UDC 631.423.2:631.58(477.5)

SOIL MOISTURE POTENTIAL OF AGROCENOSES IN THE FOREST-STEPPE OF UKRAINE

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Received February 02, 2020 / Received May 10, 2021 / Accepted July 19, 2021

Aim. To determine the main regularities in the formation of soil moisture potential, the accumulation and exploitation of soil resources of productive moisture by agricultural crops under the cultivation in the ecosystems of different crop rotations in the Forest-Steppe of Ukraine. **Methods.** Field, permanent, laboratory, analytic, statistical methods. **Results.** During a short-term grain-row crop rotation, the total loss of available moisture without the introduction of mineral fertilizers was 317 mm, and in the variant with fertilizers it increased by 107 %. The total loss of moisture under different ways of tillage in the variants without any fertilizers was the lowest for the surface tillage and increased 1.05 times for ploughing and 1.08 times for deep tillage. After the introduction of fertilizers, the total loss of moisture increased by 23.0 mm or 107 % on average. In case of long-term (10–36 years) surface tillage, the efficiency of using the reserves of productive moisture increased by 25–40 % and the coefficients of water consumption of crops decreased by 35–40 %. **Conclusions.** Short-term crop rotations were found to be more productive, and the relation between energy accumulation in dry matter, the yield of fodder and cereal units and energy accumulation in the yield per 10 t of used productive (available) moisture was at the level of strong direct correlation (R>+0.70). Regression coefficients for the variables: dry matter, fodder and cereal units, dry matter per 10 t of moisture in dependence equations were 3.06, 1.25, 7.25, and 2.89 times higher, respectively, as compared with long-term crop rotations, which demonstrated 2.59-fold increased productivity and use of the total moisture circulation in short-term crop rotations as compared with long-term ones.

Key words: crop rotations of different duration, predecessors, rotation norms, moisture provision, soil properties, evaporation, agrotechnical measures, cultivation culture.

DOI: https://doi.org/10.15407/agrisp8.02.049

INTRODUCTION

Due to unstable moisturization in the Forest-Steppe zone of Ukraine, the level of water availability for soil and crops is one of the decisive factors of productivity formation in modern agrophytocenoses. Zonal systems of agriculture are based on the implementation of the complex of agrobiological and agrotechnical measures, aimed at maximal fixation of atmospheric precipitation, rational use of soil moisture and precipitation to increase the effectiveness of agricultural crops in modern crop rotations (Konoplin MA et al, 2008). The rotation of crops in the combination with resource-preserving and soil-protective systems of soil tillage and fertilization ensures enhanced efficiency of moisture accumulation in soil and its more effective use by crops, which is one of the main ways to mitigate negative consequences of drought (Cherkasov HN et al, 2016; Novikov VM, 2014; Krasilnikova TM, 2016) The study of the regularities of the ascending movement of soil moisture during evaporation is necessary to substantiate and elaborate rational crop rotations and soil tillage systems, aimed at reducing the losses of soil moisture for physical evaporation which would facilitate the evaluation of soil conditions of available moisture and nutrients (Litvinov DV, 2015). The deterioration of aqueous-physical properties of typical chernozem is directly related to the loss of humus and thus aridization of soil conditions for the growth of field crops and soil formation in agrocenoses (Panov VI, 2016).

One of the most important factors for the formation and increase in the yield of agricultural crops under unstable moisturization in the Forest-Steppe of Ukraine is the accumulation and efficient use of the moisture from atmospheric precipitation which is a relevant abiotic factor, limiting the productivity of field crops; water deficiency in soil during the vegetation of field crops leads to the decrease in the efficiency of the mineral fertilizers, the system of plant protection from pests, etc. (Ivashchenko OO, 2018). Taking into consideration the specificities of climatic conditions in the region, biological peculiarities of crops in terms of water consumption and the regime of soil moisturization under crops, one may define the directions of the most efficient use of soil moisture and atmospheric precipitation by field crops in the process of their cultivation in crop rotations of different duration (Boiko PI, 2016). In the subzone of unstable moisturization, the management of intake and loss of moisture in soil should be done via optimal selection and rotation of crops in the rotations which would ensure the most efficient use of available moisture and replenishment of its resources (Akimenko AS, 2015, 2018, 2019; Soderbaum P et al, 2011; Fredlund DG et al, 1993; Pidgeon JD et al, 2001; Richter GM et al, 2001; Ober E.S et al, 2002; Hamlyn GJ, 2007; Baigy MJ et al, 2012; Konishchuk VV et al, 2018).

