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MOISTURIZATION REGIME AND IMPLEMENTATION OF CHORNOZEM AGROPOTENTIAL UNDER CLIMATE CHANGES IN THE CENTRAL FOREST-STEPPE

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The aim of the study. To demonstrate the main regularities in the formation of moisturization regime and to determine the impact on the implementation of agropotential and restoration of fertility of chornozem under the effect of crop rotations, fertilization, and tillage in conditions of current climate changes in the central Forest-Steppe. **Methods of studies.** Field method (to select samples in the depth of chornozem in different study periods), laboratory method (for thermogravimetric determination of the productive moisture reserves during the study period), mathematical, statistical, and comparative evaluative methods (to substantiate the reliability of the obtained moisture reserves in soil and elaboration of statistical models of interactions). **Results of studies.** On average, in 75 years of observations, the average moisture reserves in a one-meter-deep layer were 61.6 mm in November, and 51.5 mm by the median, that tended to the lower typical value which demonstrated a decrease in autumn moisture reserves. The oscillation coefficients (K_{os}) and K_{var} were 40% and 54.4%. The moisture reserves in April, on average and by the median value, were 156–155 mm at K_{os}=37% and K_{var}=10.3%. The average accumulation of moisture in the one-meter-deep layer in the cold period of the year was 94 mm with the median value of 99 mm, which tended more to the higher typical value ($L_{0.75}$) at K_{os}=98% at K_{var}=25.3%. In July, the moisture reserves in the one-meter-deep layer were 50.1 mm and by the median value — 45.5 mm which demonstrated tending to the lower typical value (L0.25) and the intensification of drought conditions, when the index of moisturization (Im) was within 0.77–0.88 (weakly arid conditions), and at the maximal typical value of I_m=1.13–1.22 (wet conditions) at K_{os}=65% and K_{var}=18.6%. The average loss of moisture from soil in April–July was –105 mm, which corresponded to the median value and tended to the higher typical values of losses (–108...–122 mm) at K_{os}=33% and K_{var}=9.3%, which is a stabilized loss, tending to increase. Between the parameters of productive moisture content and climate indices, there were direct and indirect correlational relations of high correlation rate (R=±0.61–0.95±0.02, R^2=37–0.90), and the relations between I_m and D_m increased to strong correlation (R=±0.68–0.96±0.03, R^2=0.46–0.65). It was found that in the 0–30 cm layer of podzolic chornozem, the average humus content after crop rotation with plowing was 2.34%, under surface tillage, the humus content increased by 0.15% (10 years of surface tillage), and in case of No-till, the humus content increased by 0.07–0.08%. In the crop rotation on typical chornozem, the average reserves of $C–CO_2$ in the 0–30 cm layer of chornozem were 273 t/ha, and in the 0–20 cm soil layer — 182 t/ha. The average reserves of $C–CO_2$ under No-till were 19.8 t/ha higher compared to plowing, and the reserves of $C–CO_2$ in the 0–30 cm layer of soil started from 296 t/ha, which was 21–23 t/ha higher compared to plowing. Under surface tillage, the average reserves of $C–CO_2$ were 14 t/ha higher than under plowing. The reserves of sequestered $C–CO_2$ in the 0–30 cm layer corresponded to the interval of values of 285–300 t/ha and was higher than under plowing but tended to decrease compared to No-till. The reserves of $C–CO_2$ in the 0–20 cm chornozem layer were at the level of the median values (202.5 t/ha) and exceeded the reserves of carbon oxide under plowing by 21 t/ha, which demonstrated the increase in the sequestered ability of the 0–20 cm layer under surface tillage or No-till. In modern climatic conditions, the agropotential of chornozem is maximally implemented in the central Forest-Steppe, and a type of crop rotation is a relevant factor in increasing agrocenosis performance. In a crop rotation with peas, saturated with cereals by 80%, including 40% of grain corn, the yield of cereals was 5.56–6.15 t/ha, which exceeded the crop rotation with perennial grasses and 20% corn 1.06–1.05 times, and the yield of cereals — 1.31–1.4 times. The content of digestible protein was 0.67 t/ha or 19.7% higher in the crop rotation with grasses. Long-term (10 years) application of 8–10 cm surface tillage in a cereal crop rotation ensured the yield of cereals at the plowing level, whereas in case of No-till for 5 years, the yield of cereals was considerably lower compared to plowing and surface tillage. **Conclusions.** The relation, determined between climate parameters and the response of a one-meter-deep chornozem layer in the form of normalized parameters of productive moisture reserves, allows for parameterizing the moisturization regime within the periodic washing water regime of the central Forest-Steppe of Ukraine. The analysis of weather and climate parameters in the complex with the formation of productive moisture reserves in one-meter-deep layer in spring and summer periods in 1947–2022 demonstrated that in the central part of the Left-Bank Forest-Steppe, water regime is formed which corresponds to the periodically washing type, but in terms of the moisturization regime (time-wise), there is a clear stable tendency towards the manifestation of features of non-washing water regime, which mostly indicates the aridization of soil conditions for the vegetation of crops in modern conditions of global climate change in the Forest-Steppe zone. Therefore, the typization of moisture change in the one-meter-deep chornozem layer in the seasonal cycle (moisturization regime) can be used as an indicator of response to synoptic changes within climatic factors in the formation of the periodic washing regime of the central Forest-Steppe of Ukraine in modern climatic conditions.

Keywords: productive moisture, one-meter-deep layer, trend, autocorrelation, periodicity, factor analysis, moisturization regime, climate, chornozem, Forest-Steppe.

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One of the key tasks of agriculture is to find ways to optimize the water regime of chornozem, utilizing agricultural techniques that reduce productive moisture losses and promote its accumulation and preservation through precipitation during the autumn-winter and spring periods. Predecessors and main soil tillage systems play a significant role in regulating the water regime. The water regime of the soil is essential in the formation of crop yields. The need for soil moisture is monitored throughout the entire ontogenesis of the plant, from the moment the seed enters the soil to the formation of the crop. The distribution of precipitation during the growing season is crucial for crops. Still, precipitation is often uneven, which can ultimately have a negative impact on the productivity of agrocenoses [*Petrenko S.V., Petrenko S.V., Hurtovenko V.O., Tsiuk O.A. et al., 2023*].

Weather fluctuations mostly affect the annual accumulation of productive moisture in soil in spring, and the efficiency of management decisions in agrarian production depends on it [*Heino, M.; Guillaume, JHA; Muller, C.A.,2020, Kryvoshein O.O., Odnolietok L.P., Dziuba L.P.,2016, Lopez-Urrea, R., Martin de Santa Olalla, F., Fabeiro, et al., 2006,* Kalytka V.V., 2009, Funk C., Peterson, 2015]. The productivity of agricultural lands is determined by a complicated set of conditions: rotation of crops, reserves of accessible biogenic elements, agrophysical properties of soil [15], state and structure of soil biota, biological specificities of species and hybrids, level of application of organic and mineral fertilizers, climatic and agrometeorological conditions [*Challinor, A.J.; Watson, J.; Lobell, D.B., 2014, Dovhal H.P., 2017, Howden, S., 2007, 2009, Holzkamper, A.; Calanca, P.; Fuhrer, J., 2013, Kostiuchenko Yu.V., 2015, Chendev Yu.G., Gennadiev A.N., Smirnova M.A., Lebedeva M.P., et al., 2022, Balabukh V.O., 2017, Bo Liu, Renming Ma, Haoming Fan, 2017*].

The level of soil moisture provision also affects the availability of nutrients in soil and their utilization by plants. Under a considerable moisture deficit in the soil, available macro- and microelements do not give any positive effect and may negatively impact yield formation. Excessive moisturization disrupts the water and air regime in soil [Liua, H.L., Yanga, J.Y., Tana, C.S., 2011], inhibits nitrification processes, reduces the input of nutrients to plants, promotes accumulation of toxic substances [Hamaiunova V.V., Lytovchenko A., Dvoretskyi V., Hlushko T.V., 2017, Hospodarenko H.M., Cherno O.D., Martyniuk A.T., et al., 2021, Kudria S.I., 2020, Makukh Ya.P., Remeniuk S.O., Kopchuk K.M., 2021].

Water regime of chornozem soils, including their profile moisture exchange, has a decisive impact on hydrological characteristics. Processes such as infiltration, evaporation, and moisture migration to the frost line are largely responsible for the mechanisms of surface and underground runoff formation and their interaction. Classical studies have shown that climate is the main factor in the formation of the water regime of soils observed in recent decades. A number of studies conducted in recent years have assessed the impact of climate change on evaporation and moisture exchange processes in soils during the winter and spring periods [Miuller D., Yunhandreas A., Kokh F., Shirkhorn F., 2016].

In actual conditions, the zonal water regime of soils is formed not only throughout the year, but often over a period of many years, which complicates the study of the water regime in the aggregate of processes that determine it: vertical soil moisture flow, the direction and magnitude of which characterize evaporation, infiltration, and moisture migration in thawed and frozen soils. In winter, rising temperatures reduce the depth of freezing and, accordingly, the outflow of moisture from the surface of groundwater during the process of frost migration of moisture, and a decrease in the depth of freezing leads to an increase in the infiltration capacity of soils and a more intensive replenishment of groundwater reserves in the spring [Ek M.B., Mitchell K. E., Lin Y., Rogers E., Grunmann P., Koren V., et al., 2024, McNally A., Arsenault K., Kumar S., et al, 2017, Chendev Yu.G., Petin A.N., Lupo A.R. 2012, Stanton, J.S., Ryter, D.W., Peterson, S.M., 2013., Soldevilla-Martinez, M., Quemada, R., López-Urrea, R., Munoz-Carpena, J.I., Lizaso, J.I., 2014].

The additional factor, decreasing the infiltration component, is an increase in the intensity of melting of snow, caused by higher temperatures. Moisture flows in soils are formed under the effect of the infiltration of rain precipitation and evaporation of soil moisture in the summer-autumn period, as well as processes of water migration to the frost line and infiltration of thawed waters in the winter-spring period [*Gelaro R., McCarty W., Suárez M.J., et al., 2017*].

Urgency of conducting the studies. The adaptation to climate change in the central part of Ukraine's Forest-Steppe is a process of adjustment in natural or human systems in response to actual or expected climatic effects, which helps mitigate their negative consequences and take advantage of favorable possibilities due to the warming. Considering the dependence of agricultural production on weather conditions, the timely development of adaptation measures to climate change is urgent. In this regard, it is essential to scientifically substantiate measures for the most effective use of additional agricultural resource potential in the form of heat, as well as to minimize possible risks in the form of various extreme phenomena that can significantly worsen not only the ecological state of agricultural landscapes, but also considerably reduce the productivity of agroecosystems or the agropotential of chornozems, which primarily concerns the intensification of the strength and spatial spreading of drought phenomena. To date, the issue of adapting agricultural production to climate change has not been fully resolved; therefore, the problems highlighted in the article are relevant to agricultural production.

The aim of the study. To demonstrate the main regularities in the formation of the moisturization regime and to determine its impact on the implementation of agropotential and restoration of chornozem fertility under the effect of crop rotations, fertilization, and tillage in conditions of current climate changes in the central Forest-Steppe.

MATERIALS AND METHODS OF THE STUDY

The study (Object No. 1) was conducted in the central part of the Left-Bank Forest-Steppe of Ukraine in the Drabiv experimental field of the Cherkasy State Agricultural Experimental Station, NSC "Institute of Agriculture", the NAAS of Ukraine. In terms of soil-ecological zoning on the adaptive grounds, the observations over the formation of spring reserves of productive moisture depending on agroclimatic indices of the cold period of the year, were carried out in conditions of the Forest-Steppe moisturized zone (8.7b) of typical chornozem (Cht) with the precipitation amount of 140–160 mm in the cold period of the year at the precipitation assimilation of 52% with the HTC (hydrothermal coefficient by Selianinov) in May–July (1.00–1.10), August-September (0.91–1.00). Soil characteristics were as follows: typical chornozem, heavy-clay-light loamy, with the humus content of 3.8–4.2%, mobile phosphorus compounds — 120–140 mg/kg of soil, mobile potassium compounds — 80–100 mg/kg of soil, pHwater 6.8–7.0

The moisture dynamics is the one-meter-deep layer and the accumulation of productive moisture reserves were analyzed in the 10-field crop rotation using the bulk of data from 1947 till 2023 in the materials of scientific study reports. The evaluation was conducted to a depth of 0–100 cm. The initial ascending data of moisture values were analyzed as a percentage of the weight of dry soil. The samples were taken by drilling to a depth of 0–100 cm. The sampling was done in three repeats.

The study (Object No. 2) was conducted at the experimental base of the Cherkasy State Agricultural Experimental Station of the National Scientific Center "Institute of Agriculture", the NAAS of Ukraine, established in 2010. The soil cover of the field was podzolic, heavily regraded, low-humus, medium-clay chornozem on the carbonate loess layer. The humus content in the arable horizon was 2.58–3.08%, with the amount gradually decreasing with depth, reaching 0.96% at a depth of one meter. In terms of soil-ecological zoning: in the Forest-Steppe zone of increased moisturization (9,7b), podzolic chornozem, with the precipitation amount in the cold period of the year of 140–160 mm, at the assimilation of 55–58% for HTC for May–July HTC=1.10–1.20, and in August–September, HTC=0.91–1.00.

The field permanent experiment investigated the performance of the 5-field cereal-hoed crop rotation, which included spring barley – peas – winter wheat – soy beans – spring wheat. The structure of the crop rotation was as follows: cereals — 60%, including winter wheat — 20%; spring spiked cereals — 40%; grain legumes (peas) — 20%; technical (soy beans) — 20%.

1. Systematic plowing — for 22–25 cm (disking for 0–10 cm prior to sowing winter wheat);

2. No-till system (5th year of implementation) after systematic plowing for 22–25 cm;

3. No-till system on the background of surface tillage for 10–12 cm (5 years);

4. Surface tillage for 10–12 cm (10 years).

Fertilization system on the background of two tillage systems: control without fertilizers, $N_{55}P_{55}K_{65}$, $N_{75}P_{65}K_{82}$ per one hectare of crop rotation area.

The effect of various tillage systems on the agrophysical condition of podzolic chornozem was studied during the transition to the No-till system through minimum tillage and transitional specialized cereal crop rotation after systematic plowing and surface tillage. The effect of transitional soil conditions on the productivity and quality of cereal crops in a 5-field crop rotation was established.

The current period of water regime study was based on the determination of the volumetric moisture content of the soil using the known density of dry matter. The moisturization index in the soil depth was estimated as follows: I_m — index of moisturization; ($I_m=W_{a.r.}/0.85W_{lw}$, where $W_{a.r}$ — actual reserves of productive moisture, mm; W_{lw} — reserves of productive moisture at the least field moisture capacity, mm (about 145 mm)). The hydrothermal coefficient by Selianinov, HTC — index of territory moisturization. It is determined by the ratio between the precipitation amount (P) in mm for the period with average daily air temperatures over 10°C and the sum of temperatures ($\sum T$) for the same time, decreased ten times: $HTC=R/0.1\sum T$; where P — precipitation amount for the period with the temperature over 10; $\sum T>10°$ — sum of active temperatures over 10°C.

