline hydrolysable nitrogen – 120–140 mg kg⁻¹ (low supply level, according to DSTU 7863:2015).

The soil bulk density in the arable layer was 1.21–1.33 g cm⁻³, which is typical for chernozem soils of the Forest-Steppe zone and ensures favorable conditions for root penetration and water movement within the soil profile. The soil is classified as a silty medium loam Haplic Chernozem with high water-holding capacity, with field capacity averaging 28–30% and the wilting point ranging from 12–14%. Groundwater occurs at a depth of 8–14 m, which excludes any significant capillary rise contribution to crop water supply within the 0–150 cm soil layer. The experimental field is located on flat terrain and is not equipped with an artificial drainage system. Under these conditions, vertical water movement is primarily governed by soil texture and pore structure, which limit rapid percolation beyond the root zone. The absence of excessive precipitation during the growing seasons (87–112% of the long-term norm), combined with the high moisture retention capacity of the soil, minimizes water losses due to deep percolation and surface runoff. No signs of temporary waterlogging or preferential flow were observed during the experimental period. Therefore, soil moisture reserves and atmospheric precipitation were considered the

main sources of crop water supply. The soil water balance was calculated assuming negligible contributions from groundwater and minimal losses beyond the 0–150 cm soil layer. These assumptions are supported by the stable dynamics of soil moisture and the absence of abrupt decreases in moisture reserves that would indicate significant water losses below the measured profile.

The accounting plot area was 100 m², with three replications. Crop cultivation technology followed regional agronomic recommendations for the forest-steppe zone of Ukraine, including standard tillage, fertilization, and crop protection practices. Crop rotation schemes: 1. cereal-fodder-tilled crop rotation: vetch-oat mixture – winter wheat – sugar beet – barley + clover – clover – winter wheat (the share of fodder crops 33%, tilled 17%, cereals 50%); 2. tilled crop rotation: vetch-oat mixture – winter wheat – sugar beet – barley – soybean – sunflower (the share of fodder crops 17%, tilled 50%, cereals 33%); 3. cereal-tilled crop rotation: vetch-oat mixture – winter wheat – sugar beet – barley – spring vetch – 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 (NH₄NO₃) 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: spring vetch – Yaroslava, Oat – Denka, winter wheat – Lyrica, sugar beet – Zluka, barley – Commander, clover – Predkarpatska 6, soybeans – Apollo, vetch – Bilotserkivska 96, sunflower – P64LE25.

The study was conducted over one cycle of three cereal-sugar beet crop rotations, which made it possible to trace patterns of soil moisture accumulation, precipitation utilization, total water consumption, and the water consumption coefficient both during the growing season and across the six-year rotation, recalculated per hectare of crop rotation area. Precipitation in crops was assessed for the period between harvesting the preceding crop and sowing the subsequent crop, based on calendar dates (Table 1).

Productive soil moisture reserves were determined using the gravimetric (thermostat-weight) method, which is a widely accepted international approach for assessing soil moisture in agronomic

Table 1. Calendar dates of sowing and harvesting of crops

Year	Crop	Sowing date	Harvesting date	Number of days between harvesting of the predecessor and sowing of the crop
2020	Vetch–oat mixture	22.05.20	17.06.20	311
2021	Winter wheat	21.09.20	19.07.21	96
2022	Sugar beet	17.04.22	29.09.22	272
2023	Spring barley	23.04.23	02.08.23	206
2024	Clover	31.03.24	01.06.24	242
2025	Winter wheat	19.09.24	09.08.25	110
2024	Soybean (tilled crop)	05.05.24	12.09.24	277
2024	Spring vetch (cereal-tilled crop)	09.04.24	26.07.24	251
2025	Sunflower (tilled crop)	25.04.25	26.09.25	225
2025	Winter wheat (cereal-tilled crop)	19.09.24	09.08.25	55

studies (ISO 11465; FAO guidelines). The method is based on determining the mass fraction of water in soil samples by drying them to constant weight. Soil samples were collected using a soil auger at 10 cm intervals to a depth of 0–150 cm for all crops. Soil moisture content was determined by drying the collected samples in a drying oven at 105 °C until constant weight was reached. The gravimetric soil moisture content (W , %) was calculated as the ratio of the mass of lost water to the mass of absolutely dry soil.

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

$$W = \frac{u \times \gamma \times h}{10} \quad (1)$$

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.

The obtained values were summed for the 0–150 cm soil layer, which allowed the determination of the total reserves of productive soil moisture at the time of observation. The determination and calculation of productive soil moisture reserves were carried out before sowing each crop (1–2 days prior to sowing) and after harvesting (1–2 days before harvest).

Total water consumption of crops was determined using the soil water balance method, which is based on accounting for all water inputs and outputs within the soil–plant–atmosphere system during the growing season. The calculation was performed by determining the productive soil moisture reserves at the beginning and at the end of the growing period, taking into account

the amount of atmospheric precipitation received during this time.

Total water consumption was calculated according to the soil water balance equation:

$$ET = (W_b - W_e) + P \quad (2)$$

where: ET – total water consumption during the growing season, mm; W_b – productive soil moisture reserves at the beginning of the growing season, mm; W_e – productive soil moisture reserves at the end of the growing season, mm; P – precipitation during the growing period, mm.

The WCC characterizes the efficiency of water use by crops and reflects the amount of water consumed to produce a unit of yield. It was determined as the ratio of total crop water consumption during the growing season to the yield level of the main and by-products.

The WCC – the ratio of total water consumption to the yield level of main and by-products in $\text{m}^3 \text{ ha}^{-1}$ – was determined using the formula:

$$K = \frac{W_n - W_k + O}{y} \times 10 \quad (3)$$

where: W_n – initial reserves of productive moisture in the soil, mm; W_k – final reserves of productive moisture in the soil, mm; Y – yield of main and by-products, t ha^{-1} ; O – precipitation, mm; 10 – conversion coefficient from mm to m^3 . The coefficient 10 is used to convert a water layer from millimeters to cubic meters per hectare, since a water layer of 1 mm over an area of 1 ha corresponds to a volume of 10 m^3 (1 ha = $10,000 \text{ m}^2$; 1 mm = 0.001 m).