THE AIM OF THE STUDY

To determine the main regularities in the formation of soil moisture potential, the accumulation and exploitation of soil resources of productive moisture by agricultural crops in the systems of different crop rotations in the Forest-Steppe of Ukraine.

MATERIALS AND METHODS

The study was conducted on Drabiv experimental field (1965–2015) and Panfilska Experimental Station (1965–2018), located in the Prydniprovska lowland in the Central-Left-Bank-Prydniprovsky agroecologic district of Ukraine (Konishchuk VV, Yegorova TM, 2018), which is a moderately wet and humid forest-steppe subzone (Polupan M, Velychko V, 2002), according to soil-ecologic zoning, and during the permanent experiment of the Department of Soil Science and Soil Conservation of the National University of Life and Environmental Sciences in the moderately wet forest-steppe soil-ecologic subzone.

The soil of Panfilska Experimental Station, NSC Institute of Agriculture, NAAS (50º13’22” north latitude, 34º44’46” east longitude, 128 m above the sea level) is typical low-humus heavy-loamy light-clay chernozem on forest-like clay (Zaryshnyak A et al, 2016). The humus content in the arable layer is 3.08–3.15 %, in the subarable layer – 2.72–2.90 %, and this amount decreases with depth down to 1.33 % in the 70–110 cm layer and to 0.97 % at the depth of 110–115 cm.

The soil of the Drabiv experimental field of Cherkasy State Agricultural Experimental Station of NSC Institute of Agriculture, NAAS (50º13’22” north latitude, 34º44’46” east longitude, 128 m above the sea level) is typical low-humus light-clay chernozem on carbonate forest layer. The structuredness index (SI) is 25–38 %. The ratio between physical sand (PS) and physical clay (PC) is 1.76–2.52. The factor of potential aggregation (FPA) is 0.25–0.27.

By soil-ecologic zoning, Poltava lowland of the South-Poltava agroecologic district is in the forest-steppe of moderate moisturization on typical medium humus chernozem (5.55–5.65 %). By the content of PC and PS, chernozem may be referred to light-clay soil: PC = 62.9–64.0 %, PS = 35.0–37.1 %. The study was conducted in 1982–1992 during a multifactor permanent experiment of the Department of Soil Science and Soil Conservation of the National University of Life and Environmental Sciences in 10-field cereal-beet crop rotation on typical medium-clay chernozem: cereals – up to 40 %, technical crops – up to 30 %, grain legumes – up to 10 %, forage crops – up to 20 %, where three technologies of soil tillage were investigated: deep ploughing for 22–32 cm, surface tillage for 22–32 cm, subsurface tillage for 10–12 cm with the introduction of 15 t/ha of manure + $N_{85}P_{75}K_{65}$.

To determine the change in aqueous-physical indices and moisturization regime, soil samples were taken from the layers of field soil every 10 cm according to the schemes of experiments. The analyses of soil samples and plant material, registration and calculations were done according to specific methods: humidity – using the thermogravimetric method, by the main periods of crop growth, the density of composition (structure) – by the method of cutting rings in the modification of N.A. Kachynsky during the periods of intense growth; moisture reserves – by calculations, up to the depth of 150–180 cm.

The structure of crop rotations in the objects under observation for the moisturization regime is presented in Table 1. The generalization of productivity of crop rotations, indices of soil moisturization regime, climatic parameters and calculations of study results was conducted using Statistica program with non-parametric methods of statistics, correlation, and factor analysis.