The index of moisture deficit (D_m) in soil is of practical value. The moisture deficit in soils, not saturated with water, is understood as the difference between LW and actual moisturization at a given moment: $D_m=LW-Wr$, where LW — the least field moisturization, mm; Wr — real moisture reserves, mm.

The oscillation coefficient (K_{os}) is a relative index, characterizing the fluctuations in the extreme values of the characteristic regarding the average level which demonstrates the degree of variation (variability) of the characteristics and allows for estimating how much the maximal (max) and minimal (min) values differ from the average value: $K_{os}=\Delta a:X_{av}^{X}100\%$; where Δa — amplitude interval ($\Delta a=max-min$); X_{av} — average value. The variation coefficient (K_{var}) is a relative value that serves to characterize the trait variance. It is a ratio between the mean square deviation S and the mean arithmetic {\displaystyle {\bar {X}}}, expressed in percents: c.v = S/{\displaystyle {\bar {X}}.

Quartiles are values that divide the ordered series of the data into four equal parts. The lower quartile ($L_{0.25}$) is a value, below which there are 25% of the data, and above which — 75%. The higher quartile ($L_{0.75}$) is a value, below which there are 75% of the data, and above which — 25%. Median ($L_{0.50}$) is the second quartile, dividing the data in half. Δn — quartile normalized interval ($\Delta n=L_{0.75}-L_{0.25}$). It corresponds to 50% of the probability level. $L_{0.10}$–$L_{0.90}$ — higher and lower deciles (the probability level of 10%).

The method of R/S analysis investigates the fractality of temporal series. This method was suggested by B. Mandelbrot and is based on the research, conducted by Hurst. This index reflects the maximal interval, in our case, the interval of climatic parameters for the given period. This index is used as a measure of long-term memory of temporal series, and its value is between 0.5 and 1. $RS(x) = an^H$, where RS is the interval of the variance of the constant x, which is a temporal series with the number of observations n, a — a constant. The fractal dimensionality was estimated according to K.G. Moiseev (2014), using the equation: $D=1-|\pm bx|$, where ±bx — the index of degree of the exponential function of the exponential equation for the time-wise trend of the index; the index of Hurst: $H=2-D$; the autocorrelation degree: $C=2^{2H-1}-1$. The resistant series: H=1.01–1.40; the resistance threshold: H=1.4–1.60; the unstable state of the series: H>1.60.

The interval is the range (maximal value minus minimum value) of the sums or partial sums x (after calculating the sampling mean), divided by the standard deviation of the sampling. If x is white noise (zero mean, zero variance), then the range of disturbance sets that form random walks scales with the standard deviation, growing as the square root of the series size, giving an expected Hurst index value of 0.5. If the value obtained exceeds 0.5, then we can conclude that there is persistence, i.e. the series represents a generalized Brownian motion and is characterized by long-term memory. This means that what happens today affects the future. If the Hurst value is between 0 and 0.5, then we can conclude that there is anti-persistence. Such a time series is much more volatile than a random series because it fluctuates constantly. If we observe a decline in the previous period, then we should expect growth in the next period, and vice versa. When H=0.5, it corresponds to ordinary white Gaussian noise, random Brownian motion, i.e. a process that has no memory.

To calculate the cyclic nature of the dynamics series in terms of climate parameters and soil moisture reserves, singular spectral analysis (SSA) was employed, which enabled the study of the structural features of the data, smoothing and forecasting time series, and modeling the cyclicality of parameter changes. In fact, it divides the initial time series into a set of numerous components with characteristic properties. In this way, trends or noise can be isolated from the series and used when comparing the series [Levi L.I., Petrovskyi O.M., 2016]. The accumulation of the carbon dioxide amount ($C-CO_2$) was estimated using the following parameters (*Anishyn L.A., Hrytsaienko Z.M., Ponomarenko S.P. et al., 2014, Buendia L., Miwa K., Ngara T. and Tanabe K., IPCC, 2006*):

- crop performance in different rotations;
- yield of by-products, after-harvest residues, and crop roots in rotations according to the regression equations, presented for low and high levels of crop performance, since the amount of plant residues does not always depend on the yield increase;
- dry matter yield from the obtained mass;
- carbon content in the mass of by-products, stubble, and roots calculated into carbon dioxide ($C_{org}CO_2$) (coefficient 3.7);
- amount of humus (C_h), formed as carbon reservoir depending on the level of the input of straw, by-products, and mass of the plant root system into soil [Buendia L., Miwa K., Ngara T. and Tanabe K., 2006]. The content of total humus was determined according to Turin's method, modified by Simakov.

The analysis of weather and climatic parameters involved: for conditions of the central part of the Left-Bank Forest-Steppe — the observations at the observation site of the Drabiv experimental field (1947–2024), and for conditions of the central part of the Forest-Steppe — the observations of the Smila meteorological station of the Cherkasy regional center of hydrometeorology, situated within the boundaries of the Smila experimental field.

The results of field studies were statistically processed by the dispersion analysis method using the following statistical methods: dispersion, factor, cluster analysis, and the method of non-parametric statistics. The study results were summarized using Statistica-10.

RESULTS OF STUDIES

The changes in the climatic conditions of the central part of the Left-Bank Forest-Steppe (Object No. 1). Climate change is one of the most pressing global issues, both on a worldwide scale and for the Forest-Steppe zone of Ukraine [8]. While it was discussed in scientific circles two or three decades ago, it has become evident in many areas of human activity today. Winters and springs have become warmer, and the weather has become increasingly changeable and unpredictable. The average daily air temperature has risen by +1.5–2.0°C, which may seem insignificant at first glance. Still, on a continental scale, such an increase has serious consequences, leading to the death of many animals and plants that are not adapted to the new conditions. Humans are also feeling the effects of climate change: various natural disasters associated with the instability of the global climate system are intensifying, and their number is growing every year [*Medvedev V.V., 2012a, Medvedev V.V., 2012в, Malytska L.V., Balabukh V.O., Kostiuchenko Yu. V.Ye., 2015*].

The analysis of atmospheric precipitation dynamics in the central part of the Left-Bank Forest-Steppe (Object No. 2) for the period 1947–2024 revealed that trends in average monthly precipitation increased during the autumn, winter, and spring periods. Compared to 1947–1956 (the initial observation period), precipitation increased in 2017–2024: +49 mm (autumn), +94 mm (winter), +34 mm (spring). During the summer period, the dynamics of atmospheric precipitation declined, and the amount of precipitation compared to 1947–1956 decreased by 107 mm in 2017–2024. On average, the annual precipitation showed an upward trend, and in 2017–2024, atmospheric precipitation amount increased by +124 mm compared to 1947–1956. The analysis of weather and climate indicators for 1947–2024 showed that, on average, 115 mm of precipitation fell in autumn, 98 mm in winter, 107 mm in spring, 186 mm in summer, and 505 mm per year (*Fig. 1*, *Table 1*).

The analysis of exponential equations of precipitation growth trends showed that the formed stable (R^2=0.39–0.74), reliable trends related to persistent series, where the Hurst index had a value of H=1.03–1.10, indicating that in future periods, precipitation dynamics will continue to grow According to the fractal dimensionality (D=0.90–0.95), the dynamic series are stable over time. The precipitation variation coefficient was 20.8%.

The analysis of the dynamics of the average monthly air temperature demonstrated that, in general, the trends were upward in terms of the seasons of the year. Compared to the initial observation period, in autumn, spring, and summer of 2017–2024, the increase in the average monthly air temperature was as follows: +2.5°C, +3.8°C, +3.3°C, respectively, and in winter, the air temperature changed from –5.7°C (1947–1956) to –1.6°C (2017–2024) or 3.56 times, and in one year, the increase in the average annual air temperature was +3.8°C (*Fig. 1*).

Table 1. The typization of weather and climate parameters of conducting the study in the central part of the Left-Bank Forest-Steppe of Ukraine in 1947–2024

Months of the year	Average, X_{av}	Mediana, X_{med}	Min.	Max.	Quartiles		K_{var}*, %
					$L_{0.25}$	$L_{0.75}$	
Precipitation, mm (in Drabiv experimental field)							
Autumn	115	108	40	257	82	139	41.8
Winter	98	90	22	232	64	129	47.6
Spring	107	106	39	204	73	135	36.1
Summer	186	187	39	361	148	226	34.4
For the year	505	489	290	782	432	579	20.8
Air temperature, t°C (in Drabiv experimental field)							
Autumn	+8.0	+8.0	+4.1	+11.6	+7.1	+8.7	17.6
Winter	–4.0	–3.7	–11.8	+1.6	–5.5	–2.5	–62.0
Spring	+8.2	+8.2	+3.6	+11.2	+7.2	+9.4	19.8
Summer	+19.9	+20.0	+16.8	+23.9	+18.7	+20.9	7.3
For the year	+7.8	+7.6	+5.2	+10.9	+7.1	+8.7	17.0
Air temperature, t°C (in Ukraine)							
Autumn	8.0	8.0	4.1	11.6	7.1	8.9	17.6
Winter	–4.0	–3.7	–11.8	1.6	–5.5	–2.4	61.5
Spring	8.3	8.3	3.6	11.5	7.2	9.7	20.0
Summer	19.9	20.0	16.8	23.9	18.7	21.0	7.6
For the year	8.1	7.9	5.2	11.1	7.2	8.9	15.9

Note: * K_{var} — variation coefficient, %.

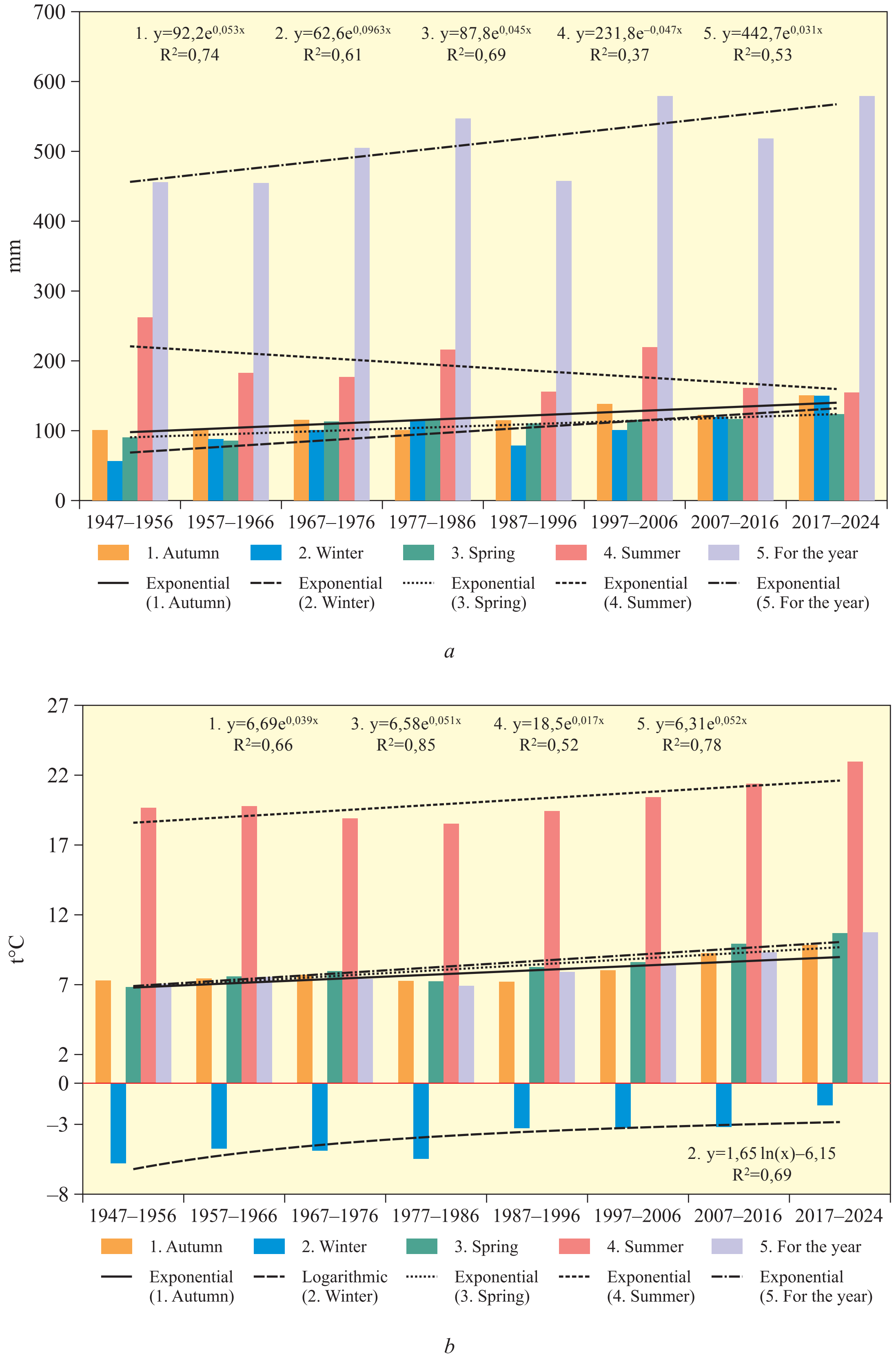


Fig. 1. The dynamics of the average monthly precipitation (*a*) and average monthly air temperature (*b*) in the conditions of the central part of the Left-Bank Forest-Steppe in 1947–2024

According to the data of the State Emergency Service of Ukraine, the dynamics in the average monthly air temperature in Ukraine was upward in 1947–2024, in general. The gain in the increasing air temperature in winter, autumn, spring, summer and for a year was as follows: +1.4 ºC, +1.5 ºC, +1.4 ºC, and +1.8 ºC, respectively, but this gain was smaller compared to the indices in the central part of the Forest-Steppe (Drabiv experimental field) — 1.8, 2.5, 2.3, 2.1 times, respectively. In the winter period, on average in Ukraine, the average daily air temperature increased from –3.6 ºC to –0.9 ºC, which was 1.5 times higher compared to the central Left-Bank Forest-Steppe (*Fig. 2*).

The typization of the average monthly air temperature (t_{av}°C) over 77 years demonstrated that the median air temperature in the periods of the year was above the average value and tended towards the upper threshold of typical values ($L_{0.75}$), indicating an increase in air temperature. The quartile deviation (ΔH) of the air temperature in autumn, spring, summer, and for the year and the winter period increased 3.4 times on average. The variation coefficient of the average monthly air temperature was higher than 33%, which characterizes the variation rate as high.