The yield of the main crops was determined by harvesting and weighing the total biomass from each experimental plot in triplicate. For sugar beet, the yield of tops was estimated from samples of forty individual plants, whereas the straw yield of barley, wheat, vetch, sunflower, and soybean was assessed using representative sheaves from each sample. All results are reported as means ± standard deviation (n = 3), based on three independent field replicates.

RESULTS AND DISCUSSION

According to data from the Bila Tserkva Meteorological Station, agroclimatic conditions during the study years were characterized by significant deviations from long-term averages. In 2019–2020, total monthly precipitation varied considerably, with high rainfall in May (102.4 mm), June (60.7 mm), and July (73.8 mm), whereas the early autumn months received relatively low precipitation (September–October: 22.3 and 1.2 mm, respectively) (Figure 1). Air temperatures in 2019–2020 ranged from 0.4 °C in January to 21.2 °C in June, with a hot summer and mild autumn conditions supporting crop growth. In 2020–2021, precipitation patterns were even more variable, with exceptionally high rainfall in October (97.5mm) and May (132 mm), while other months showed moderate values. Temperatures range from -4.6 °C in February to 23.0 °C in July. A warm winter with adequate snow cover ensured substantial productive soil moisture reserves for

spring crops. Elevated precipitation in May and July, combined with above-average temperatures in June and July, positively affected early crop development and overall growth dynamics.

In 2022, total precipitation during the growing season amounted to 336 mm; however, its distribution was extremely uneven both monthly and by ten-day periods. Precipitation ranged from 151.8–182.0% of the long-term monthly average in April, August, and September to only 43.5–63.4% of the monthly norm in May–July. Air temperature exceeded long-term average values in all months except May and September and was, on average, +2.3 °C higher than the climatic norm. Such hydrothermal conditions contributed to irregular soil moisture replenishment and increased evaporative demand during critical crop growth stages. In 2023, winter precipitation accounted for only 70% of the long-term norm. At the same time, a rainy April (101 mm) promoted the accumulation of productive soil moisture reserves prior to the onset of active vegetation. However, May was characterized by moisture deficit. During the summer months, precipitation reached 83% of the norm, while the average air temperature exceeded the long-term mean by +2.3 °C. Autumn was warm and relatively wet, yet the total annual precipitation remained 45 mm below the climatic norm. In 2024, a substantial 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 long-term averages, while precipitation remained within the climatic norm. Summer was the hottest

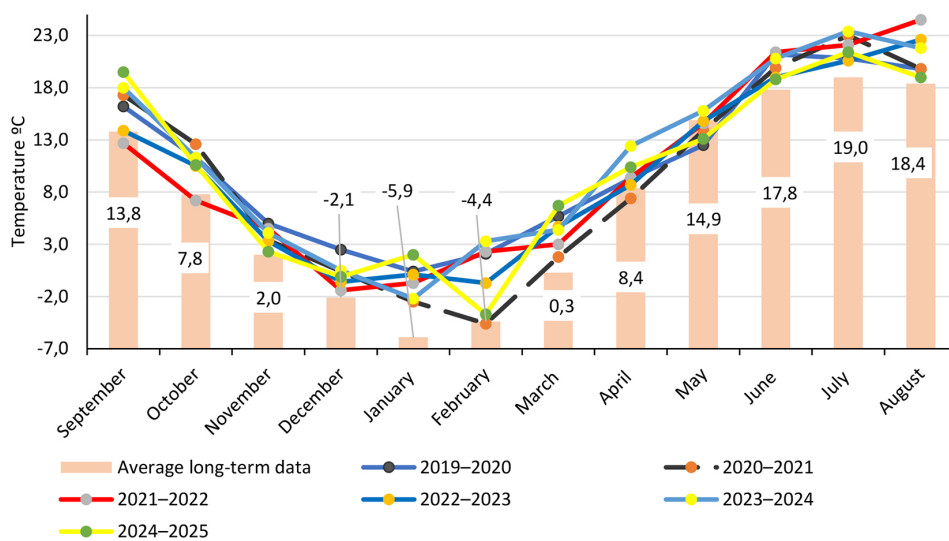


Figure 1. Air temperature, °C

among the studied years, with temperatures exceeding the long-term average by +3.6 °C and precipitation reaching only 73% of the norm, with July being especially dry. The autumn period was also characterized by elevated temperatures (+3.5 °C above the norm) and precipitation at 89% of the long-term average (Figure 2).

A warm winter and sufficient precipitation during the autumn–winter period of 2024–2025 contributed to favorable overwintering conditions for winter wheat and to the accumulation of adequate productive soil moisture reserves. Total precipitation during the growing season amounted to 447.4 mm. Air temperature exceeded long-term average values in all months except May and was, on average, +1.0 °C higher than the climatic norm.

In most studies, the impact of weather conditions on the formation of productive soil moisture and crop yield is primarily assessed based on the calendar year. At the same time, during 2020–2025, mean annual precipitation generally corresponded to the long-term norm of 526 mm, ranging from 87 to 112%. However, analysis of precipitation distribution across different periods revealed significant intra-annual irregularity, which is of considerable agroecological importance. The greatest fluctuations were observed during the growing season (April–October) and the agricultural year (September–August). For example, precipitation during the growing season ranged from 271–304 mm in the dry years of 2023–2024 (75–88% of the norm) and 399–417 mm in 2020 and 2025 (115–118% of the norm), indicating a deviation amplitude of ±43%. Agricultural year totals varied from 393 mm (61% of the norm in 2022) to 644 mm (135% in the 2021), reflecting pronounced interannual variability. In contrast, calendar-year totals were more stable due to compensatory rainfall in other seasons,

remaining close to the norm even in years with moisture deficits (87–99%).

Our results indicate that precipitation during the growing season and the agricultural year is a more sensitive indicator of hydrothermal conditions for crop cultivation than total annual precipitation. This supports the use of these indicators in analyses of agrocenosis productivity, crop water consumption, and the efficiency of technological measures under increasing climate variability.