Table 1. The structure of crop fields and the productivity of crop rotations in the experiments

Structure of crop rotations	Soil tillage technology	Productivity of crop rotations, t/ha		
		Fodder units	Cereal units	digestableprotein
Drabiv experimental field (typical low-humus light-clay chernozem on carbonate forest layer), average for 1965–2015				
10-field crop rotation (N40P40K40 + 6 t/ha of humus), average for 1965-1968				
50 % – cereals; 10 % – grain legumes; 20 % – sugar beet; 20 % – fodder crops		6.62	5.19	–
10-field crop rotation (N56P58K58 + 7 t/ha of by-products), average for 2010-2015				
50 % – cereals; 10 % – grain legumes; 20 % – sugar beet; 20 % – fodder crops		8.44	6.39	–
5-field crop rotation, average for 2010-2015				
30 % – cereals; 20 % – grain legumes; 20 % – sugar beet (without fertilizers)	ploughing	5.95	5.07	–
	surface	6.38	5.46	–
	subsurface	6.61	5.41	–
30 % – cereals; 20 % – grain legumes; 20 % – sugar beet (N62P66K81 + 6 t/ha of manure)	ploughing	9.32	8.15	–
	surface	9.66	8.55	–
	subsurface	9.32	7.99	–
Panfilska Experimental Station (typical low-humus heavy-loamy light-clay chernozem on forest-like clay layer), average for 2016–2018				
8-field crop rotations				
62.5 % – cereals; 25 % – soybeans + sunflower; 12.5 % – fodder crops		8.32	7.26	0.76
62.5 % – cereals; 25 % – sugar beet + soybeans; 12.5 % – fodder crops		11.34	8.73	1.08
7-field crop rotation				
57.2 % – cereals; 42.8 % – soybeans + sunflower + + rape		7.22	6.73	0.75
6-field crop rotation				
66.8 % – cereals; 33.4 % – sugar beet + soybeans		9.85	8.25	1.02
66.8 % – cereals; 16.7 % – soybeans + sunflower		7.27	5.83	0.65
5-field crop rotations				
80 % – cereals; 20 % – sunflower		9.63	8.17	0.81
4-field crop rotations				
100 % – cereals (no fertilizers)		6.98	6.98	0.56
100% – cereals ($N_{45}P_{45}K_{45}$)		10.1	10.1	0.81
100% – cereals (by-products + $N_{45}P_{45}K_{45}$)		10.7	10.7	0.84
100 % – cereals (by-products)		8.76	8.76	0.67

RESULTS OF STUDIES

In 1965–1969, the weather conditions in the Drabiv experimental field were close to average perennial values by parameters of average daily temperature (Table 2). The period of March-May exceeded the norm by +1.1 °C. In terms of atmospheric precipitation at an annual rate, the norm of precipitation was exceeded by +20 mm. During a cold period, there were 53 mm more precipitations, and in summer there were 43 mm less precipitation, which reduced the amount of precipitation during the warm period by 72 mm. In 2010–2015, the annual amount of precipitation was 1.15 times less as compared with the initial period of the study, the decrease in which occurred due to 1.29 times less amount of precipitation during a cold period of the year. There was 1.09 times less spring precipitation, 1.2 times less summer amount of precipitation which reduced the total amount of precipitation during a warm period 1.09 times.

In 2010–2015, the temperature background increased by +1.6 °C on average for the year – during a cold period of the year – by –1.9 °C, in spring – by +1.6 °C, in summer – by +2.4 °C, during a warm period of the year – by +1.8 °C. During 2010–2015, a considerable change in climatic parameters occurred regarding average perennial indices in terms of average daily air temperature towards its increase, and in terms of precipitation – towards the decrease. Perennial climatic parameters for 1913–2000 include the period of 1965–1969, so the regularity of the established change was preserved.