In April–August, the average evaporation of moisture (1947–2024) was 428 mm, and within the interval, the evaporation reached the maximal value of 561 mm, and the minimal value of 325 mm. The normalized interval of evaporation was 122 mm (50%). The coefficient of evaporation variation was 18.2%. The median value of evaporation tended more to the higher typical value ($L_{0.75}$), which demonstrates the increase in evaporation from 1947 to 2024. The average value of the moisturization coefficient (K_{mc}) was at the level of optimal moisturization. By the median, the value of K_{mc} tended more to the lower typical value ($L_{0.25}$), which is related to the increase in arid conditions. The variation coefficient (K_{mc}) was 18.6%, which demonstrated a stable increase in arid conditions in the observation period from 1947 to 2024.

During the observation period (1947–2024), the moisturization index (I_m) for the one-meter-deep layer of chornozem in November was, on average, at the level of the arid conditions, and by the median, it reached the level of extremely arid conditions. The amplitude interval of Im was $\Delta_{Im(a)}$=0.90, and the normalized one: $\Delta_{Im(n)}$=0.16, which determined a high level of variation coefficient of I_m, exceeding 50%.

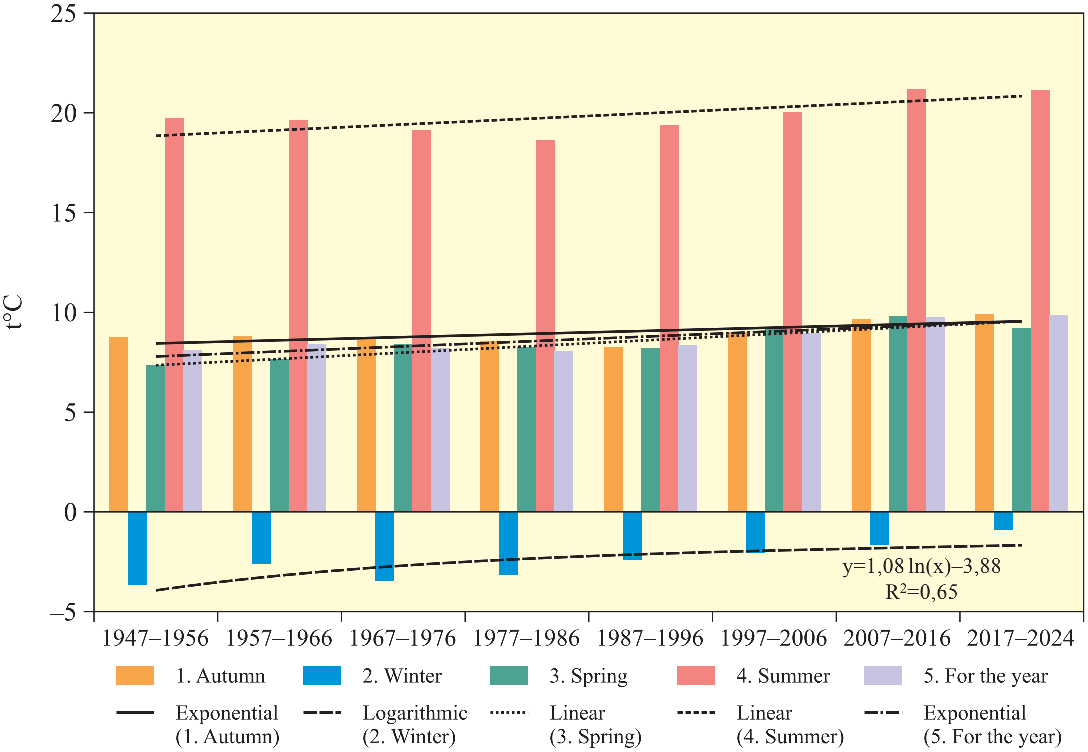


Fig. 2. The dynamics of the average monthly precipitation and average monthly air temperature in the conditions of the central part of the Left-Bank Forest-Steppe in 1947–2024

Table 2. The typization of climatic parameters of the conditions for the formation of the moisturization regime of typical chornozem in the conditions of the central part of the Left-Bank Forest-Steppe in 1947–2024

Parameters	Average	Median	Amplitude interval		Normalized interval				K_{var}*, %
			Min.	Max.	$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.95}$	
					50% significance level		10% significance level		
Index of moisturization, I_m									
I_m for XI	0.42	0.35	0.21	1.11	0.30	0.46	0.28	0.51	56.0
I_m for IV	1.05	1.10	0.65	1.36	1.01	1.13	0.79	1.21	17.5
I_m for VII	0.34	0.31	0.17	0.55	0.27	0.43	0.24	0.48	32.9
Moisture deficit in soil (D_m), %									
Dm XI	59.0	65.0	0.00	81.0	54.0	70.0	49.0	72.0	35.0
Dm VII	66.0	69.0	45.0	83.0	57.0	73.0	52.0	76.0	17.0
Hydrothermal coefficient of moisturization (HTC according to Selianinov)									
IV–V	1.00	0.95	0.65	1.51	0.79	1.19	0.69	1.29	26.3
IV–XIII	0.99	1.00	0.76	1.21	0.91	1.09	0.79	1.13	13.5
VI–XIII	0.97	1.06	0.61	1.18	0.78	1.13	0.66	1.15	21.2

Note: * K_{var} — variation coefficient, %.

The average value of I_m in April was at the level of optimal moisturization. The level of I_m variation was 17.5% which demonstrated a stable level of I_m in April for the entire observation period with a weak tendency towards the decrease in Im in 2010–2024 (*Table 2*).

On average, the moisturization index in July was 1.23 times lower than in November, and 3.1 times lower than in April. The Im variation coefficient reached 32.9%, indicating significant fluctuations in the moisture content of the one-meter-deep soil layer in November.

The moisture deficit (D_m) in the one-meter-deep layer in November averaged 59.0%, with a median value of 65.0%, indicating an increase in moisture deficit in November over 77 years of observations. A significant deviation from the average in terms of amplitude and normalized interval of D_m is associated with a high coefficient of variation, which exceeded 30%. The moisture deficit in July was 66%, and the median value reached 69.0%, which exceeded the average moisture deficit value. The level of amplitude and normalized deviation from the average provided a coefficient of variation of 17%, which indicates the formation of stable arid conditions in the soil.

The normalized parameter of the hydrothermal coefficient (HTC) according to Selianinov shows that in April–May during the observation period (77 years), it corresponded to optimally moist conditions, and according to the median, to weakly arid conditions, which indicates an increase in arid atmospheric conditions. According to the amplitude interval, the spring period had a range from excessively wet conditions (HTC>1.5) to moderately arid conditions (HTC=0.79). The amplitude interval was $\Delta_{HTC(a)}$=0.86. The normalized interval was $\Delta_{HTC(n)}$=0.40. The variation coefficient for the change in HTC exceeded 25%, which demonstrates a high level of HTC fluctuation, especially in the period from 2010 to 2024.

The average HTC value in summer corresponded to weakly arid conditions. The amplitude interval and the normalized interval ensured the variation coefficient values over 20% which is 1.2 times lower compared to the spring period. On average, for April–August, HTC corresponded to weakly arid conditions. The minimum values of the HTC in spring and summer corresponded to moderately arid conditions, and in case of the normalized interval, the deviation from the median corresponds to arid and extremely arid conditions. In summer, the HTC index had the variation coefficient of 13.5% which demonstrated the stability of the formed hydrothermal conditions in 1947–2024 with a stable tendency towards the increase in arid atmospheric conditions.

The precipitation variation in November–March was 2.3 times higher than the formed reserves of productive moisture in April. The amplitude interval of moisture reserves was 128 mm, and the normalized one — 24.5 mm. The moisture reserves by the median tended more to $L_{0.25}$, which demonstrated a decrease in the moisture reserves in the one-meter-deep soil layer from 1945 to 2024. The variation coefficient was 54.4% which corresponded to a very high deviation from the average and demonstrated a high fluctuation level for the annual moisture reserves (*Table 3*).

The precipitation amount in April–August was 257 mm on average during the observation period, and by the median, the average precipitation value was 9 mm higher, and the amount of precipitation by the median tended more to the higher typical value, which is related to its increasing amount from 1947 to 2024.

On average, in the cold period of the year, the soil accumulated about 94 mm of moisture from atmospheric precipitation. Moisture accumulation in the soil tended to be closer to the higher typical value, indicating that the less moisture was accumulated before the onset of winter, the more moisture from precipitation was retained by the soil layer in spring, which was more characteristic of the early observation periods, while in 2020–2024, the pattern was reversed. The amplitude interval of moisture input into the one-meter-deep layer was 92 mm, and the normalized one — 13 mm. The variation coefficient exceeded 25% which demonstrates a high variation in the precipitation accumulation during the last decade of observations. The average precipitation for November–March was about 191 mm, and its amount by the median was at the average level. The coefficient of variation exceeded 20%, indicating an average level of variability (*Table 3*).

The average and median productive moisture reserves in the one-meter-deep soil layer in April were 156–158 mm. The coefficient of variation of moisture reserves in April was 10%, which was 5.3 times lower than the variation in reserves in November.

The average and median productive moisture reserves in the one-meter-deep chornozem layer in July during the observation period were 50–55 mm, indicating a decrease in the amount of moisture in the one-meter-deep layer in July from 1947 to 2024.

The amplitude interval of moisture reserves in July was 56 mm. The normalized interval was 24 mm — 35 mm. The variation coefficient for moisture reserves in the 0–100 cm layer in July exceeded 30% which demonstrates a high variability level, exceeding the variability in April by 3.2 times.

The average potential (Pt) moisture reserves (reserves in April in the one-meter-deep soil layer + precipitation in April–August) were 421 mm, and

Table 3. The typization of precipitation, reserves, and losses of productive moisture from the depth of typical chornozem in the conditions of the central part of the Left-Bank Forest-Steppe in 1947–2024

Variable parameters	Mean	Median	Amplitude interval		Normalized interval				K_{var}*, %
			Min.	Max.	$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.95}$	
Precipitation, mm									
November–March	190.6	195.0	121.0	266.0	160.5	209.0	128.0	257.0	23.2
April–August	257.2	266.0	200.0	292.0	239.5	277.0	218.0	285.0	11.0
Reserves of productive moisture in 0-100 cm, mm:									
November	61.6	51.5	32.0	160.0	44.0	68.5	42.0	75.0	54.4
April	155.7	157.5	130.0	188.0	145.0	165.0	135.0	170.0	10.3
Moisture input into soil in spring	93.9	99.0	26.0	118.0	91.5	105.0	80.0	115.0	25.3
Pt (potential)	421.1	419.5	362.0	473.0	405.5	442.0	388.0	457.0	7.3
July	50.1	45.5	25.0	81.0	39.0	63.0	35.0	70.0	32.8
Loss of moisture from soil, mm									
April–July	–105.0	–105.0	–90.0	–125.0	–99.5	–108	–99	–122	9.3
Loss in IV–VIII from Pt, mm	362.7	376.0	307.0	391.0	340.5	384.0	317.0	389.0	8.4
Evaporation, mm	428.4	392.5	325.0	561.0	385.0	507.5	350.0	535.0	18.2
K_{mc}	1.02	1.02	0.75	1.41	0.88	1.13	0.77	1.22	18.6

Note: K_{mc} — moisturization coefficient; Pt — moisture reserves (reserves in April in the one-meter-deep soil layer + precipitation in April–August), * K_{var} — variation coefficient, %.

about 420 mm by the median. The amplitude interval was 111 mm, and the normalized one — 36 mm. The moisture potential by the median tended more to $L_{0.25}$, which demonstrated a stable regularity in the Pt decrease from 1947 to 2024. The variation coefficient for moisture potential was 7.3%, which is 3.5 times lower than the variability of productive moisture accumulation in April, indicating a high level of stabilization of growing conditions by atmospheric precipitation from April to August.

The average loss of moisture potential in April–August was 363 mm, and 13 mm more by the median. The loss by the median tended to the higher typical value ($L_{0.75}$), which demonstrates an increase in the moisture potential loss from 1947 to 2022. The amplitude interval of moisture loss was 84 mm, and the normalized one — 43–72 mm. The proximity of Pt loss by 10% reliability level to the amplitude interval demonstrates the stability of the mentioned parameter, reflected in the variation coefficient below 10%, which was 1.2 times lower than the moisture reserves from soil.

The loss of the productive moisture reserves from the one-meter-deep soil layer in April–July, by the average value and the median, were close. The loss of moisture from the soil, as indicated by both statistical indices, tended towards the higher typical value, which demonstrates the intense use of soil moisture during the entire observation period. The amplitude interval of the moisture loss from the soil was 35 mm. The normalized interval was from 8.5 mm to 23 mm. The variation coefficient for the loss of productive moisture reserves was under 10%, which demonstrates the established stability of moisture loss from the soil depth. There was a moderate direct correlation between the moisturization indices in July and April, and a strong direct correlation between Im in November and July. There was a strong negative correlation between the moisture deficit in the soil and Im from November to July (*Table 4*).

Table 4. The matrix of paired correlation coefficients between the moisturization indices and moisture deficit in soil in conditions of the central part of the Left-Bank Forest-Steppe in 1947–2024

Climate parameters	I_m for XI	I_m for IV	I_m for VII	D_m XI	D_m VII
I_m for XI	1.00	0.68	0.83	–0.96	–0.83
I_m for IV		1.00	0.65	–0.66	–0.65
I_m for VII			1.00	–0.87	–0.95
D_m XI				1.00	0.87
D_m VII					1.00

Note: I_m — moisturization index, D_m — index of moisture deficit.

The established cyclicity of precipitation was as follows: autumn — 5, 10, 37 years; spring — 5, 15 years; autumn — 5, 25 years, and for the year — 5, 10, 25 years. The cyclicity in the change in air temperature was as follows: autumn — 5, 37, 75 years; winter — 10, 15 years; spring — 5, 10, 15 years; autumn — 5, 10, 40, 75 years, and for the year — 5, 10, 20, 37 years (*Fig. 3*). The cyclicity in the change of atmospheric precipitation correlated with the cyclicity of the average monthly air temperature with the “delay” at the level of moderate correlations.

The changes in the climatic conditions of the central part of the Forest-Steppe (Object No. 2). The observations in the central part of the Forest-Steppe demonstrated that the precipitation amount in December–February was 74% (in 2020) of the precipitation amount in the cold period. The precipitation amount in December–February decreased from 64% in 2021 to 39% in 2024, and in 2025, the precipitation amount increased to 47%. On average, from 2022 to 2025, the share of precipitation in the winter period accounted for 40% of the total precipitation in the cold period, which is 1.9 times less than the share in 2021. In 2021–2025, on average, the share of precipitation in the cold period was 53% which is 6% less than the average perennial value (*Table 5*).