Integrated analysis of productive soil moisture dynamics across crop rotations indicates that both the formation and utilization of soil water reserves are controlled by the combined effects of preceding crops, species-specific morphophysiological traits, and fertilization regimes. Productive soil moisture at sowing primarily reflects the legacy effects of crop rotation and hydrothermal conditions of the autumn–winter period, whereas moisture levels at harvest characterize the depth and intensity of water extraction by crop root system during the growing season.

Crops differed substantially in their strategies of soil moisture utilization. Thus, in the cereal-fodder-tilled crop rotation winter wheat exhibited a conservative water use pattern, as evidenced by the increase in productive soil moisture reserves at harvest (by 37–50 mm) compared with sowing (Figure 3). This indicates limited exploitation of deeper soil horizons and a predominance of water uptake from the upper (0–30–40 cm) soil layer, combined with partial compensation of water consumption by in-season precipitation (Panchenko, 2024; Matviichuk et al., 2023; Pichura et al., 2024a).

In contrast, sugar beet demonstrated an intensive water use strategy. Under the organo-mineral fertilization system (40 t ha⁻¹ of manure + N₁₀₀P₉₀K₉₀), soil moisture depletion reached up to 96 mm, which was twice that of the unfertilized

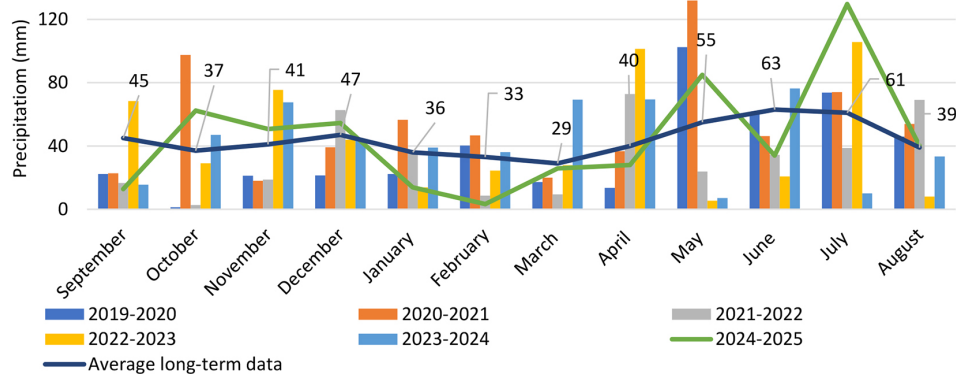


Figure 2. Precipitation amount, mm

Table 2. Distribution of precipitation across different observation periods, mm

Year	Growing season (April–October)	% of norm	Agricultural year (September–August)	% of norm	Calendar year	% of norm
2020	417	118	442	75	554	108
2021	362	106	644	135	567	112
2022	336	99	393	61	509	95
2023	304	88	524	99	481	87
2024	271	75	514	97	521	99
2025	399	115	540	104	530	101
Average	340	100	526	100	526	100

treatment. This reflects active extraction of water from deeper soil layers (50–150 cm), driven by a well-developed taproot system, prolonged vegetation period, and high transpiration demand. This reflects active Enhanced nutrient availability further amplified this effect by stimulating leaf area development and photosynthetic activity, thereby increasing transpiration intensity and overall water uptake. A similar fertilization-driven intensification of water use was observed in spring barley, where the residual effect of organo-mineral fertilization resulted in the highest moisture depletion (up to 179 mm). This suggests that improved nutrient supply enhances plant physiological activity and biomass accumulation, thereby increasing water consumption, particularly from the 50–100 cm soil layer.

The greatest depletion of the soil moisture profile was observed under clover. With the application of $N_{40}P_{40}K_{40}$, productive soil moisture reserves decreased by 205–212 mm, indicating

that clover utilized moisture throughout the entire 0–150 cm soil profile. Such intensive water consumption is associated with the biological characteristics of perennial legumes, particularly their well-developed and deeply penetrating root system, which allows plants to extract water from deeper soil horizons. Studies have shown that the root system of clover may penetrate to depths exceeding 1.2–1.5 m, enabling efficient use of soil moisture accumulated in deeper layers (Hoekstra, et al., 2014; Vleugels et al., 2024). As a result, after clover cultivation the lowest productive soil moisture reserves before winter wheat sowing was recorded, ranging from 43 to 62 mm. Similar patterns have been reported in previous studies, where perennial legumes significantly reduced soil moisture reserves in deeper soil layers due to prolonged vegetation and high transpiration rates (Xolocotzi-Acoltzi et al., 2024). At the same time, despite higher water consumption, clover plays an important role in crop rotations by improving

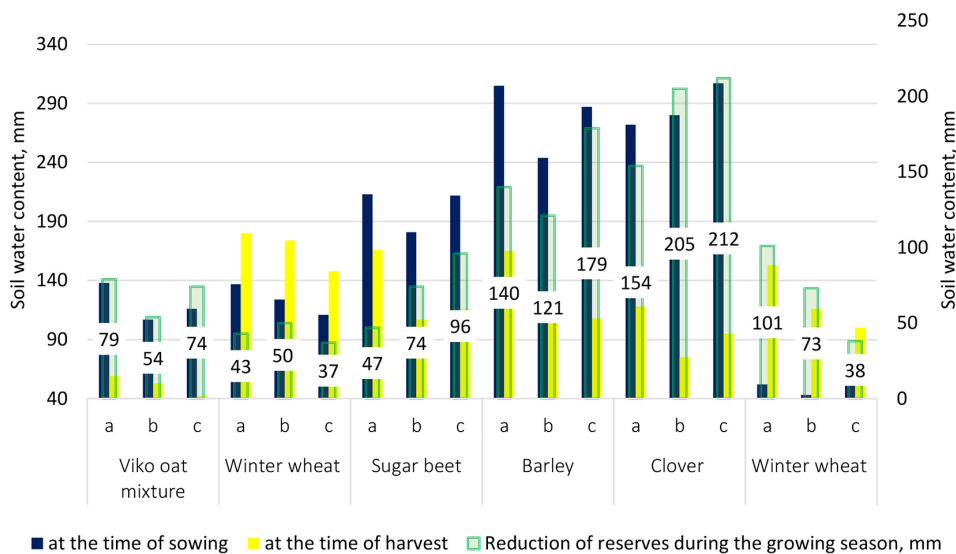


Figure 3. Dynamics of productive soil moisture in the 0–150 cm soil layer in the cereal–fodder–tilled crop rotation, mm

soil structure, increasing organic matter content, and enhancing nitrogen availability, which may positively influence subsequent crops and partially compensate for the reduction in soil moisture reserves (Tello-García et al., 2023).