In 2016–2018, the climatic conditions in the Panfilska Experimental Station deviated by the temperature background towards the increase regarding the average perennial parameters. The average annual daily temperature increased by +2 °C, during a warm period of the year – by 1.8 °C, in summer – by +2.4 °C, in spring – by +2.3 °C. During the cold period of the year, air temperature increased by +1.7 °C. The amount of precipitation for the year was 91 mm less, during the warm period of the year – 76 mm less, during summer – 60 mm less. On average for 2016–2018, the climatic conditions were characterized by the increase in the average daily temperature both generally for the year, and during the periods of the year: the increase exceeded the norm 1.13–1.3 times or by +1.8–2.4 °C. The amount of atmospheric precipitation was regularly decreasing both for the year and during summer and

Table 2. The amount of atmospheric precipitations and average daily air temperature during the study

Years of observations	Period of the year				
	XI–II	III–V	IV–VIII	III–X	For the year
Drabiv experimental field					
1965–1969	–3.7* / 189	+8.2 / 124	+19.2 / 181	+12.9 / 367	+7.4 / 554
Perennial for 1913–1960	–3.6 / 136	+7.1 / 121	+19.1 / 224	+12.4 / 439	+7.0 / 574
2010–2015	–1.8 / 147	+9.8 / 99.0	+21.6 / 151	+14.7 / 338	+9.0 / 484
Perennial for 1913–2000	–3.4 / 132	+7.4 / 114	+19.2 / 205	+12.6 / 401	+7.2 / 533
Panfilska Experimental Station					
2016–2018	–1.5 / 110	+9.8 / 126	+20.9 / 132	+13.8 / 349	+9.2 / 465
Perennial observations 1990–2010	–3.3 / 109	+7.6 / 100	+18.7 / 158	+11.9 / 333	+7.3 / 442
On average for 2010-2018					
2010–2018	–1.7 / 121	+9.8 / 100	+21.3 / 155	+14.3 / 344	+9.1 / +463
Perennial observations 1913–2010	–3.4 / 121	+7.5 / 107	+18.9 / 215	+12.5 / 420	7.1 / 554

Note. The numerator – average daily air temperature (t °C); the denominator – amount of atmospheric precipitation, mm.

warm period of the year: by 60, 76 and 91 mm respectively, which formed insufficient conditions of moisturization for the growth and development of agricultural crops in agrocenoses.

In 1982–1992, there were different weather and climatic conditions for the studies in South-Poltava region. The sum of average daily temperatures for the vegetation period was +2,842 °C, which was 17 % higher as compared with the average perennial values. The sum of precipitations in terms of crop vegetation phases in crop rotations was within the norm. In April-June, the amount of precipitation exceeded the norm by 6 %, though during this period the mentioned years had 6–60 % less precipitation. During other years, the sum of precipitations exceeded the norm by 2–7 %. During the driest summer period (July-August) the average amount of precipitation exceeded the norm by 5 mm, but in some years (1989–1990) the amount of precipitation was 13–44 % under the norm. In September-October the precipitation for 1989–1992 was within the norm.

In general, the vegetation period (April-October) for 10-field crop rotations was characterized by 7 % increase in the amount of precipitation.

On average during the years of the study, the amount of precipitations was within the norm and exceeded the average perennial observations by 6 mm, though in 1989 there was maximal amount of precipitation – 532 mm.

In 1989–1992, the values of hydrothermal coefficient, which corresponded to very dry conditions of moisture supply, were registered less frequently: HTC = 0.38 was noted only in July 1989. In other cases, the conditions of growth and development of plants corresponded to weakly drought-afflicted and drought-afflicted conditions. A warm period of the year was characterized by weakly drought-afflicted and drought-afflicted conditions.

The study of the productivity of 10-field grain-row crop rotation started in the Drabiv experimental field in 1965. In 1965–1969, the average resources of productive moisture in the one-meter-deep layer of soil prior to winter in the grain-row crop rotation was 75 mm, and 88 mm – by the median. The amplitude interval was 70 mm and the typable normalized interval of the change in moisture reserves – 60 mm. The coefficient of the variation in the change of moisture reserves in soil was 35 %. In the modern period, in 2010–2015 the average reserves of productive moisture in one-meter-deep soil layer were 2.0–2.2 times poorer (Table 3).