It was determined that the share of precipitation in November–December in 2020 in that for the cold period of the year was 28%, whereas in the following years (2021–2022), the share of precipitation increased to 68%, (+109–116 mm), in 2023 — 48% (+136 mm), 2024 — 80% (+132 mm), and in 2020–2025 — 56% (+109 mm) of moisture. On average in 2021–2025, the share of precipitation in November–December was 63% (+123 mm). The share of precipitation compared to 2020 was exceeded by +71 mm, and compared to the average perennial value, the share of precipitation in November–December was 1.3 times higher, or there were additional 30 mm of precipitation.

On average, in 2021–2025, the precipitation amount in January–March reached 83 mm and was 44% from the precipitation in the cold period of the year. In 2024, the precipitation amount for the mentioned period was 147 mm, and the share

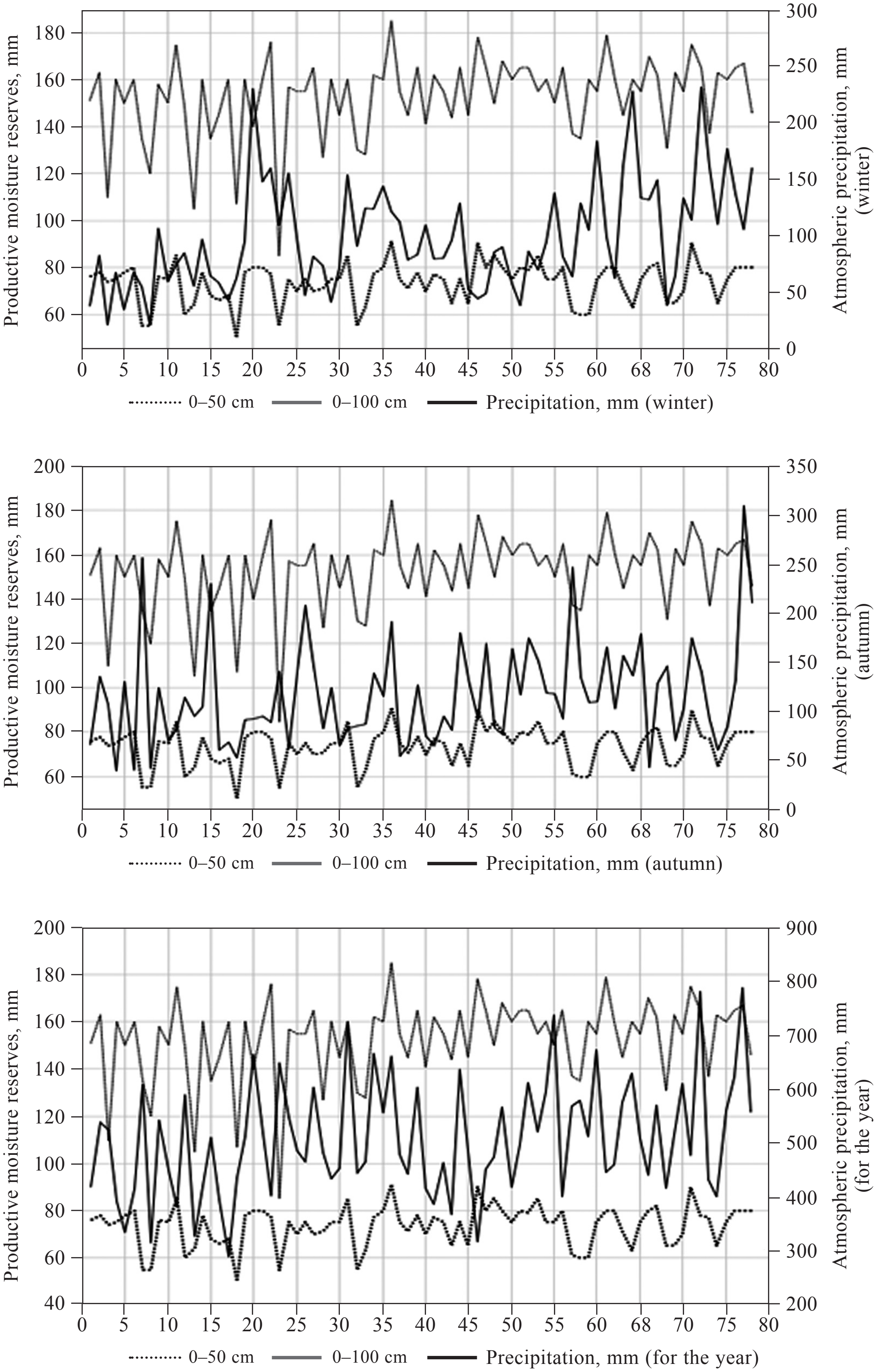


Fig. 3. The dynamics in the atmospheric precipitation and productive moisture reserves in the 0-100 cm layer in the central part of the Forest-Steppe of Ukraine in 1947–2024: 0–80 — in years of observations; 0–50 cm and 0–100 cm — moisture reserves, mm

Table 5. The meteorological parameters of the cold period of the year in the central part of the Forest-Steppe in 2020–2025

Months of the cold period of the year, precipitation, mm					Precipitation in:	
XI	XII	I	II	III	XI–III cold period	XII–II winter
2020		2021				
15.0	37.0	51.0	49.0	32.0	184.0	137.0
2021		2022				
35.0	74.0	27.0	9.0	15.0	160.0	110.0
2022		2023				
68.0	48.0	6.0	21.0	28.0	171.0	75.0
2023		2024				
90.0	46.0	28.0	36.0	83.0	283.0	110.0
2024		2025				
75.0	57.0	10.0	11.0	13.0	166.0	78.0
2020–2025		2021–2025				
57.0	52.0	24.0	25.0	34.0	193	102.0
Values for many years						
39.0	40.0	37.0	33.0	38.0	187.0	110.0
Average monthly air temperature, t°C					t°C in periods:	
2020		2021				
+3.9	–0.2	–2.0	–5.3	+1.8	–0.4	+1.3
2021		2022				
+4.5	–0.5	–1.3	+1.4	+1.9	+1.2	–0.1
2022		2023				
+3.8	–0.1	–0.1	–0.2	+5.2	+1.7	+1.6
2023		2024				
+4.8	+1.1	–1.7	+3.5	+4.4	+2.4	+1.0
2024		2025				
+11.5	+0.7	+2.3	–4.5	+6.8	+3.4	–0.5
2020-2025		2021–2025				
+5.7	+0.2	–0.56	–1.0	+4.0	+1.7	–0.5
Values for many years						
+2.7	–0.1	–3.5	–2.6	+2.3	–0.6	–2.6

of the total precipitation amount for the cold period of the year was at the level of 52%.

In November, the average daily air temperature increased from 2020 to 2024 by +7°C or 2.6 times. Compared to the perennial increase, the exceeding was +3°C. The average monthly air temperature in the cold period of the year from 2022 to 2025 was over 0°C and had a regular increase in 2025 too. From 2022 to 2025, the average monthly air temperature increased by +2.2°C. In 2021–2025, the temperature of the cold period of the year was +1.7°C, in winter — –0.5°C, which is 5.2 times higher than the average perennial value (*Table 5*).

A direct correlation was established between the precipitation amount in November–March and the precipitation in November ($R=+0.70\pm0.02$, $R^2=0.49$), and the relation to the precipitation amount in March increased to $R=+0.88\pm0.02$, $R^2=0.77$. In February and

December, the relation to the precipitation amount was at the level of reverse correlation R=–0.71±0.02, R^2=0.50. The dependence between the moisture reserves in the one-meter-deep soil layer in March and the precipitation amount in March and in November–March was as follows: R=+0.75–0.85±0.02, R^2=0.56–0.72. A high rate of determination coefficients demonstrates a considerable impact of the precipitation in November and March on the moisture reserves in the one-meter-deep layer in March. There was a moderate direct correlation between the moisture reserves in the one-meter-deep layer in April and the precipitation in March (R=+0.55±0.02, R^2=0.30). The correlation between the moisture reserves in the 0–100 cm layer and precipitation in November-March increased to R=+0.65±0.02, R^2=0.42. The correlation between the moisture reserves in the one-meter-deep layer in April and the reserves in March was at the level of R=+0.86±0.02, R^2=0.74. The loss of moisture from the one-meter-deep soil layer in March–April correlated with the moisture reserves in the one-meter-deep layer in March at the level of R=–0.45–0.58±0.02, R^2=0.20–0.34, which demonstrated the impact of higher temperature regime on the moisture loss from the one-meter-deep soil layer.

The measurement of the amount of atmospheric precipitation in the cold period of the year demonstrated that in November, the average precipitation amount was 54.7 mm, and the values by the median were 2.3 mm higher and tended to $L_{0.75}$. The amplitude interval was Δ_a=64 mm, which ensured the variation coefficient of 50.1%. The average value for the precipitation in December was 50.4 mm, which was close to the median values. The amplitude interval was Δ_a=62 mm with the variation coefficient for the precipitation in the cold period of 43.9%. A high variation coefficient rate demonstrates instability in the formation of conditions for sufficient moisture accumulation during the cold period of the year (*Table 6*).

The average amount of the atmospheric precipitation in November–December was 104.7 mm at the amplitude interval Δ_a=95 and the normalized interval — 77 mm. The precipitation variation coefficient was 34.6%. The average precipitation amount in January–March was 84.3 mm, which corresponded to the value by the median, but compared to the precipitation in November–December, its amount was 1.24 times smaller (–20.4 mm). On average, the precipitation amount in November–March was 189.7 mm at the amplitude interval Δ_a=138 mm and the normalized interval Δ_n=36 mm, which ensured the variation coefficient of 23.4%.

The precipitation amount in November–December was 55% of the total amount for November–March, and the precipitation in January–March was 45% which demonstrates that the precipitation in November–December supplied moisture. There was a 1.44-

Table 6. The normalized parameters of atmospheric precipitation and reserves of productive moisture in the cold period of the year in conditions of the central part of the Forest-Steppe in 2019–2025 (estimation using the observations of the Smila meteorological station, the Cherkasy CGM)

Seasons of the year	Mean	Median	Amplitude		Quantiles		K_{var}, %***
			Min	Max	$L_{0.25}$	$L_{0.75}$	
Precipitation, mm							
XI	54.7	37.0	26.0	90.0	35.0	90.0	50.1
XII	50.0	48.0	15.0	77.0	33.0	74.0	43.9
XI–XII	104.7	114.0	52.0	147.0	59.0	136.0	34.6
I–III	84.3	85.0	34.0	146.0	51.0	132.0	49.8
XI–III	189.7	181.0	144.0	282.0	165.0	201.0	23.4
Moisture reserves in 0–100 cm							
X	75.6	69.0	33.0	150.0	40.0	100.0	56.6
III	165.7	172.0	130.0	201.0	135.0	179.0	15.2
± III–X	90.1	82.0	28.0	161.0	65.0	139.0	50.7
IV	149.9	157.0	108.0	184.0	125.0	166.0	17.1
± III– IV	–15.9	–17.0	–22.0	–8.0	–22.0	–10.0	–36.8

Note: * Δ_a=max–min (amplitude interval); ** Δ_n=$L_{0.75}$–$L_{0.25}$ (normalized interval); *** K_{var} — variation coefficient, %.

fold decrease in the precipitation variation coefficient compared to the period of January–March.

The increase in the moisture reserves in the 0–100 cm layer in the cold period of the year was 90.1 mm (93 mm by the median). The amplitude interval was Δ_a=133 mm at $К_{os}$=148%, which ensured $К_{var.}$=50.7%. The efficiency of fixing precipitation on average in the years of observations was 45–47% of the precipitation amount in the cold period of the year. Under the normalized interval of the moisture accumulation in the cold period of the year, the efficiency of fixing precipitation by the soil layer was 39–69%.

The average moisture reserves in April were 149.9 mm, with the reserves by the median — 157 mm. The amplitude interval was Δ_a=76 mm at $К_{os}$=51%, which ensured $К_{var.}$=17.1% and characterized the process of forming the moisture reserves in April as the most stabilized process with a normalized interval of 125 mm, tending to the higher typical value and being a sign of increasing moisture reserves in April. The average moisture loss from the one-meter-deep layer due to evaporation in March–April was 15.9 mm at the amplitude interval of 14 mm, which ensured the variation in moisture loss of 36.8.

A strong direct correlation was found between the precipitation in March and the reserves of productive moisture in the 0–100 cm layer (*Table 7*), with one unit (mm) in the increasing moisture reserves corresponding to 1.37 units of precipitation. By the determination coefficient, this interaction is determined at the level of 54%.

The precipitation in January and moisture reserves in the one-meter-deep chornozem layer in March correlated on an average level, and the regression coefficient was 1.6 times smaller, with a 1.5-fold decrease in the values of the free term of the dependence equation. The correlation between February precipitation and March moisture reserves weakened to moderate. A high rate of direct correlation was found between the amount of precipitation in November–March and the moisture reserves in the one-meter-deep layer in March. Each 10 mm of the increasing moisture reserves in the 0–100 cm layer corresponded to 8.1 mm of the precipitation of the cold period. A strong direct correlation was found between the moisture reserves in the 0–100 cm layer in March and those in April, with each 10 mm increase in moisture reserves in April corresponding to 10.5 mm of moisture in March. A direct correlation was found between the high precipitation rate in March and the moisture

Table 7. Regression equations, coefficients of correlation, and determination between the parameters of forming the productive moisture reserves in the 0–100 cm layer in the Smila experimental field of the Cherkasy state agricultural experimental station

Regression equation	Coefficients:	
	of correlation, R	of determination, R^2
Precipitation in March (x): moisture reserves in 0–100 cm in March (Y)		
Y = 124.8 + 1.37x	0.76	0.57
Precipitation in January (x): moisture reserves in 0–100 cm in March (Y)		
Y = 84.5 + 0.87x	0.67	0.45
Precipitation in November–March (x): moisture reserves in 0–100 cm in March (Y)		
Y = 12.8 + 0.81x	0.73	0.51
Moisture reserves in March in 0–100 cm (x): moisture reserves in 0–100 cm in April (Y)		
Y = 13.7 + 1.05x	0.97	0.95
Precipitation in March (x): precipitation input in March–November (Y)		
Y = –2.53 + 3.13x	0.69	0.48
Precipitation in November–March (x): input of moisture to 0–100 cm layer in the cold period		
Y = –148.9 + 1.27x	0.82	0.68
Moisture reserves in 0–100 cm in October (x): moisture input in March–November (Y)		
Y = –146.3 + 0.79x	–0.84	0.70

input in the one-meter-deep layer from March to November. Each 1 mm of the increasing moisture reserves in March-November corresponded to 3.13 mm of the precipitation in March (*Table 7*).