In the tilled crop rotation, a clear differentiation in water use patterns was observed depending on crop biological characteristics. Short-duration crops such as the vetch-oat mixture exhibited moderate moisture depletion (56–63 mm), reflecting lower cumulative transpiration (Figure 4). In contrast, crops with extended growing periods and high biomass production (sugar beet, soybean, sunflower) demonstrated substantially higher water consumption. Under fertilization, moisture depletion increased significantly (e.g., up to 132 mm in sugar beet and 166–173 mm in spring barley), indicating that nutrient availability enhances water uptake through increased canopy development and transpiration demand. Winter wheat exhibited a fundamentally different pattern of water use. In all treatments, productive soil moisture reserves at harvest exceeded or were close to those at sowing (80–119 mm), indicating substantial precipitation during the spring-summer growing period and a more conservative pattern of soil moisture utilization by the winter crop.

In soybean crops, moisture depletion was among the highest in the rotation, ranging from 130 to 165 mm. Application of $N_{40}P_{40}K_{40}$ increased water consumption compared with the control, which is associated with enhanced growth processes and biomass accumulation. Soybean is

characterized by a relatively high transpiration rate and an intensive water uptake during the reproductive growth stages, particularly during flowering and pod formation. As a result, soybean crops actively utilize soil moisture reserves from deeper soil layers (Kunert et al., 2016; Li et al., 2020). In sunflower crops, productive soil moisture reserves decreased by 110–122 mm under $N_{90}P_{60}K_{60}$ application, further confirming the influence of nutrient supply level on the intensity of crop water use.

In the cereal-tilled crop rotation, the highest initial productive soil moisture reserves were recorded under spring barley (286 mm) and the vetch-oat mixture (114–132 mm), indicating favorable conditions for moisture accumulation after the preceding crop and its effective conservation during the period between harvest and sowing (Figure 5). Compared with the Northern Steppe zone, where productive soil moisture reserves amount to 150–160 mm and moisture use ranges from 107 to 123 mm (Shevchenko et al., 2025), the studied conditions were characterized by higher initial moisture availability. The greatest depletion of productive soil moisture reserves was observed under spring vetch, reaching 172–207 mm, reflecting its high transpiration activity and well-developed leaf surface. Similarly, moisture depletion increased under barley (101–165 mm) and sugar beet (54–102 mm). The maximum moisture use was recorded under the organo-mineral fertilization system, indicating

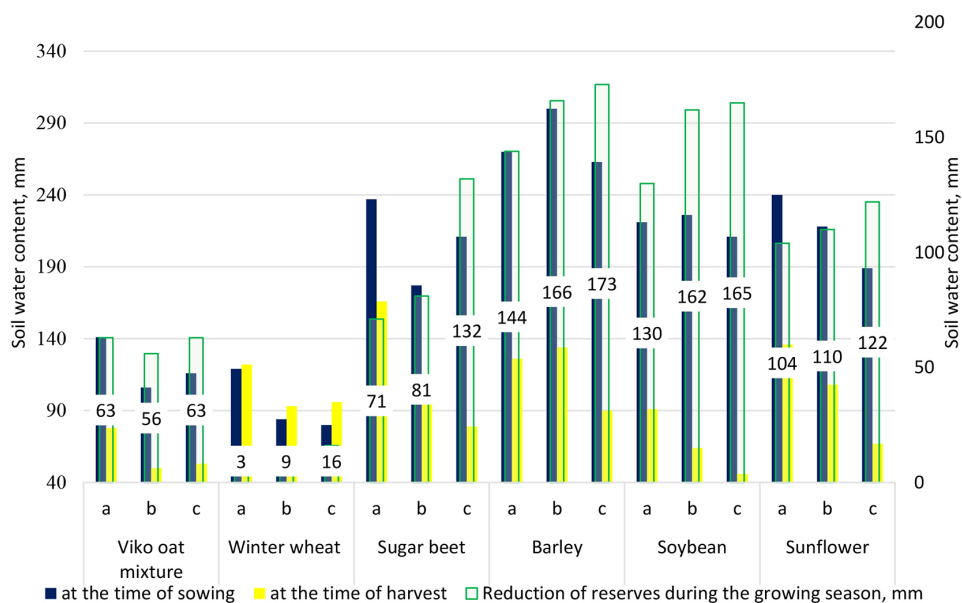


Figure 4. Dynamics of productive soil moisture in the 0–150 cm soil layer in the tilled crop rotation, mm

enhanced physiological activity of plants under optimal nutrient supply.

Within the structure of the cereal-tilled crop rotation, winter wheat was represented by two fields, which made it possible to assess its response to preceding crops and nutrient supply levels. Regardless of the fertilization system, productive soil moisture reserves at harvest exceeded those at sowing by 3–40 mm. Following spring vetch, productive soil moisture reserves before sowing winter wheat were considerably lower (43–62 mm), whereas after harvest they ranged from 100 to 153 mm, resulting in moisture accumulation of 68–78 mm during the growing period.

Overall, across the crop rotations, the greatest decrease in productive soil moisture reserves was recorded under the application of 6.7 t ha⁻¹ of manure + N₅₃P₄₂K₄₂ per 1 ha of crop rotation area in the tilled crop rotation (107 mm), whereas in the cereal-fodder-tilled and cereal-tilled crop rotations the corresponding reductions were 81 and 74 mm, respectively.

An integrated analysis of crop water consumption and productivity within short-rotation cereal-sugar beet systems revealed that total water use is primarily governed by crop biological characteristics, duration of the growing period, root system architecture, and fertilization regimes (Table 3). Across the studied rotations, total crop water consumption varied widely from 2193 to

5137 m³ ha⁻¹, with the highest values recorded for crops characterized by prolonged vegetation and a large transpiration surface, such as winter wheat, sunflower, and sugar beet. In particular, winter wheat exhibited water consumption of 5073–5137 m³ ha⁻¹, while sunflower and sugar beet reached 4220–4400 and 3430–3850 m³ ha⁻¹, respectively.