The coefficient of the variation in the reserves of productive moisture prior to winter was 2.1 times lower, which indicated the stability of drying the one-meter-deep chernozem layer during the vegetation period in the crop rotation. In 1965–1969, the percentage of fixing atmospheric precipitation in the cold period of the year was 31–34 % with the amplitude interval of 21–49 %. The typical interval of fixing atmospheric precipitation coincided with the amplitude interval. In 2010–2015, the percentage of fixing atmospheric precipitation by the average value and median increased 1.55 and 1.14 times, and the amplitude interval was at a much higher quantitative level. The typical normalized interval of fixing atmospheric precipitation had higher values as compared with the initial period of observations (see Table 3).

In 1965–1969, the productive moisture reserves in the one-meter-deep soil layer in April, prior to field work, was 175–177 mm with the amplitude interval from 160 to 185 mm and normalized interval of values of 168–180 mm. The variation coefficient was 45 %. In 2010–2015, the reserves of productive moisture in the one-meter-deep soil layer were 10 mm smaller, and the amplitude interval and normalized interval of moisture reserves was at a somewhat lower quantitative level. The variation coefficient was at the level of 5.1 % which indicated the stabilization in the level of accumulating the productive moisture reserves in April.

The saturation of the one-meter-deep typical low-humus chernozem layer with productive moisture in the 5-field grain-row crop rotation during the initial period of the study was 97–98 % from the lowest field moisture capacity (LM). The amplitude interval was 89–101 % LM, and the normalized interval – 93–100 % LM which demonstrated the formation of optimal stable moisture reserves in the one-meter-deep chernozem layer in April.

In 2010–2015, the saturation of the one-meter-deep typical low-humus chernozem layer was lower, amounting to 90–92 % LM by the average and median values. The amplitude interval by the minimal value of saturation was 83–100 % LM, and the normalized interval shortened to 86–94 % LM which indicated the formation of smaller reserves of productive moisture in April. This may be explained by the reduction in the amount of atmospheric precipitation for the cold period, which was 35 mm less as compared with the initial period of the study.

In 1965–1969, the reserves of productive moisture in the third decade of June was 80–90 mm on average with the amplitude interval from 40 to 150 mm and at the typical interval of values of 46–120 mm. The variation coefficient was 51 %. In 2010–2015, the reserves of productive moisture during this period were 10–15 mm smaller.

In 1965–1969, the reserves of productive moisture were at the level of 44–50 % LM, in terms of the amplitude interval – 22–83 % LM and normalized interval of values – from 23–25 to 78–79 % LM. During the period of observing the saturation of the one-meter-deep layer with productive moisture, in June a considerably insufficient saturation with productive soil moisture was detected by both the average values, and the amplitude interval and normalized interval of values. For instance, the minimal saturation with moisture was 14–19 % LM which corresponded to moisture reserves at the withering point (WP) whereas the moisture reserved in June exceeded WP and approximated the discontinuous capillary moisture (DCM).

During 1965–1969, in April-June, 85–97 mm, or 49–55 %, of productive moisture reserves were spent in the grain-row crop rotation, which was 38–122 mm or 21–72 % by the typical interval value. During the modern period of studies, the losses of the productive moisture reserves increased up to 95–100 mm or 58 % from the reserves in April, and by the typical interval of values it was 45–125 mm or 27–80 % which demonstrated more intense use of productive moisture reserves from soil during April-June.

On average, as of the end of September, during the initial period of the study the productive moisture reserves were 52–59 mm with the amplitude interval of 45–88 mm and normalized interval of 50–60 mm. The variation coefficient was 11 %. Modern determination findings of moisture reserves at the end of September demonstrated 65 mm with a 1.87 times wider amplitude interval and 4.4 times larger normalized interval. The variation coefficient for productive moisture reserves as of the end of vegetation period increased 8.4 times which demonstrated the instability of forming moisture reserves in the grain-row crop rotation as of the end of crop vegetation (Table 4). The loss of moisture from the one-meter-deep typical low-humus chernozem layer during the vegetation period of 1965–1969 was

Table 3. The moisturization regime in 10-field grain-row crop rotation (Drabiv experimental field)