The moisture input into the one-meter-deep layer during the cold period of the year and the precipitation in November–March showed a direct, strong correlation, where each 10 mm increase in soil moisture reserves corresponded to 12.7 mm of atmospheric precipitation. The reverse relation at the level of strong correlation was found between moisture reserves in October and the moisture input in the 0–100 cm soil layer in March–November, where a 10 mm increase in moisture reserves in March corresponded to a 12.7 mm decrease in moisture reserves in the 0–100 cm layer, which indicates that the lower the moisture reserves in the 0–100 cm layer before the onset of winter, the more effectively the moisture from precipitation during the cold season is accumulated in the soil in March, provided there is sufficient precipitation during the cold season.

The dynamics of the moisturization regime of the one-meter-deep layer of podzolic chornozem. Regardless of the way of soil tillage in the 5-field crop rotation in the spring period, the trends in the moisture reserves in the layers of 0–20 cm, 0–50 cm, 50–100 cm, and 0–100 cm were downward. The difference in the productive moisture reserves in 2025 compared to 2021 was as follows: –87 mm (plowing), –75 mm (surface tillage), –60 mm (No-till after plowing) and –79 mm (No-till after surface tillage) with the moisture reserves in 2025 of 108 mm, 120 mm, 143–145 mm for No-till, respectively.

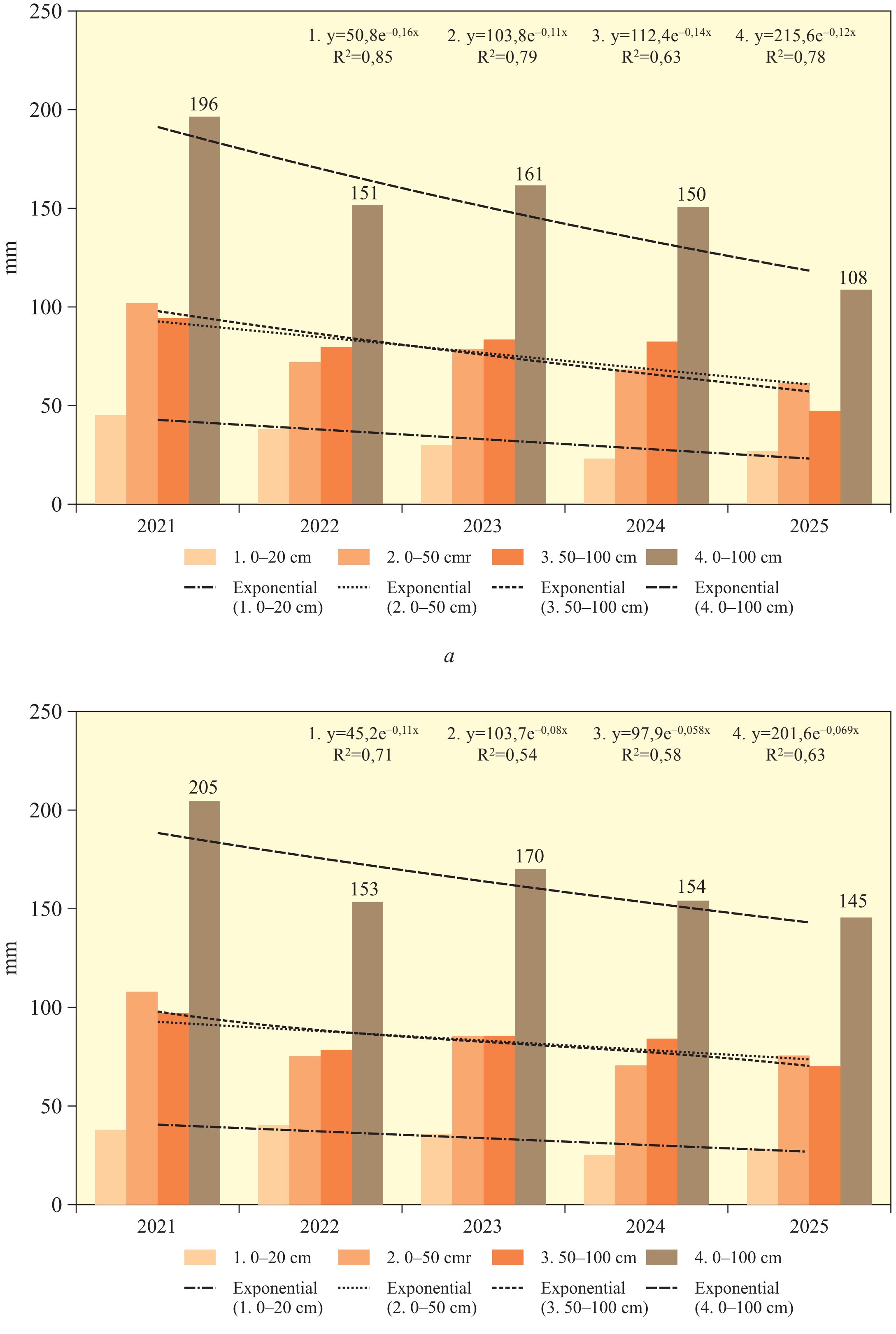
The intensity of the decrease in moisture reserves was evaluated by the value of the regression coefficient in the exponential equations for the trends in the moisture reserve change. In the 0–20 cm layer, the coefficients for exponential equations for No-till were 1.5–1.6 times smaller compared to the coefficient value for plowing. In the 0–50 cm layer, the regression coefficients were 1.4–1.5 times smaller, and in the 50–100 cm layer, they were 1.4–2.5 times smaller. In the 0–100 cm layer, the regression coefficients for exponential equations for surface tillage and No-till were 1.4–1.7 times smaller compared to plowing (*Fig. 4, 5*).

Regardless of the soil layer capacity with No-till, surface tillage, and plowing, free terms of exponential equations were close in the values, and the reliability of the regression equations was high. In terms of Hurst's index, the dynamics series were stable (H=1.01–1.31), and by the index of fractal dimensionality, the series were persistent (D=0.69–0.94) (*Fig. 4, 5*).

The typization of the moisturization regime in the spring period in the one-meter-deep soil layer demonstrated that in the 0–20 cm layer, the average reserves of productive moisture were 31.2–33.2 mm regardless of the tillage method, with the highest amplitude interval for plowing — Δ_a=22 mm against Δ_a=15 mm under No-till, which was 1.5 times less. The variation coefficient for the productive moisture reserves in the 0–20 cm layer under plowing and surface tillage was 26.1–27.8% whereas under No-till, the variation coefficients for moisture reserves were 1.4–1.5 times smaller.

In the 0–50 cm layer, the average productive moisture reserves for No-till were 7.0–7.5 mm higher compared to plowing and surface tillage. The highest amplitude interval was determined for plowing (Δ_a=41 mm), whereas for No-till and surface tillage, the amplitude interval was 1.3–1.6 times smaller under equal normalized interval which impacted the variation coefficient for the productive moisture reserves, which was the highest for plowing, and in case of No-till, the variation of the moisture reserves was 2.2–5.2% lower. In the 50–100 cm layer, the average productive moisture reserves for No-till compared to plowing were 5.8–10.8 mm higher than the amplitude interval, with the lowest level for No-till after plowing and surface tillage. The variation coefficient for moisture reserves in case of No-till was 1.5–1.9 times smaller compared to plowing. In the 0–100 cm layer, the average reserves of productive moisture under plowing and surface tillage were 153.2–156.4 mm. In case of No-till, the moisture reserves were 10.6–16.6 mm higher on average. The amplitude interval of moisture reserves was the highest in case of plowing. In case of No-till, the amplitude interval was 9–28 mm smaller. Under the surface tillage, the amplitude interval was 13 mm smaller, which impacted the variation coefficient for moisture reserves, which was at the rate of substantial variation for plowing and weak variation in case of No-till.

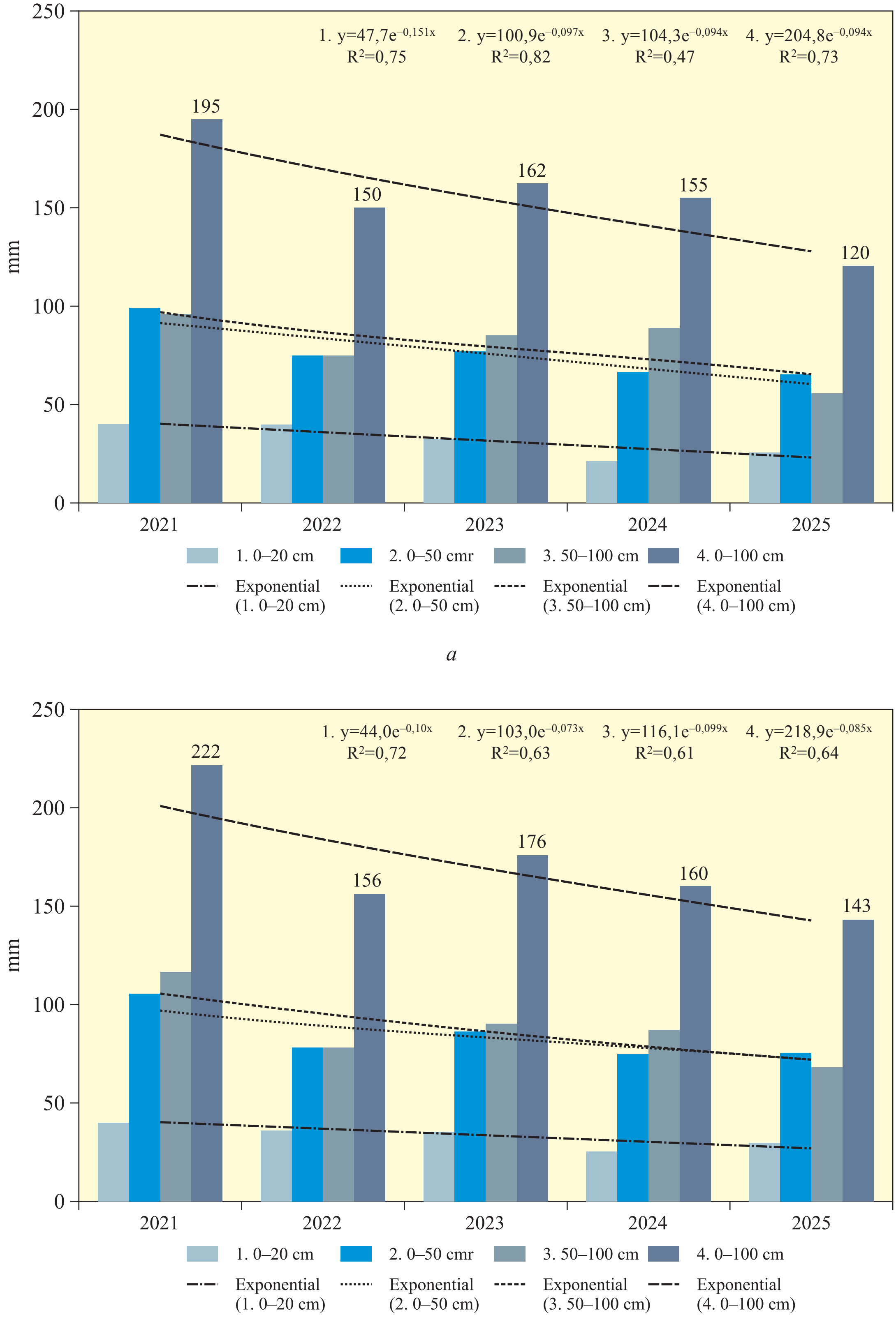
The typization of the moisture reserves in July in 2021–2025 demonstrated that, regardless of the tillage method, in the 0–20 cm layer, the moisture reserves were within 14.4–17.8 mm in case of the equal amplitude interval and the 1.4–1.5 times smaller variation coefficient in case of No-till compared to plowing. In



a

b

Fig. 4. The dynamics of spring productive moisture reserves in the 5-field crop rotation with plowing (*a*) and No-till (*b*) after plowing



a

b

Fig. 5. The dynamics of spring productive moisture reserves in the 5-field crop rotation with surface tillage (*a*) and No-till (*b*) after surface tillage

Table 8. The typization of the chornozem moisturization regime in the agrocenosis of the 5-field crop rotation under different tillage in April-August of 2021–2025 (central part of the Forest-Steppe)

Way of tillage	Mean	Median	Amplitude		Quantiles		K_{var}, %***
			Min	Max	$L_{0.25}$	$L_{0.75}$	
Quantiles							
0–20 cm							
Plow	32.4	30.0	23.0	45.0	26.0	38.0	27.8
Plow+n	33.2	35.0	25.0	40.0	28.0	38.0	19.5
Surf	31.2	32.0	21.0	39.0	25.0	39.0	26.1
Surf+n	33.0	35.0	25.0	40.0	29.0	36.0	18.1
0–50 cm							
Plow	76.2	72.0	61.0	102.0	68.0	78.0	20.6
Plow+n	33.2	35.0	25.0	40.0	28.0	38.0	18.4
Surf	76.4	75.0	65.0	99.0	66.0	77.0	17.9
Surf+n	83.6	78.0	74.0	105.0	75.0	86.0	15.4
0–100 cm							
Plow	153	151	108.0	196.0	150.0	161.0	20.5
Plow+n	165	154	145.0	205.0	153.0	170.0	14.5
Surf	156	155	120.0	195.0	150.0	162.0	17.2
Surf+n	171	160	143.0	222.0	156.0	176.0	17.9
June							
0–20 cm							
Plow	8.8	6.0	4.0	20.0	4.0	10.0	76.4
Plow+n	13.4	14.0	5.0	25.0	5.0	18.0	64.3
Surf	10.6	9.0	3.0	24.0	5.0	12.0	78.0
Surf+n	13.0	11.0	5.0	24.0	10.0	15.0	54.7
0–50 cm							
Plow	25.0	20.0	13.0	53.0	18.0	21.0	63.8
Plow+n	28.2	25.0	16.0	55.0	20.0	25.0	54.8
Surf	25.6	21.0	10.0	55.0	21.0	21.0	66.8
Surf+n	29.2	26.0	15.0	54.0	25.0	26.0	50.1
0–100 cm							
Plow	58.6	48.0	38.0	111.0	40.0	56.0	51.4
Plow+n	70.6	60.0	55.0	115.0	60.0	63.0	35.4
Surf	57.2	49.0	25.0	113.0	47.0	52.0	57.6
Surf+n	66.4	57.0	40.0	119.0	51.0	65.0	46.4
August							
0–20 cm							
Plow	18.5	20.0	2.0	45.0	4.0	26.0	72.3
Plow+n	20.8	20.0	5.0	40.0	10.0	28.0	56.7
Surf	19.1	21.0	3.0	39.0	5.0	28.0	64.9
Surf+n	21.3	23.0	5.0	40.0	10.0	29.0	52.8
0–50 cm							
Plow	43.1	45.0	5.0	102.0	18.0	68.0	69.0
Plow+n	47.7	37.0	15.0	108.0	20.0	75.0	63.7
Surf	43.4	37.0	5.0	99.0	21.0	66.0	68.7
Surf+n	47.7	37.0	5.0	105.0	25.0	75.0	66.9
0–100 cm							
Plow	88.7	87.0	24.0	196.0	39.0	150.0	62.8
Plow+n	101	72.0	45.0	205.0	55.0	153.0	53.1
Surf	89.9	84.0	25.0	195.0	41.0	150.0	63.2
Surf+n	101	84.0	40.0	222.0	43.0	156.0	59.0

Note: * Δ_a — amplitude interval; ** Δ_n — normalized interval; Plow — plowing; Plow+n — No-till after plowing; Surf — surface tillage; Surf+n — No-till after surface tillage.

the 0–50 cm layer, the moisture reserves were equal for plowing and surface tillage, while under No-till, they were 4–5 mm higher, with a high rate of variation coefficient. In case of No-till after plowing, the variation coefficient was the lowest. In the 50–100 cm layer, the average productive moisture reserves for No-till compared to plowing were 7.2–9.0 mm higher under the amplitude interval from 27 mm to 31 mm regardless of the tillage method. The variation coefficients of moisture reserves under No-till were 1.4–2.5 times smaller, and 1.5–1.7 times smaller compared to surface tillage. The observed regularity was preserved in the 0–100 cm layer: the average productive moisture reserves under No-till exceeded the reserves for plowing by 13.2 mm. The variation coefficients for moisture reserves under No-till were smaller compared to plowing and surface tillage, 1.1–1.4 times and 1.2–1.5 times, respectively, which demonstrates the stabilization of moisture reserves in the one-meter-deep layer in July (*Table 8*).