Despite high total water consumption, water use efficiency, expressed as the water consumption coefficient (WCC), varied substantially depending on crop type and fertilization system. Crops with high biomass production capacity, such as sugar beet and legume-cereal mixtures, demonstrated the lowest WCC values, indicating more efficient conversion of water into yield. For example, the vetch-oat mixture maintained WCC values of 50–93 m³ t⁻¹, reflecting highly efficient water use due to complementary resource utilization and optimized canopy structure. The obtained results are consistent with findings from international studies confirming that legume-cereal mixtures are characterized by high water use efficiency due to complementary resource utilization by the components of the agroecosystem (Wang et al., 2022). Moreover, according to a meta-analysis of long-term experiments, mixed sowing of forage crops can increase yield by 40–70% and water use efficiency by 20–30% compared with monocultures. This effect is explained by differences in rooting

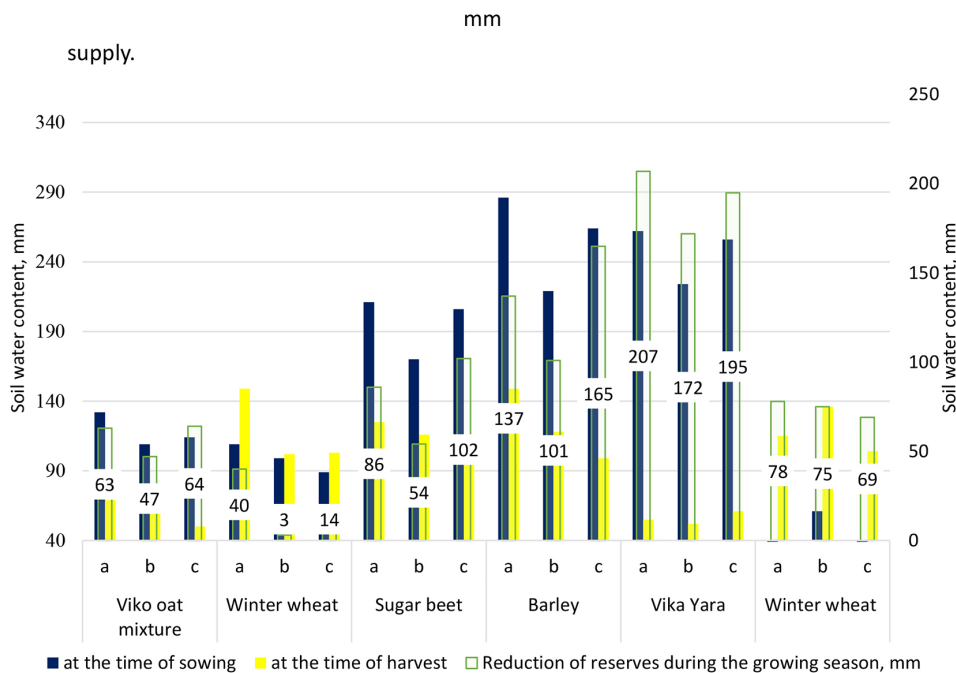


Figure 5. Dynamics of productive soil moisture in the 0–150 cm soil layer in the cereal-tilled crop rotation, mm

Table 3. Analysis of crop productivity and water consumption in crop rotations

Crop	Fertilization system	Water use by plants, m ³ ha ⁻¹	Crop yield, t ha ⁻¹		Water consumption coefficient, m ³ t ⁻¹	
			The main and by-products	The main products	The main and by-products	The main products
Vetch-oat mixture	Zero fertilization	2353	25.3 ^{±1.50}		93	
		2193	31.2 ^{±1.69}		70	
		2340	40.0 ^{±1.47}		50	
Winter wheat	Zero fertilization	5073	8.81 ^{±0.63}	3.92 ^{±0.28}	576	1294
	N ₉₀ P ₆₀ K ₆₀	5153	13.45 ^{±0.61}	5.18 ^{±0.23}	383	995
	N ₉₀ P ₆₀ K ₆₀	5137	15.96 ^{±0.58}	5.96 ^{±0.22}	322	862
Sugar beet	Zero fertilization	3430	21.9 ^{±1.67}	15.1 ^{±0.87}	157	227
	N ₁₀₀ P ₉₀ K ₉₀	3447	49.9 ^{±2.73}	35.2 ^{±1.70}	69	98
	40 t ha ⁻¹ cattle manure + N ₁₀₀ P ₉₀ K ₉₀	3850	62.6 ^{±3.50}	42.8 ^{±2.10}	62	90
Barley	Zero fertilization	2783	4.61 ^{±0.38}	2.21 ^{±0.15}	604	1259
	Residual effect	2673	7.31 ^{±0.54}	3.24 ^{±0.18}	366	825
	Residual effect	3103	9.19 ^{±0.62}	3.97 ^{±0.22}	338	782
Clover	Zero fertilization	2310	16.4 ^{±1.76}		141	
	N ₄₀ P ₄₀ K ₄₀	2820	26.0 ^{±1.81}		108	
	N ₄₀ P ₄₀ K ₄₀	2890	32.6 ^{±1.74}		89	
Soybean	Zero fertilization	2570	5.28 ^{±0.38}	2.38 ^{±0.07}	487	1080
	N ₄₀ P ₄₀ K ₄₀	2890	7.65 ^{±0.53}	3.15 ^{±0.14}	378	917
	N ₄₀ P ₄₀ K ₄₀	2920	9.02 ^{±0.72}	3.51 ^{±0.14}	324	832
Spring vetch	Zero fertilization	3680	3.30 ^{±0.25}	1.38 ^{±0.07}	1115	2667
	N ₄₀ P ₄₀ K ₄₀	3330	2.97 ^{±0.27}	1.10 ^{±0.09}	1121	3027
	N ₄₀ P ₄₀ K ₄₀	3560	3.15 ^{±0.30}	1.23 ^{±0.09}	1130	2894
Sunflower	Zero fertilization	4220	5.83 ^{±0.53}	1.82 ^{±0.12}	724	2319
	N ₉₀ P ₆₀ K ₆₀	4280	7.53 ^{±0.73}	2.87 ^{±0.17}	568	1491
	N ₉₀ P ₆₀ K ₆₀	4400	10.92 ^{±1.02}	3.87 ^{±0.22}	403	1137
Winter wheat	Zero fertilization	3975	10.98 ^{±0.54}	4.83 ^{±0.25}	362	823
	N ₉₀ P ₆₀ K ₆₀	4130	15.47 ^{±0.86}	6.52 ^{±0.31}	267	633
	N ₉₀ P ₆₀ K ₆₀	4335	17.22 ^{±0.75}	7.05 ^{±0.25}	252	615