Years of observations	Reserves of productive moisture						Coef. var., %
	Medium	By the median	Minimal, min	Maximal, max	$^*L_{0.25}$	$^*L_{0.75}$	
			Amplitude interval, Δa = max–min		Normalized interval, $\Delta N=L_{0.75}–L_{0.25}$		
Moisture reserves prior to winter – 0–100 cm							
1965–1969	75.0	88.0	40.0	110	50.0	110	35.0
2010–2015	35.0	40.0	25.0	30.0	35.0	45.0	17.0
Percentage of atmospheric precipitation fixation by one-meter-deep soil layer							
1965–1969	34.0	31.0	49.0	21.0	48.0	20.0	
2010–2015	48.0	44.0	58.0	36.0	47.0	35.0	
Moisture reserves in spring – April – 0–100 cm							
1965–1969	175	177	160	185	168	180	4.5
2010–2015	165	167	150	165	155	170	5.1
Heading-up on winter cereals, closing of sugar beet lines – June – 100 cm							
1965–1969	90.0	80.0	40.0	150	46.0	142	51.0
2010–2015	75.0	70.0	35.0	120	30.0	125	40.0
Losses in April-June							
1965–1969	$\frac{85.0}{49.0}$	$\frac{97.0}{55.0}$	120	35.0	$\frac{122}{72.0}$	$\frac{38.0}{21.0}$	–
2010–2015	$\frac{95.0}{58.0}$	$\frac{97.0}{58.0}$	115	45.0	$\frac{125}{80.0}$	$\frac{45.0}{26.5}$	–

110–117 mm at the amplitude interval of 78–160 mm and the normalized interval of values of 85–155 mm, and the variation coefficient was 28.5 %.

In 2010–2015, the loss of productive moisture reserves from soil increased 1.15–1.23 times at a considerably reduced amplitude fluctuation and normalized interval of values and a 1.68 times lower variation coefficient. It demonstrated more active absorption of productive moisture from the one-meter-deep soil layer.

In 1965–1969, the total loss of moisture from soil and precipitation during the vegetation of crops in the grain-row crop rotation was 400–410 mm at the amplitude interval of 335–525 mm. During the modern period of the observations the loss of moisture was 10–15 mm higher, and by the normalized interval – 15–35 mm higher. It should be noted that during the initial period of the study (1965–1969), the average fraction of moisture loss from the soil was 28–29 % from the total loss whereas in the modern period it was 32–35 %. A similar increase was noted for the amplitude interval and normalized interval of the values of moisture loss during the vegetation. The calculations demonstrated that the total loss of moisture per 1 t of the main product in the dry matter (Cw-c, water consumption coefficient) was Cw-c = 9.1–10.6 at the normalized interval of values of Cw-c = 10.6–11.5. In modern conditions, the value of Cw-c decreased 1.31–1.42 times. There was a similar decrease in the total loss of moisture per yield of fodder and cereal units – 1.24–1.58 and 1.20–1.43 times respectively, which demonstrated more economic loss of moisture due to the formation of the harvest of crops in the grain-row crop rotation.

The comparative assessment of the productivity of 10-field grain-row crop rotation demonstrated that in 2010–2015 the dry matter yield of the main product increased 1.35 times, the yield of fodder units –1.28 times, and that of cereals – 1.23 times. The increase in the productivity of grain-row crop rotation occurred due to the 2.7-fold increase in the yield of corn. The fraction of the dry matter yield was 12 % from the to-

Table 4. The formation of autumn reserves of productive moisture and the coefficients of water consumption in the grain-row crop rotation (Drabiv experimental field)