The balance of productive moisture reserves in 2021–2025 demonstrated that under plowing and surface tillage, 153–155 mm moisture accumulated in the 0–100 cm layer, and under No-till, the moisture reserves were 11–17 mm higher. The moisture reserves in the half-layers correlated regardless of the tillage method as 1 to 1, but in case of larger reserves for No-till (*Table 9*), the reserves of productive moisture in June in the 0–100 cm layer under No-till were 14–15 mm higher compared to plowing and surface tillage. The layer-wise re-distribution of moisture demonstrated that the ratio of the moisture reserves regardless of the tillage method was 0.7–0.8 to 1, with the reserves in the 0–50 cm layer of 25–30 mm for tillage, and in the 50–100cm layer, the moisture reserves under No-till were 8–13 mm higher compared to plowing and surface tillage. The loss of moisture from the one-meter-deep layer in April–June, regardless of the tillage method, was 98–103 mm. The layer-wise loss of moisture from the 0–50 cm layer regardless of the tillage method was 51–54 mm, and it was the lowest in the 50–100 cm layer under surface tillage and No-till after plowing — 40 mm and 46–47 mm, respectively, and the highest loss of moisture was registered for No-till after surface tillage — 50 mm.

The productive moisture reserves in the 0–100 cm layer in July under plowing and surface tillage were 27–30 mm, while under No-till, the moisture reserves were 20–21 mm higher. The layer-wise moisture reserves in the 0–50 and 50–100 cm layers were 11 mm higher under No-till (50–100 cm), similar to the 0–50 cm layer (*Table 9*).

In April–July, the loss of moisture from the one-meter-deep layer after plowing was 125–130 mm, and in case of No-till, the loss of moisture was 8–10 mm less, which is positive for the use of productive mois-

Table 9. The impact of the chornozem tillage method on the productive moisture balance in the 5-field cereal crop rotation in 2021–2025

Depth, in cm	Reserves of productive moisture, mm					
	April-May	June		July		± to April
	mm	mm	± to April	mm	± to June	
			Plowing			
0–50	76.0	25.0	–51.0	8.0	–17.0	–68.0
0–100	153.0	55.0	–98.0	27.0	–32.0	–130.0
			No–till after plowing			
0–50	82.0	28.0	–54.0	20.0	–8.0	–62.0
0–100	165.0	71.0	–94.0	50.0	–21.0	–115
			Surface tillage			
0–50	77.0	26.0	–51.0	11.0	–15.0	–66.0
0–100	155.0	58.0	–97.0	30.0	–28.0	–125
			No–till after surface tillage			
0–50	83.0	30.0	–53.0	19.0	–11.0	–64.0
0–100	171.0	68.0	–103.0	49.0	–19.0	–122.0

ture under No-till in the crop rotation for 5 years while cultivating winter wheat, peas, and spring spiked crops.

Restoration of the organic matter of humus. The preservation of organic matter in soil is a prerequisite for stable and high-quality plant production. Soil is the primary natural industrial resource, and its fertility determines the final result of agrarian production in many aspects [Krupnik T.J., Andersson J.A., Rusinamhodzi L. et al., 2019, Dmytruk Yu.M., Semenchuk V.H., 2021, Ahmad K.W., Wang G., 2023].

Extensive agricultural systems, which spread and developed widely, did much damage to the soil cover of Ukraine. Gradually, a series of soil-protective (conservative) systems for primary soil tillage were developed, which either minimize the application of deep plowing or mitigate its usage. In recent years, wide application has been noted for the systems of zero soil tillage (No-till), which may be promising from the standpoint of maximal protection of soils from degradation due to the development of erosion processes, disruption of natural agrophysical structure, and sequestration of organic carbon [*Feng Q., An C., Chen Z., Wang Z., 2020*].

In the central part of the Left-Bank Forest-Steppe, under systematic plowing, the average reserves of humus in the 0–30 cm layer were at the level of 88 t/ha. The amplitude interval was 122 t/ha and the normalized one — 81–93 t/ha. Humus reserves by the median were below the average value by 2.1 t/ha and tended more to the lower typical interval value. Humus reserves by $L_{0.75}$ and $L_{0.90}$ were at the level of 128–136 t/ha, which corresponded to the reserves in the 0–30 cm layer.

Under No-tillage, the average humus reserves were 7 t/ha larger compared to plowing. The amplitude interval was 10 t/ha smaller than the higher values of humus reserves by 5 t/ha compared to the minimal value. The normalized typical interval by a 50% significance level was 1.15 times higher due to the increase in the higher typical value by 10 t/ha. Humus reserves in the 0–30 cm soil layer corresponded to the values of $L_{0.75}$ and $L_{0.90}$ and were higher, compared to plowing, by 10 t/ha and 6 t/ha (*Table 10*).

The difference in humus reserves between $L_{0.75}$ and $L_{0.90}$ was 4 t/ha, which is half the amount compared to plowing, demonstrating ae reliable increase in humus reserves in the 0–30 cm soil layer under No-till. Humus reserves by the median (95 t/ha) corresponded to humus reserves in the 0–30 cm soil layer and exceeded the reserves by the median, which demonstrates the increase in humus reserves.

Under surface tillage, the average humus reserves were 93 t/ha, which is 4.9 t/ha higher compared to plowing, and had a strong tendency towards a decrease compared to No-till. The amplitude interval of humus reserves was 105 t/ha, which is 17 t/ha and 7 t/ha less compared to plowing and No-till, respectively. The normalized typical interval with a 50% significance level was 89 t/ha which is 9 t/ha more compared to plowing and 2 t/ha less compared to No-till. Humus reserves by $L_{0.75}$ were 7 t/ha higher and close to the reserves under No-till. Humus reserves by $L_{0.75}$ and $L_{0.90}$ corresponded to the reserves in the

Table 10. The normalized parameters of the reserves of humus and carbon dioxide in humus depending on the tillage method in the grain-hoed crop rotations in 1976–2023 (for typical chornozem in the central part of the Left-Bank Forest-Steppe)

Parameters of humus state	Reserves in t/ha				Normalized interval, t/ha				Coef. Var, %*
	Mean	Median	Min.	Max.	$L_{0.25}$	$L_{0.75}$	$L_{0.10}$	$L_{0.90}$	
			Δ_a=max–min**		$\Delta_n=L_{0.75}–L_{0.25}$***		$\Delta_n= L_{0.90}–L_{0.10}$***		
Plowing									
Humus	88.1	86.0	38.0	160.0	47.0	128.0	43.0	136.0	41.7
$C–CO_2$ (hum.)	186.3	182.0	82.0	296.0	100.0	273.0	93.0	286.0	40.9
No-tillage									
Humus	94.8	95.0	43.0	155.0	47.0	138.0	45.0	142.0	41.6
$C–CO_2$ (hum.)	205.8	205.0	95.0	326.0	103.0	296.0	96.0	307.0	40.8

Note: * Coef. Var., % — variation coefficient; ** Δ_a=max–min — amplitude interval; *** $\Delta_n=L_{0.75}–L_{0.25}$ — normalized interval by the level of 50% significance; *** $\Delta_n=L_{0.90}– L_{0.10}$ — normalized interval by the level of 10% significance level; **** P(org) — organic phosphates.

0–30 cm soil layer and exceeded the reserves for plowing by 7 t/ha and 4 t/ha.

The average reserves of sequestered C–CO_2 under plowing were 186.3 t/ha, with the amplitude interval — 214 t/ha, normalized interval — 173 t/ha (50%), and 193 t/ha (10%). The organic carbon reserves in the 0–30 cm chornozem layer were 273 t/ha and 286 t/ha. The average reserves of C–CO_2 under No-till were 19.8 t/ha higher compared to plowing with the amplitude interval, wider by 17 t/ha, normalized by a 50% significance level. The average reserves of organic carbon in the 0–30 cm soil layer were in the range from 296 t/ha to 307 t/ha, which was 21–23 t/ha higher compared to plowing. There were 23 t/ha more accumulated sequestered C–CO_2 in the 0–20 cm layer compared to plowing.

It was found that in conditions of the central part of the Forest-Steppe, in podzolic chornozem, after plowing, the content of total humus in the 0–20 cm soil layer under crops of the 5-field crop rotation changed in the interval of 2.21–2.45%, in the 20–30 cm layer — 2.26–2.49%, and in the 0–30 cm layer — 2.24–2.47%. In case of surface tillage, the change in the humus content was as follows: 2.29–2.65% (0–20 cm), 2.21–2.53% (20–30 cm), and 2.27–2.53% (0–30 cm). In case of No-till after plowing — 2.29–2.65%, 2.23–2.53% and 2.27–2.53%; in case of No-till after surface tillage — 2.35–2.68%, 2.21–2.44% and 2.33–2.56% in the soil layers, respectively.

Under surface tillage and No-till, the intervals of change in the humus content under crops in the rotation were wider, compared to the values of the humus content after plowing in the 0–20 cm layer, and in general in the 0–30 cm layer, and in the 20–30 cm layer, the interval of the humus content were close regardless of the tillage method, but there was a tendency towards the increase in the interval of values of humus content under No-till after plowing and surface tillage.

The typization of the humus state parameters (*Table 11*) demonstrated that in the 0–20 cm layer under plowing, the average humus content was 2.31%, under surface tillage, the humus content was 0.27% higher, and under No-till — 0.14–0.18% higher on the reliable level. By the median, the humus content values under plowing and No-till after surface till-

Table 11. The typization of humus state parameters in the 5-field crop rotation under different tillage methods on the fifth year of implementation in the spring period in conditions of the central part of the Forest-Steppe

Way of tillage	Mean	Median	Amplitude		Quantiles		K_{var}, %***
			Min	Max	$L_{0.25}$	$L_{0.75}$	
0–20 cm							
Plow	2.31	2.29	2.21	2.45	2.22	2.39	4.6
Plow+n	2.45	2.46	2.29	2.65	2.31	2.55	6.3
Surf	2.58	2.68	2.26	2.79	2.45	2.72	8.5
Surf+n	2.49	2.48	2.35	2.68	2.45	2.49	4.8
HIP_{05}	0.09	0.08	—	—	—	—	—
20–30 cm							
Plow	2.38	2.41	2.26	2.49	2.31	2.45	4.0
Plow+n	2.34	2.33	2.21	2.53	2.23	2.41	5.7
Surf	2.39	2.36	2.09	2.69	2.35	2.45	9.0
Surf+n	2.34	2.36	2.21	2.44	2.31	2.39	3.7
HIP_{05}	0.06	0.05	—	—	—	—	—
0–30 cm							
Plow	2.34	2.33	2.21	2.53	2.23	2.41	5.7
Plow+n	2.41	2.42	2.27	2.53	2.38	2.43	3.8
Surf	2.49	2.54	2.18	2.74	2.41	2.56	8.4
Surf+n	2.42	2.42	2.33	2.56	2.35	2.43	3.7
HIP_{05}	0.06	0.08	—	—	—	—	—

Note: * Δ_a — amplitude interval (max-min); ** Δ_a — normalized interval ($L_{0.75}$–$L_{0.25}$); *** K_{var} — variation coefficient, %; Plow — plowing, winter crops, wild; Plow+n — No-till after plowing, 5 years; Surf — surface tillage, 10 years; Surf+n — No-till after surface tillage.

age tended to the lower typical value, and in case of No-till after plowing and under surface tillage, the humus content tended to the higher typical value, which demonstrates stabilization in humus accumulation in the former and its intense accumulation in the latter.

The variation coefficient for humus content in the 0–20 cm layer under plowing and No-till after surface tillage was 4.6-4.8% whereas under No-till after plowing it was 6.3%, and under surface tillage — 8.5%. In the 20–30 cm soil layer, the average humus content for plowing was 2.38% (+0.07% to the 0–20 cm soil layer). Under No-till after plowing and surface tillage, the humus content was 0.04% smaller compared to plowing, and in case of surface tillage, it was 0.01% higher. In case of surface tillage and No-till, the humus content was smaller compared to the content in the 0–20 cm layer, which demonstrates the differentiation of the humus content in the 0–30 cm layer, when humus is mostly accumulated in the 0–20 cm layer.

In the 0–30 cm layer, the average humus content for plowing was 2.34%, under surface tillage, the humus content increased by 0.15% (10 years of surface tillage), and in case of No-till, the humus content increased by 0.07–0.08%. Under plowing, the humus content by the median was below the average value and tended to the lower typical value, which demonstrates a moderate process of humus formation, whereas under surface tillage and No-till, the humus content by the median exceeded the average content which demonstrates enhanced humus accumulation. The variation coefficient for the change in the humus content under the crops of the rotation under different tillage methods did not exceed 10% which is acceptable for the evaluation of the humus content in the crop rotation.

The implementation of chornozem agropotential in the central part of the Left-Bank and the central Forest-Steppe. The typization of the yield of cereals without the introduction of any fertilizers by the median (Med) was below the average values, which tended more towards the lower typical value, demonstrating a downward trend in the performance of cereals. On the contrary, when introducing fertilizers, the yield of cereals by the median tended to the higher typical value and exceeded the average one, demonstrating an upward trend in performance. The amplitude interval for the yield of cereals without the introduction of fertilizers increased from the values for winter wheat to corn: from 3.84 t/ha to 6.36 t/ha, and in total for cereals — 2.85 t/ha (*Table 12*).