Note: The yields of crops repeated within the crop rotations were evaluated as average values.

depth and the more complete utilization of soil moisture across the soil profile (Guo et al., 2025).

The application of mineral and organo-mineral fertilizers consistently enhanced crop productivity while reducing WCC, indicating improved physiological efficiency of water use. This effect was particularly pronounced in sugar beet, where fertilization with 40 t ha⁻¹ of manure combined with N₁₀₀P₉₀K₉₀ increased root yield to 42.8 t ha⁻¹ and reduced WCC to 90 m³ t⁻¹, compared with 227 m³ t⁻¹ under unfertilized conditions. Such results indicate intensive utilization of productive soil moisture, including extraction from deeper soil horizons (50–150 cm), combined with enhanced nutrient-driven biomass accumulation. Fertilized sugar beet actively extracted moisture from the

50–150 cm soil layers, significantly increasing the efficiency of its conversion into yield, as confirmed by previous studies (Makukh et al., 2023; Barratt et al., 2023; Syromyatnikov, 2023).

A similar pattern was observed in winter wheat, where N₉₀P₆₀K₆₀ fertilization increased grain yield from 3.92 to 5.96 t ha⁻¹, while reducing WCC from 1294 to 862 m³ t⁻¹ per unit of grain, consistent with findings reported by Hai et al., (2022); Pichura et al., (2024b). It has been established that the water consumption of winter wheat varies depending on phenological growth stages and reaches maximum values during heading and grain filling, when intensive yield formation and dry matter accumulation occur (Zheng et al., 2022). In addition, a substantial proportion of

crop water consumption is supplied by soil moisture reserves accumulated prior to sowing. Under drought conditions, up to 60–80% of seasonal evapotranspiration may be derived from water extracted from deeper soil layers, which are actively utilized by the well-developed root system after flowering (Fang et al., 2024).

In contrast, leguminous crops such as soybean and spring vetch were characterized by relatively high WCC values, especially under unfertilized conditions. For instance, the WCC for soybean grain reached up to $1080 \text{ m}^3 \text{ t}^{-1}$, while that for spring vetch exceeded $2667 \text{ m}^3 \text{ t}^{-1}$. This reflects their morphophysiological characteristics, including a higher proportion of vegetative biomass and lower harvest index. Fertilization partially mitigated these effects by improving biomass formation and nutrient uptake; however, inherent biological traits maintained relatively high water expenditure per unit of yield.

Intermediate patterns were observed for sunflower, which exhibited high total water consumption and strong responsiveness to fertilization. Application of $\text{N}_{90}\text{P}_{60}\text{K}_{60}$ increased yield by 1.3–1.9 times, while WCC decreased to 403–568 $\text{m}^3 \text{ t}^{-1}$ (for total biomass), although values per unit of grain remained relatively high ($1137\text{--}1491 \text{ m}^3 \text{ t}^{-1}$), reflecting the crop's substantial water demand and biomass allocation features. According to Gul et al. (2021), the WCC of sunflower ranges from 450 to $600 \text{ m}^3 \text{ t}^{-1}$, which is significantly higher than that of maize, sugar beet, and cereal crops. During the growing season, sunflower plants may utilize $1000\text{--}1150 \text{ m}^3 \text{ ha}^{-1}$ of soil moisture (Dehtiarova, 2023).

Spring barley sown after sugar beet exhibited total water consumption of $2673\text{--}3103 \text{ m}^3 \text{ ha}^{-1}$ under limited growing season precipitation (138 mm). Despite moderate water use, yield formation remained constrained: total biomass reached 4.61 t ha^{-1} and grain yield only 2.21 t ha^{-1} in the unfertilized treatment. Elevated air temperatures likely intensified soil moisture depletion and evapotranspiration (Porodko, 2023; Pavlova and Litvinov, 2024). The residual effect of fertilization increased grain yield to $3.24\text{--}3.97 \text{ t ha}^{-1}$; however, productivity remained relatively low. Consequently, the water consumption coefficient (WCC) ranged from 338 to $366 \text{ m}^3 \text{ t}^{-1}$ for total biomass and increased to $782\text{--}825 \text{ m}^3 \text{ t}^{-1}$ when calculated per unit of grain. These results indicate that reduced barley productivity is primarily associated with the preceding sugar beet, which

substantially depletes productive soil moisture reserves within the 0–150 cm soil layer (Makukh et al., 2023), thereby limiting water availability for subsequent crops.

The obtained results confirm that the combination of an optimal soil water regime and mineral nutrition systems promotes more efficient water use by plants and enhances crop productivity. Under such conditions, nutrient uptake by the root system improves, plant growth and development intensify, and this ultimately leads to a reduction in the WCC. Similar patterns have been reported by other researchers who found that the application of mineral fertilizers, particularly nitrogen fertilizers, increases plant water use efficiency and represents one of the key factors determining winter wheat yield formation (Hai et al., 2022; Adil et al., 2022; Wang et al., 2025). At the same time, under conditions of increasing climatic aridity, wheat plants may shift toward more intensive utilization of available soil moisture, which is reflected in changes in water consumption patterns and improvements in water use efficiency indicators (Ren, 2026).