Years of observations	Reserves of productive moisture						Coef. var., %
	Medium	By the median	Minimal, min	Maximal, max	$^*L_{0.25}$	$^*L_{0.75}$	
			Amplitude interval, Δa = max–min		Normalized interval, $\Delta N=L_{0.75}-L_{0.25}$		
Moisture reserves in September – 0–100 cm							
1965–1969	59.0	52.0	45.0	88.0	50.0	60.0	11.0
2010–2015	65.0	65.0	30.0	110	35.0	79.0	70.0
The losses of productive moisture from one-meter-deep soil layer during vegetation							
1965–1969	117	110	78.0	160	85.0	155	28.5
2010–2015	135	135	85.0	169	125	152	17.0
General losses of moisture from soil and precipitation							
1965–1969	410	400	335	525	345	505	19.3
2010–2015	420	415	330	529	380	492	18.0
Total loss of moisture per 1 t of the main product in dry matter, Cw-c (water consumption coefficient)							
1965–1969	9.1	10.6	16.5	5.44	10.6	11.5	–
2010–2015	6.9	7.51	11.6	4.65	9.38	6.51	–
Total loss of moisture per 1 t of fodder units							
1965–1969	6.18	7.58	12.1	3.78	6.96	6.36	–
2010–2015	4.99	4.79	8.14	4.14	6.69	4.33	–
Total loss of moisture per 1 t of cereal units							
1965–1969	7.89	9.59	11.1	3.65	10.4	7.70	–
2010–2015	6.57	6.68	8.35	4.45	9.78	5.59	–

tal yield which was 2.3 times higher as compared with 1965–1969. In July a direct correlation between the dry matter yield and moisture content in the one-meter-deep layer was established at the average level of R = 0.50 ± 0.03, which demonstrated the dependence of productivity of the 10-field crop rotation on the amount of atmospheric precipitation during the vegetation period. During the initial period of the study, moisture supply in the crop rotation was equally ensured by soil reserves and precipitations, whereas during 2010–2015 the formation of crop rotation productivity was mainly dependent on the amount of atmospheric precipitation for the vegetation period.

The regularities of forming productive moisture reserves in the soil for agricultural crops in the system of crop rotations of different duration were also studied at the Panfilska Experimental Station of NSC Institute for Agriculture, NAAS. It was determined that at the beginning of field work, the productive moisture reserves in the one-meter-deep layer were 168–170 mm regardless of the duration of crop rotations. When long-term crop rotations were introduced, the amplitude interval of moisture reserves was 1.6 times smaller as compared with short-term crop rotations. Therefore, the normalized interval was 1.8 times reduced for the benefit of short-term crop rotations, the variation coefficient for spring reserves of productive moisture was 2.1 times lower (Table 5).

The losses of productive moisture reserves from soil during the vegetation period were almost the same – 126–127 mm, but the amplitude interval and the normalized interval after the introduction of short-term crop rotations was 1.39 and 1.45 times larger, and the variation coefficient increased 1.55 times as compared with long-term crop rotations. The total losses of moisture with the consideration of atmospheric precipitation for the formation of dry matter, the yield of fodder and cereal units were 295–301 mm at the 1.3-fold increase in the amplitude interval and 1.52-fold increase in the variation coefficient for the total loss of moisture in long-term crop rotations. The dry matter yield in long-term crop rotations was 1.48 times higher, and the amplitude interval – 2.22 times higher as compared with short-term crop rotations which affected the variation coefficient for the dry matter yield which increased 1.34 times at the formation of productivity of long-term crop rotations.

The yield of fodder units in long-term crop rotations was 1.2 times higher with the 1.28-fold decrease in the variation coefficient. There was a similar change in the yield of cereal units, which was 1.16 times higher as compared with the 1.3-fold increase in the amplitude

Table 5. The parameters of moisturization regime for crop rotations with different duration at the Panfilska Experimental Station, average for 2016–2018

Periods of determining moisture reserves	Reserves of productive moisture, mm						Coef. var., %
	Medium	By the median	Minimal, min	Maximal, max	$^*L_{0.25}$	$^*L_{0.75}$	
			Amplitude interval, Δa = max–min		Normalized interval, $\Delta N = L_{0.75} - L_{0.25}$		
7–8-field crop rotations							
Start of field work	168	168	119	198	161	172	9.32
Losses from the soil	126	125	98.3	167	116	134	13.1
*Total loss	295	299	193	378	279	324	14.8
4–6-field crop rotations							
Start of field work	170	164	128	254	152	172	19.5
Losses from the soil	127	123	94.0	187	110	136	20.3
*Total loss	301	294	232	377	278	324	13.4
Average values for crop rotations							
Start of field work	169	166	119	254	159	172	13.6
Losses from the soil	126	124	94.0	187	116	135	15.7
*Total loss	297	297	193	378	279	325	14.17