In case of introducing fertilizers, the average yield of cereals increased compared to the control without fertilizers by +1.33 t/ha (winter wheat), +1.20 t/ha (spring barley), +0.31 t/ha (corn), and +1.13 t/ha (cereals, total). The yield by the median was above the average value, which demonstrates the upward

Table 12. The typization of cereal performance parameters on typical chornozem in the 10-field crop rotation in conditions of the central part of the Left-Bank Forest-Steppe in 1974–2024

Variable parameters	Mean	Median	Amplitude interval		Normalized interval				Coef. var., %*
			Δ_a=Max–Min		$\Delta_n(0.50\%)= L_{0.75}–L_{0.75}$ $\Delta_n(0.10\%)=L_{0.95}–L_{0.10}$				
			Min.	Max.	L0.25	L0.75	L0.10	L0.95	
	t/ha								
No fertilizers									
Winter wheat	3.06	2.98	1.19	5.03	2.34	3.71	1.80	4.38	31.0
Spring barley	2.50	2.47	1.17	4.92	1.97	2.95	1.59	3.28	30.4
Corn	5.14	4.98	2.13	8.51	4.09	6.31	3.52	6.81	28.1
Cereals, total	3.37	3.27	1.91	4.76	2.81	4.08	2.35	4.39	23.2
With fertilizers									
Winter wheat	4.39	4.49	2.49	7.32	3.50	5.05	2.98	5.74	24.2
Spring barley	3.68	3.75	1.96	6.83	3.05	4.23	2.36	4.73	26.5
Corn	5.45	5.96	1.88	12.8	4.65	8.36	3.84	9.30	35.9
Cereals, total	4.50	4.55	3.06	6.60	4.00	5.28	3.65	5.79	18.5

* Variation coefficient: Coef. var., %.

trend in performance over time. Compared to the control without fertilizers, the amplitude interval was 1.26–1.70 times wider which determined the variation coefficient for the yield of cereals which decreased after the introduction of fertilizers for winter wheat, barley, and cereals cumulatively — 1.2–1.3 times, and increased 1.28-fold for corn.

The normalized interval of the cereal yield after the introduction of fertilizers increased 1.20–1.67 times on average, compared to the relative quartile deviation that was 1.35 times smaller than in the control without fertilizers (winter wheat), 1.25 times (barley), 1.38 times (corn) in case of higher yield values.

A type of crop rotation is a relevant factor in increasing agrocenosis performance. For instance, in the crop rotation B, saturated with cereals for 80%, including 40% of grain corn, the yield of cereals was 5.56–6.15 t/ha, which exceeded the crop rotation A with 20% corn 1.06–1.05 times, and the yield of cereal units was 1.31–1.4 times higher. The content of digestible protein was 0.67 t/ha or 19.7% higher in the crop rotation with grasses (*Table 13*).

The introduction of an optimal dose of $N_{31}P_{33}K_{41}$ fertilizers in the crop rotation B promoted grain yield 1.27 times, and in the crop rotation A — 1.1 times higher compared to the control. The yield of fodder units was 1.22 times higher, and net profit increased 1.71 times. The most optimal and economically beneficial dose of $N_{46}P_{49}K_{61}$ fertilizers in 1 ha of the arable land promoted the increase in the grain yield by 6.1%, the yield of fodder units — by 10.8% compared to the dose of $N_{31}P_{33}K_{41}$. A double dose of fertilizers and estimated doses of fertilizers enhanced the performance of crop rotations, but the obtained performance did not cover the expenses for mineral fertilizers. In 1974–2024, (60 years), in the control without any fertilizers, the average yield of winter wheat was 3.06 t/ha, spring barley — 2.50 t/ha, grain corn — 5.14 t/ha, cereals cumulatively — 3.37 t/ha. After the introduction of fertilizers, the yield increased by +1.33 t/ha, +1.18 t/ha, +0.31 t/ha, and +0.68 t/ha, respectively.

The study, conducted in conditions of the central part of the Forest-Steppe demonstrated (*Table 14*) than long-term (10 years) application of 8–10 cm surface tillage in a cereal crop rotation ensured the yield of cereals at the level of plowing, whereas in case of No-till for 5 years, the yield of cereals was considerably lower compared to both plowing and surface tillage (*Table 14*).

Table 13. The performance indices of short crop rotations with different content of cereals depending on the introduced fertilizers in 2016–2023

Fertilizers	Crop rotation A — 60% of cereals, including 20% barley + grasses, 20% grain corn				Crop rotation B — 80% of cereals, including 20% winter wheat, 40% grain corn			
	Yield from 1 ha of the arable land, t/ha							
	cereals	grain	fodder units	digestible protein	cereals	grain	fodder units	digestible protein
No fertilizers	3.95	2.37	5.38	0.39	4.36	3.49	6.84	0.41
$N_{62}P_{66}K_{82}$	5.86	3.48	8.57	0.69	6.18	4.89	9.55	0.58
$N_{82}P_{40}K_{46}$	5.89	3.54	8.59	0.69	6.20	4.96	9.49	0.57

Table 14. The impact of the tillage method on the yield of cereals in the 5-field crop rotation in the central part of the Forest-Steppe

Methods of soil tillage	Yield of cereals in years, t/ha				
	2021	2022	2023	2024	Average
Plowing	6.65	5.06	4.97	4.44	5.28
Surface tillage, 10 years	6.60	4.88	4.85	4.45	5.20
No-till after plowing, 5 years	6.26	4.15	4.18	3.85	4.61
No-till after surface tillage, 5 years	6.24	4.00	4.25	3.80	4.57
$HIP_{0,5}$	—	—	—	—	0.51

The reasonability of applying the data of the crop yield in perennial experiments of the network of the NAAS, the Ministry of Agrarian Policy, the universities of the Ministry of Education and Science of Ukraine, and other institutions, studying the natural potential of soil and agrosoil potentials of natural and effective fertility, was substantiated in Ukraine (Polupan MI et al., 2005; Polupan MI, Velychko VA, 2014). At present, there are published data about the parameters of crop performance for 1960–2015. Under natural and climate changes, the average annual indices of the agropotentials of effective fertility on typical chornozem for this period were as follows for the following crops: winter wheat — 3.4–3.7 t/ha, spring barley — 3.4-3.6 t/ha, grain corn — 5.0–5.3 t/ha (Polupan MI et al., 2015).

In the current climate conditions of the central Forest-Steppe and its central Left-Bank part, the implementation of the established agropotential exceeds the normative values by 15–20% regarding winter wheat performance in terms of both natural potential and natural fertility.

DISCUSSION OF STUDY FINDINGS

In arid conditions, chornozem is more sensitive to climate changes (air temperature and precipitation amount) than chornozem with higher moisturization. The dynamics of the soil properties are conditioned by the climatic factors in the territory of the European Forest-Steppe, which allows for detecting the impact of short-term climate changes on the environmental natural objects, including chornozem [*Mihailovich D.T., Dreskovic N., Arsenis I., et al., 2016*]. A moderate relationship between the soil humidity and hydrothermal coefficients by Selianinov was established. There was a noted delay in the changes in soil humidity values for 2-3 years, depending on the changes in hydrothermal conditions [Chendev Yu.G., Chendev Yu.G., Petin A.N., Lupo A.R., *2012*]. It was determined that climate change may have a considerable impact on soils and their properties. For instance, a study conducted in central Canada demonstrated the response of soil organic matter to climate dynamics [*Pysarenko V.M., Pysarenko P.V., Pishchalenko M.A., et al., 2022*]. Another aspect, related to soil erosion due to the precipitation amount from 1989 to 2007, was investigated in the article of German researchers [*Routschek A., Schmidt J., Kreienkamp F. 2014*]. Having determined the trend in climate change, they developed forecast models until 2100 that reflect the tempo of erosion processes in soils. A negative change in the aqueous-physical properties of the chornozem profile leads to insufficient atmospheric precipitation due to limited moisture absorption during the winter–spring and growing periods. Chornozem becomes dependent on weather and climate changes and sensitive to the manifestation of degradation phenomena related to active dehumidification, which covers the entire soil profile of chornozem, resulting in decreased yield of agrocenoses and reduced implementation of chornozem agropotential [*Medvedev V.V., 2012а-в*].

One of the relevant tasks, related to the problem of preventing further degradation of chornozem, is the search for ways to optimize the moisturization regime for chornozem in the agrocenoses of the central part of the Forest-Steppe, using soil-protective and moisture-preserving agrotechnological methods, which reduce the productive losses of soil moisture, promote its accumulation and preservation due to the precipitation in the autumn-winter and spring periods during vegetation, with simultaneous creation of conditions for humus accumulation that should promote the implementation of agropotential under global climate changes in the Forest-Steppe zone.

Our research has established that under the influence of soil-protective tillage and No-till farming, the soil formation vector tends towards the formation of more moist chornozem (increased humidity), and the observed effect of enhanced humus formation should be considered a determining criterion for the adaptability of the soil tillage system and the agriculture system in general to the conditions of increasing aridity in agrocenoses for the implementation of chornozem agropotential in the Forest-Steppe of Ukraine. The rate of facies humus accumulation rises 6.7 times in the zonal dimension from the northern part of the Forest-Steppe zone to the boundary between the Steppe and Forest-Steppe zones, and further south, the rate of facies humus accumulation decreases 2.7 times. The amount of energy in the humus addition from the use of soil-protective technologies exceeds the energy reserve in the yield addition, which indicates the reproduction of natural soil formation processes in agrocenoses in a zonal dimension, which gives grounds for the implementation of agropotential under global warming in the Forest-Steppe.

The increased degree of hydromorphism of the chornozem layer under soil-protective tillage is necessary to ensure conditions for enhancing the soil-restoring activity of root systems to deeply saturate the chornozem layer with root exudates (pre-humic substances of physiological origin) and ensure the water-soluble state of pre-humic substances at the moment of their renewed formation in the chornozem layer.

The comparison of available information on photosynthesis, nitrogen fixation in the root rhizosphere, and soil formation in the agrocenosis gives reason to conclude that all these processes are closely related to each other at the level of direct strong correlation. A schematic representation of the interaction between these processes is shown in *Fig. 6*, which shows that depositing atmospheric C–CO_2 by agrophytocenoses of different crop rotations and soil formation (deposition of organic matter into humus) should be considered as structural components of a single system that interact synergistically with each other and accumulate cumulatively under the influence of the time factor of soil-protective tillage in the agrocenosis (*Fig. 6*).

Soil formation (humus accumulation) in agrocenoses should be perceived as enhancing the cumulative effect of the biological factor in conditions of agricultural use of chornozem due to improvement in hydrothermal soil conditions in the seasonal and annual cycles under the effect of systematic application of soil protective technologies, based on surface tillage, which ensures the process of managing functional, ecologic, and facies regularities of humus accumulation in typical chornozem, ensuring enhanced implementation of chornozem agropotential in agrocenoses of the Forest-Steppe of Ukraine in current climate conditions.

Thus, the determining factor in enhancing soil formation in chornozem agrocenoses is ensuring the hydrophilization of the moisture regime within the tillage system, particularly under a periodically washing water regime. The implementation of the potential of humus internal energy is only possible in a balanced relationship with the internal energy of moisture supply. When the ratio of the internal energy of moisture

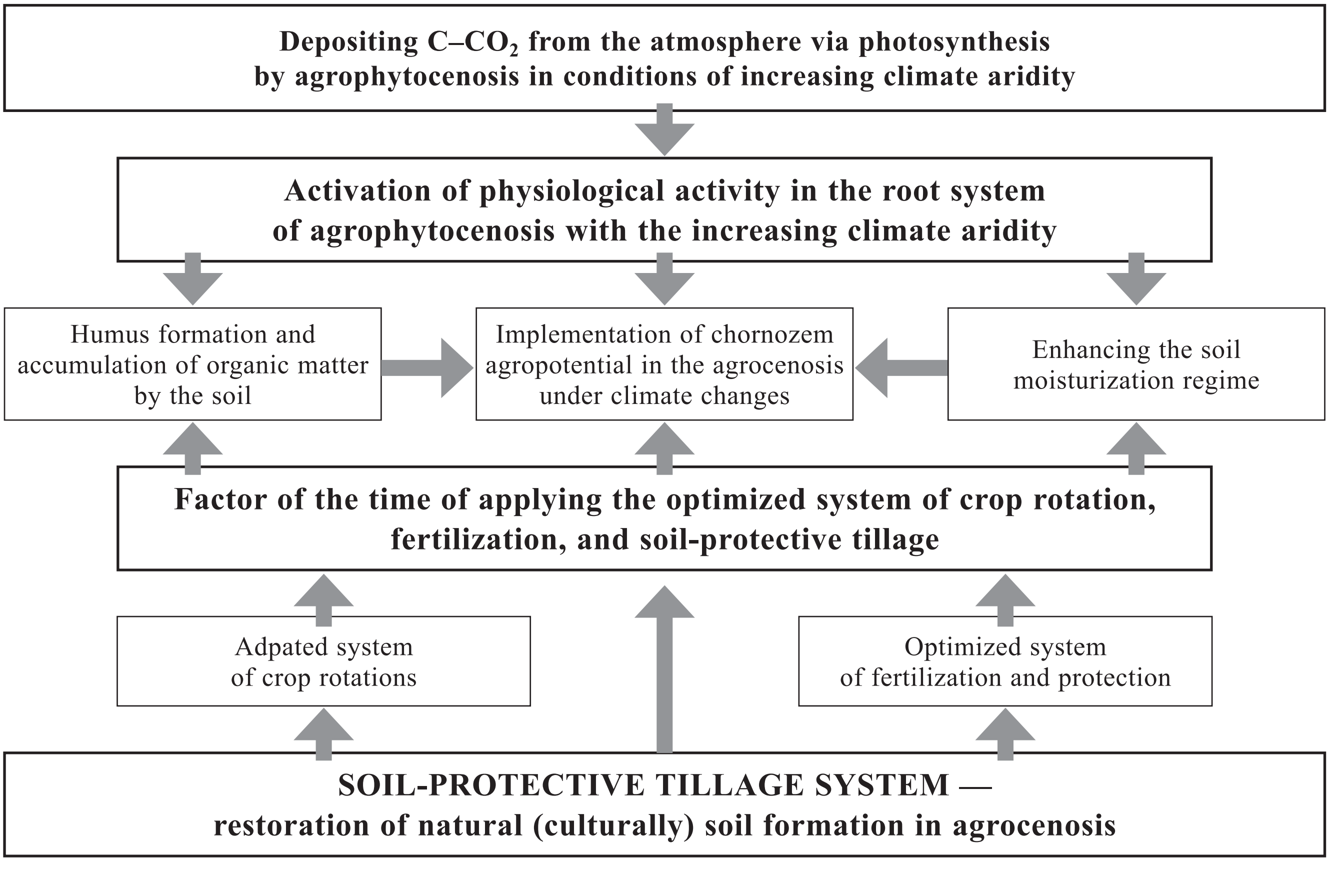


Fig. 6. The scheme of the interaction between the process of depositing CO_2 of the atmosphere, soil formation (humus accumulation), and the process of enhancing the moisturization regime in the agrocenosis for the purpose of implementing the chornozem agropotential under climate warming in the central Forest-Steppe

supply to the internal energy of humus expands, the energy of humus is realized through the growth of natural and potential fertility in an effective form, with the simultaneous reproduction of soil formation in the agrocenosis. The narrowing of the ratio of moisture supply energy to humus energy contributes to increased mineralization with the growth of aridity of soil conditions, which weakens and reduces the level of potential fertility of chornozem in the central Forest-Steppe of Ukraine.