At the system level, crop rotation structure significantly influenced water use patterns, productivity, and efficiency (Table 4). The cereal-fodder-tilled crop rotation demonstrated the most favorable combination of moderate water consumption ($3350\text{--}3610 \text{ m}^3 \text{ ha}^{-1}$) and the lowest WCC values ($118\text{--}136 \text{ m}^3 \text{ t}^{-1}$ for total biomass), indicating optimal synchronization between crop sequence, soil moisture availability, and nutrient supply. This rotation benefited from balanced alternation of crops with different rooting depths and water demand, as well as improved pre-sowing soil moisture reserves. Conversely, the tilled and cereal-tilled rotations exhibited higher WCC values (up to $296\text{--}303 \text{ m}^3 \text{ t}^{-1}$ in unfertilized treatments) and less efficient water use, despite comparable or higher total water consumption. These patterns highlight the critical role of crop sequence and preceding crop effects in regulating soil moisture dynamics and determining overall system productivity.

Fertilization further amplified these differences. Under mineral ($\text{N}_{53}\text{P}_{42}\text{K}_{42}$) and organo-mineral (6.7 t ha^{-1} manure + $\text{N}_{53}\text{P}_{42}\text{K}_{42}$) systems, WCC decreased across all rotations due to increased yield formation, with the strongest effect observed in the cereal-fodder-tilled rotation, where WCC declined to $118 \text{ m}^3 \text{ t}^{-1}$ for total biomass and $160 \text{ m}^3 \text{ t}^{-1}$ for grain. This indicates that nutrient

Table 4. Dynamics of available soil moisture and crop water use in cereal–sugar beet crop rotations, per 1 ha of crop rotation, 2020–2025

Indicator	Cereal-fodder-tilled crop rotation	Tilled crop rotation	Cereal-tilled crop rotation
	Zero fertilization		
At the time of sowing	186	205	173
At the time of harvest	140	120	110
Reduction of reserves during the growing season, mm	46	85	63
Water use by plants, m ³ ha ⁻¹	3260	3450	3570
WCC (grain + straw), m ³ t ⁻¹	221	296	303
WCC (grain), m ³ t ⁻¹	285	422	399
	N ₅₃ P ₄₂ K ₄₂		
At the time of sowing	163	185	147
At the time of harvest	91	91	98
Reduction of reserves during the growing season, mm	72	94	49
Water use by plants, m ³ ha ⁻¹	3350	3550	3430
WCC (grain + straw), m ³ t ⁻¹	136	189	186
WCC (grain), m ³ t ⁻¹	182	273	250
Fertilization system	6.7 t ha ⁻¹ of manure + N ₅₃ P ₄₂ K ₄₂		
At the time of sowing	183	178	161
At the time of harvest	102	72	87
Reduction of reserves during the growing season, mm	81	107	74
Water use by plants, m ³ ha ⁻¹	3610	3670	3680
WCC (grain + straw), m ³ t ⁻¹	118	154	162
WCC (grain), m ³ t ⁻¹	160	225	219

Note: Amount of moisture during the growing season: cereal-fodder-tilled crop rotation – 280 mm, tilled – 260 mm, cereal-tilled – 294 mm.

availability enhances the efficiency of soil moisture utilization even under conditions of increased total water consumption.

Overall, the results demonstrate that water use efficiency in crop rotations is an emergent system-level property determined by the interaction of crop biological traits, preceding crop effects, fertilization regimes, soil moisture availability, and rotation design. Crops with high biomass productivity and deep root systems (e.g., sugar beet, clover) utilize soil moisture more efficiently, whereas crops with a lower harvest index (e.g., legumes) exhibit higher water expenditure per unit of yield.

Optimizing crop rotation structure, combined with balanced mineral and organo-mineral fertilization, enables more efficient utilization of productive soil moisture, stabilization of yields under variable hydrothermal conditions, and maximization of water productivity per unit area. Such integrative management approaches, including species-specific sequencing and strategic nutrient management, are essential for enhancing the

resilience and sustainability of agroecosystems under increasing climatic variability.

The dynamics of atmospheric precipitation during the period from harvesting the preceding crop to sowing the subsequent crop were analyzed separately. This indicator is rarely considered in studies of productive soil moisture reserves; however, it is crucial for assessing soil moisture replenishment, the effectiveness of pre-sowing moisture accumulation, and the influence of weather and agronomic factors on early crop development. The most pronounced effect of precipitation during the period between harvest of the preceding crop and sowing of the subsequent crop was observed in winter wheat following the vetch–oat mixture in 2021 (231 mm), whereas after clover in the cereal-fodder-tilled crop rotation and after spring vetch in the cereal-tilled rotation in 2025, only 48 mm of precipitation was recorded, indicating limited atmospheric moisture supply during this interval (Figure 6). Previous studies have shown that the amount of precipitation occurring between the harvest of the preceding crop and the sowing of

the subsequent crop has a significant impact on winter wheat yield (Yang et al., 2025), influencing not only the initial soil moisture reserves available for early growth but also the effectiveness of moisture utilization during the early stages of crop development. This period of precipitation plays a critical role in determining crop establishment, root development, and ultimately, overall productivity under rainfed conditions.

Across the rotations, the main share of precipitation contributing to pre-sowing soil moisture reserves occurred during the autumn-winter period (October–March), with the most favorable moisture conditions typically observed prior to sowing spring crops (spring barley and vetch-oat mixture). In the case of the vetch-oat mixture, 170 mm of precipitation was recorded between harvesting winter wheat and sowing the subsequent crop. Among the studied crops, the highest amount of precipitation was recorded prior to soybean sowing in the tilled crop rotation (394 mm), followed by clover and spring vetch (325 mm), spring barley (310 mm), and sugar beet (309 mm). It is important to note that precipitation during the autumn-winter period remained stable for each crop regardless of the fertilization system. This is expected, as atmospheric precipitation is a natural factor independent of agronomic practices. Therefore, differences among fertilization treatments in subsequent soil moisture indicators were not attributable to precipitation amounts but rather to variations in the efficiency of moisture accumulation and its subsequent utilization by crops.

The duration of the period between harvesting the preceding crop and sowing the subsequent crop averaged 6–9 months in the cereal-fodder-tilled crop rotation, 5–8 months in the tilled rotation, and 4–7 months in the cereal-tilled rotation. The main proportion of precipitation contributing to the replenishment of productive soil moisture reserves occurs during the autumn-winter period (November–March). The cereal-fodder-tilled crop rotation is characterized by prolonged soil moisture recovery periods (6–9 months), ensuring relatively stable water supply to crops. The most favorable moisture conditions were observed prior to sowing sugar beet and the vetch-oat mixture. The tilled crop rotation demonstrates a relatively stable moisture replenishment regime; however, soybean and sunflower are particularly sensitive to precipitation deficits. The cereal-tilled crop rotation exhibits a more uniform distribution of precipitation among rotation crops. The relatively high-water consumption coefficient (WCC) can be attributed to the alternation of crops with different biological types (cereals-legumes-row crops), which balances water consumption and stabilizes moisture circulation within the system.

Legumes (clover, soybean) improve the soil water balance due to their deep root systems, which enhance precipitation infiltration. Row crops (sugar beet, sunflower) deplete the soil profile more intensively; however, during long periods between harvest and the sowing of the next crop, soil moisture reserves are fully restored (Al-Musawi et al., 2025; Liangang et al., 2025; Demydenko and Shapoval, 2025). According to

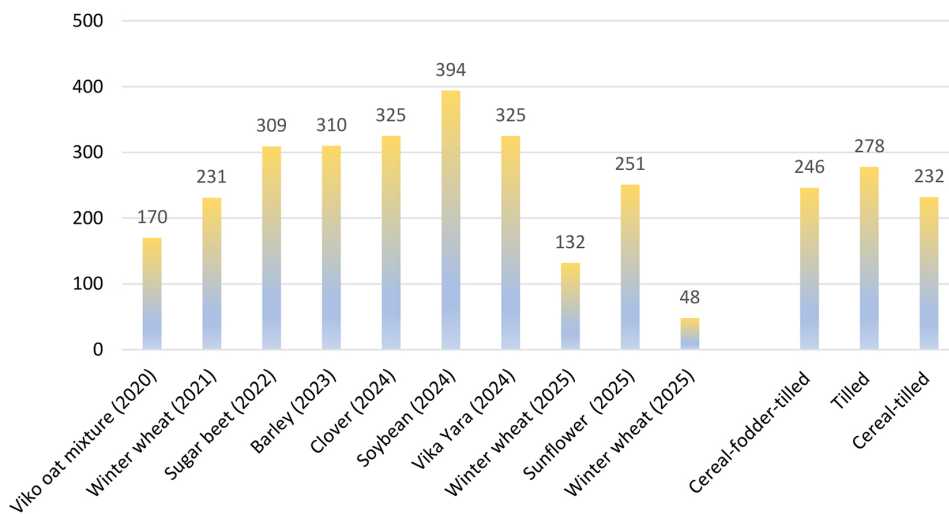


Figure 6. Dynamics of atmospheric precipitation between harvest of the preceding crop and sowing of the subsequent crop, mm

our findings, the cereal–tilled crop rotation is the most environmentally stable in terms of moisture regime, as the balanced alternation of crop types contributes to equilibrium between moisture consumption and accumulation.

The obtained results indicate that weather conditions during the period between harvesting the preceding crop and sowing the subsequent crop play a key role in the formation of initial soil moisture reserves. This interval determines the water supply potential of the agroecosystem at the early stages of crop development. Under conditions of abundant precipitation, substantial soil moisture reserves are formed, whereas low precipitation limits initial water availability regardless of fertilization system or cultivation technology. Therefore, total precipitation during the period between harvest of the preceding crop and sowing of the subsequent crop represents a fundamental hydrological indicator of the agro-phytocenosis, determining the initial soil water balance and serving as an important criterion for evaluating the effectiveness of preceding crops and technological practices within crop rotations.

CONCLUSIONS

Between 2020 and 2025, total annual precipitation remained within the climatic norm (87–112%); however, its intra-annual distribution was highly uneven. Precipitation during the growing season and the agricultural year exhibited substantially higher variability ($\pm 43\%$) compared with calendar-year totals, indicating that these periods serve as more sensitive indicators of crop water supply and agroecosystem productivity under conditions of climatic instability.

Productive soil moisture reserves at sowing primarily reflected the residual effect of the preceding crop and autumn–winter precipitation, whereas moisture levels at harvest characterized crop-specific depth and intensity of water extraction. Deep-rooted crops (sugar beet, clover, sunflower) utilized soil moisture from deeper horizons (50–150 cm), while winter wheat relied predominantly on the 0–40 cm arable layer.

Total crop water consumption ranged from 2193 to 5487 m³ ha⁻¹ depending on crop biological traits and fertilization systems. Crops with high biomass production potential (sugar beet, clover, vetch–oat mixture) demonstrated the highest water use efficiency, whereas

low-yielding crops (spring vetch and barley under stress conditions) exhibited elevated water consumption coefficients, particularly when expressed per unit of grain yield.

Mineral and organo-mineral fertilization consistently enhanced crop productivity and reduced water consumption coefficients across all crop rotations. The strongest response was observed in sugar beet and sunflower, indicating their high sensitivity to nutrient availability. Under the combined application of 6.7 t ha⁻¹ manure and N₅₃P₄₂K₄₂, the cereal-fodder-tilled crop rotation achieved the lowest water consumption coefficients – 118 m³ t⁻¹ for total biomass and 160 m³ t⁻¹ for grain-reflecting maximum efficiency of water conversion into yield.

Precipitation occurring between the harvest of the preceding crop and the sowing of the subsequent crop proved to be a critical determinant of initial soil moisture reserves. This often overlooked factor directly influenced early crop establishment and yield formation. High inter-vegetation precipitation ensured sufficient soil moisture at the beginning of the growing season irrespective of fertilization, whereas moisture deficits during this period limited crop performance even under improved agronomic practices.

Under increasing climatic variability, optimization of crop rotation structure in combination with balanced mineral and organo-mineral fertilization significantly enhances water use efficiency and stabilizes crop productivity. The integration of deep- and shallow-rooted crops within diversified rotations promotes more efficient exploitation of soil moisture across the profile, thereby improving agroecosystem resilience and sustainability.

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