In the current climate conditions of the central Forest-Steppe and its central Left-Bank part, the implementation of the established agropotential exceeds the normative values by 15–20% regarding winter wheat performance in terms of both natural potential and natural fertility.

The proposed method for restoring the fertility of chornozem and enhancing its agropotential in the agrocenoses of the central part of the Forest-Steppe has significant advantages over agrochemical and technogenic methods.

Firstly, it is agroecologically safe, soil-protective, and resource-saving, as it is based on the restoration and modeling of nature-forming processes in agrocenoses.

Secondly, this method is better from an agroeconomic point of view: the purchase, transportation, storage, and application of mineral fertilizers require significant costs, as does intensive tillage based on plowing. Their share in the cultivation of crops ranges from 40% to 68% of total costs. Therefore, if the task of increasing the fertility of chornozem is solved in a less expensive way (by modeling natural soil formation processes) via enhancing the physiological properties of cultivated plants in agrocenoses, this will have a significant agroecological and economic effect.

Thirdly, its implementation within the framework of soil-protective, resource-saving agriculture can make a significant contribution to solving some global agroecological problems, both in Ukraine and worldwide.

Fourthly, the restoration of chornozem fertility of the Forest-Steppe zone of Ukraine under the influence of No-till soil-protective cultivation is linked to the time factor: after 9–10 years of influence, the natural state of chornozem is strengthened; after 10–15 years, the soil as a system reaches a high level of self-regulation and self-preservation of processes and regimes of fertility restoration; after 20–25 years, the chornozem layer becomes autonomous from the influence of weather and climatic factors, and the productivity of agrocenoses stabilises; and after 30–35 years, the processes of soil formation of typical chornozem in agrocenoses are restored to the maximum extent, based on the strengthening of physiological principles of action.

The clarification of the relationship between photosynthesis, nitrogen fixation, and soil formation allows us to formulate two fundamentally essential principles that must be taken into account in agriculture:

Firstly, an increase in the supply of photosynthesis products to chornozem, in the form of root exudates and plant residues, activates the processes of nitrogen fixation and cultural soil formation in chornozem, and as a result, contributes to an increase in its fertility and crop yields.

Secondly, all structural components of the system under consideration are closely interrelated, and short-term suppression of any of them is unacceptable.

From this point of view, saturating technological schemes for growing crops with technogenic elements without taking into account their impact on individual processes occurring in agroecosystems will inevitably create conditions for their degradation, both as components of physiological interaction and of the chornozem itself, and, consequently, an increase in the costs of ensuring normal conditions for the growth and development of crops in crop rotation agrocenoses in the Forest-Steppe zone of Ukraine.

It is also important to note that the change in the directions of using photosynthesis products in crops towards the formation of root exudates can be used for practical purposes. By increasing the flow of root exudates into the chornozem layer in summer, it is possible to have a significant positive impact on its fertility or on the enrichment of the lower part of the chornozem profile with humus under No-till cultivation, which is a higher level of control compared to fertilizers, as it increases moisture supply on a seasonal basis, ensuring higher moisture levels during critical phases of crop development in crop rotations compared to plowing. This enables a significant increase in the input of organic matter to the chornozem layer from the plants themselves, thereby activating natural soil-forming processes in crop rotation agrocenoses. In general, strengthening the excretory functions of plant root systems may become one of the most important methods of influencing soils and increasing their fertility in the context of adaptive soil-protective, resource-saving agriculture in the Forest-Steppe of Ukraine.

In recent years, there has been a sharp increase in investments in agriculture. One of the reasons for this is soil degradation due to erosion and tillage, which disrupts its structure and reduces humus content. At the same time, a significant amount of powerful, energy-intensive, and heavy equipment has appeared in the fields. Problems of soil degradation have arisen due to its compaction and destruction under the influence of machinery moving across the field [*Crosbie, R.S., Scanlon, B.R., et al., 2013, Gabriela, J.L., Munoz-Carpenab, R., Quemadaa, M., 2012*]. One of the main approaches to solving this problem is to minimize soil tillage, i.e. to reduce the number of operations involved in cultivating crops, to lower the intensity of tillage effect on the soil, and to decrease the energy intensity of cultivation operations. It is believed that when a field is relatively free of weeds, chemical or biological methods are used to destroy them, the soil density is close to optimal for crop development, and minimizing tillage is advisable [*Jasechko, S., Birks, S.J., Gleeson, T., et al., 2014., Liua, H.L., Yanga, J.Y., Tana, C.S., et al., 20141, Lopez-Urrea, R., Martin de Santa Olalla Drurya, et al., 2006*]. Based on these assumptions, tillage minimization is possible and is practiced across most of Eurasia, especially where the equilibrium soil density is close to optimal or where there is a high risk of wind and water erosion. On the other hand, excessive enthusiasm for minimizing tillage, especially using only non-plowing methods, has in practice led to soil self-poisoning and mass weed proliferation, unless there were effective means of controlling them other than tillage.

As the experience of North American farmers, who have used minimum tillage systems for a long time, has shown, moldboard plowing cannot currently be completely excluded from tillage systems, regardless of soil and climatic conditions. The frequency of its use is determined by the reasons mentioned above. The need for plowing may arise once every few years [*Burke A., Katie L. Lewis P., Christopher J. Cobos, Rabi H., et al., 2025, Steward, D.R., Bruss, P.J., Yang, X., et al., 2013, Yang, X.Y., Yan, R.X., Li, S.Q., et al., 2024, Yue, S., Pilon, P., Cavadias, G., 2002*]. In the past 20 years, boardless plowing has transformed agricultural systems based on plowing in large areas, such as in North America, South America, and Australia. Over the last decade, the No-till system has gained popularity in Asia, Africa, and Europe. At present, these principles are used in agriculture on almost 125 million hectares of tilled soil, which is 9% of arable lands around the world on all continents and in all agroecological zones [Friedrich, T., Derpsch, R., Kassam, A., 2012].

CONCLUSIONS

The formation of climate parameters in the central part of the Forest-Steppe occurs with an increase in the average monthly amount of atmospheric precipitation during the autumn, winter, and spring periods, which affects the annual precipitation amount, corresponding to the normative indices of the Forest-Steppe zone. A reliable decrease in the amount of atmospheric precipitation in summer was established. At the same time, throughout autumn, winter, spring, summer, and the entire year, there was an increase in average monthly air temperature, which created aridization conditions for the central Forest-Steppe climate, especially in summer, when the formed temperature background is most notable for the Steppe zone.

The study in the central part of the Right-Bank and Left-Bank Forest-Steppe demonstrated that adaptive crop rotations, systems of fertilization, and soil-protective tillage, as well as No-till in combination with organic fertilizers (by-products of crops), have a positive impact on the implementation of the agropotential of typical and podzolic chornozem. In particular, stable correlations were found between the increase rate of the humus state and the moisture regime of the soil layer after adaptive measures, and the application of the adaptive system of soil-protective tillage for different depth using No-till allowed increasing the reserves of humus, enlarging the reserves of productive moisture in the one-meter-deep layer and ensuring the increase in chornozem agropotential in terms of the yield of grain units.

Taking into consideration the current state of agriculture in the Forest-Steppe zone, its ever-increasing dependence on weather conditions, it is advisable to implement adaptive measures: an optimal fertilization system, low-carbon systems of tillage, and the system of crop rotations. In this regard, it is crucial to scientifically substantiate the zone-wise application of the adaptive measures for the most effective use of agroresource potential in the form of heat, as well as to minimise possible risks in the form of various extreme phenomena that can significantly worsen not only the ecological state of agricultural landscapes, but also considerably reduce the implementation of chornozem agropotential and the productivity of agroecosystems, which is primarily related to the intensification of the depth and spatial spreading of climate changes in the central Forest-Steppe.

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РЕЖИМ ЗВОЛОЖЕННЯ ТА РЕАЛІЗАЦІЯ АГРОПОТЕНЦІАЛУ ЧОРНОЗЕМУ В УМОВАХ КЛІМАТИЧНИХ ЗМІН ЦЕНТРАЛЬНОГО ЛІСОСТЕПУ

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Мета досліджень. Показати основні закономірності формування режиму зволоження та встановити вплив на реалізацію агропотенціалу та відтворення родючості чорнозему під впливом сівозмін, удобрення та обробітку в умовах сучасних кліматичних змін Центрального Лісостепу. **Методи досліджень.** Польовий (для відбору зразків у товщі чорнозему в різні періоди досліджень), лабораторний (для термовагового визначення запасів продуктивної вологи за період досліджень), математичний, статистичний та порівняльно-розрахунковий (для обґрунтування достовірності отриманих вологозапасів у ґрунті та розроблення статистичних моделей взаємозв’язків). **Результати досліджень.** У середньому за 75 років спостережень середній запас вологи в метровій товщі у листопаді становив 61,6 мм, а за медіаною значення 51,5 мм, яке тяжіло до нижнього типового значення, що свідчить про зниження осінніх запасів вологи. Коефіцієнти осциляції ($К_{ос}$) та $К_{var}$ становили 40% та 54,4%. Запаси вологи у квітні в середньому та медіанному значенні становили 156–155 мм за $К_{ос}$=37% та $К_{var}$=10,3%. Середнє накопичення вологи у метровій товщі за холодний період року становило 94 мм за медіанного значення — 99 мм, яке більшою мірою тяжіло до верхнього типового значення ($L_{0,75}$) за $К_{ос}$=98% та $К_{var}$=25,3%. У липні запас вологи в метровій товщі становив 50,1 мм, а за медіаною — 45,5 мм, що свідчить про тяжіння до нижнього типового значення ($L_{0,25}$) та про наростання посушливих умов, коли Пз був у межах 0,77–0,88 (слабо посушливі умови), а за максимального типового значення $П_з$=1,13–1,22 (вологі умови) за $К_{ос}$=65% та $К_{var}$=18,6%. Витрата вологи з ґрунту за період квітень–липень у середньому становила –105 мм, що відповідало медіанному значенню і тяжіло до верхніх типових значень витрат (–108...–122 мм) за $К_{ос}$=33% та $К_{var}$=9,3%, що є стабілізованою витратою, яка має тенденцію до наростання. Між параметрами умісту продуктивної вологи та кліматичними показниками встановлено прямі і обернені кореляційні зв'язки високого рівня кореляції (R=±0,61–0,95±0,02, R^2=37–0,90), а між $П_з$ та $Д_в$ зв'язки зростали до сильної кореляції (R=±0,68–0,96±0,03, R^2=0,46–0,65). Встановлено, що на чорноземі опідзоленому у товщі 0–30 см середній уміст гумусу по сівозміні за оранки становив 2,34%, за поверхневого обробітку уміст гумусу зріс на 0,15% (10 років поверхневого обробітку), а за No-till уміст гумусу зріс на 0,07–0,08%. На чорноземі типовому в сівозміні середній запас С–CO_2 в 0–30 см шарі чорнозему становив 273 т/га, а у шарі ґрунту 0–20 см — 182 т/га. Середній запас С–CO_2 за безполицевого обробітку був на 19,8 т/га вищим порівняно з оранкою, а запас С–CO_2 в 0–30 см шарі ґрунту був у межах від 296 т/га, що вище порівняно з оранкою на 21–23 т/га. За поверхневого обробітку середній запас С–CO_2 був вищим за оранки на 14 т/га. Запас секверстрованого С–CO_2 у шарі 0–30 см відповідав інтервалу значень 285–300 т/га і був вищим ніж за оранки, але мав тенденцію до зниження відносно безполицевого обробітку. Запас С–CO_2 в 0–20 см шарі чорнозему був на рівні значень за медіаною (202,5 т/га) та перевищував запас оксиду карбону за оранки на 21 т/га, що свідчить про зростання секверстраційної здатності 0–20 см шару за умов виконання як поверхневого, так і безполицевого обробітків. В сучасних кліматичних умовах відбувається максимальна реалізація агропотенціалу чорноземів центрального Лісостепу, а важливим чинником зростання продуктивності агроценозу є тип сівозміни. У сівозміні горохом з насиченням зерновими 80%, у т. ч. 40% кукурудзи на зерно, збір зернових становив 5,56–6,15 т/га, що вище сівозміни з багаторічними травами з насиченням кукурудзи 20% в 1,06–1,05 раза, а збір зернових одиниць в 1,31–1,4 раза. Уміст перетравного протеїну вищий був у сівозміні з травами на 0,67 т/га або 19,7%. Довгострокове (10 років) застосування поверхневого обробітку на 8–10 см в зерновій сівозміні забезпечило урожайність зернових на рівні оранки, тоді як за No-till впродовж 5 років урожайність зернових була суттєво меншою, як відносно оранки, так і поверхневого обробітку. **Висновок.** Виявлений зв'язок кліматичних параметрів і відгуку метрової товщі чорнозему у вигляді нормованих параметрів запасу продуктивної вологи дозволяє параметризувати режим зволоження в межах періодично-промивного водного режиму Центрального Лісостепу України. Проведений аналіз погодно-кліматичних параметрів у комплексі з формуванням запасів продуктивної вологи в метровій товщі у весняний та літній періоди за 1947−2022 рр. дав можливість встановити, що в умовах центральної частини Лівобережного Лісостепу формується водний режим, який відповідає періодично промивному типу, але за режимом зволоження (перебігом у часі) проявляється стійка тенденція прояву ознак непромивного водного режиму, що є ознакою, більшою мірою, аридизації ґрунтових умов вегетації сільськогосподарських культур у сучасних умовах глобальних змін клімату в лісостеповій зоні. Таким чином, типізація зміни вологості метрової товщі чорнозему в сезонному циклі (режим зволоження) може бути використана у якості індикатора відгуку на синоптичні зміни в складі кліматичних факторів у формуванні періодично-промивного водного режиму Центрального Лісостепу України в сучасних кліматичних змінах.

Ключові слова: продуктивна волога, метрова товща, тренд, автокореляція, періодичність, факторний аналіз, режим зволоження, клімат, чорнозем, Лісостеп.