Note. *Total loss: soil reserves+precipitation.

interval, and that of the normalized interval – 2.45 times as compared with short-term crop rotations. The 1.15-fold decrease in the variation coefficient for the yield of cereal units demonstrated the stabilization of the conditions of productivity formation for long-term crop rotations (Table 6). There was average direct correlation between the dry matter yield, the amount of precipitation during the vegetation period of crops and total losses of moisture – R = 0.55–0.63 ± 0.03. 0.06 precipitation units and 0.05 units of the total moisture losses per vegetation period corresponded to one unit of the dry matter yield. The yield of fodder units per crop rotation, the amount of precipitation, and total productive moisture loss correlated at the level of average direct correlation (R > +0.70); 0.05 mm of precipitation and 0.04 mm of total moisture loss from soil corresponded to 1 t of the yield of fodder units.

There was strong direct correlation between the yield of cereal units, precipitation, and total moisture losses: R = +0.71–0.75 ± 0.02, R2 = 0.50–0.56. 0.06 precipitation units and 0.04 units of the total moisture losses corresponded to one unit of the increase in the yield of cereal units.

There was strong direct correlation, observed between energy accumulation in the dry matter and the yield of fodder units in long-term crop rotations; 0.072 t/ha and 0.081 t/ha of the yield of fodder and cereal units corresponded to 1 gigajoule/ha of energy increase in the dry matter. There was strong direct correlation between energy accumulation in the dry matter and the dry matter yield, fodder and cereal units and energy losses per 10 t of moisture at the level of strong direct correlation – R = 0.85–0.90 ± 0.02, R2 = 0.73––0.81 in short-term crop rotations, and regression coefficients with variables (dry matter, fodder units, cereal units, dry matter per 10 t of moisture) in dependence equations were 3.06, 1.25, 7.25, and 2.89 times higher as compared with long-term crop rotations. It demonstrated higher efficiency of productivity formation and use of the total moisture circulation, which was 2.59 times more effective.

The average dry matter yield in the control variant without fertilizers was 4.03 t/ha with the 3.1-fold increase in case of introducing fertilizers (Table 6). After ploughing, the increase in the dry matter yield was 318 %, and after surface and subsurface tillage – 265 and 299 %, respectively. The energy reserves in the dry matter changed according to the established regularity, when the introduction of fertilizers promoted the 1.46-fold energy increase as compared with the control variant without fertilizers. In case of introducing fertilizers, the energy reserves in the dry matter per 10 t of the total loss of moisture were 1.36 times more effective as compared with the control variant without any fertilizers. After ploughing, the efficiency increased 1.4 times, and in case of surface and subsurface tillage – 1.33–1.35 times.

In case of introducing mineral fertilizers, water consumption coefficients decreased by 18.0 % on average as compared with the control variant without fertilizers,

Table 6. The productivity of crop rotations with different duration at the Panfilska Experimental Station, average for 2016–2018

Productivity indices of crop rotations, t/ha	Statistical parameters of productivity						Coef. var., %
	Medium	By the median	Minimal, min	Maximal, max	$*L_{0.25}$	$*L_{0.75}$	
			Amplitude interval, Δa = max–min		Normalized interval, $\Delta N = L_{0.75} – L_{0.25}$		
7–8-field crop rotations							
Yield	12.3	5.66	2.74	58.3	4.59	7.66	143
Dry matter	5.50	4.50	1.53	13.7	4.04	6.08	54.9
Fodder units	6.70	6.17	1.83	14.6	4.47	7.99	45.9
Cereal units	6.42	5.63	0.76	15.2	4.22	8.70	47.1
4–6-field crop rotations							
Yield	8.52	4.62	2.27	55.3	2.91	5.96	174
Dry matter	4.02	4.04	1.95	7.44	2.55	5.12	40.7
Fodder units	5.78	5.54	1.59	14.4	4.00	7.15	58.3
Cereal units	5.80	5.06	3.18	14.4	4.13	5.96	51.9

but after ploughing, the decrease was 6.2 %, after surface tillage – 31.0 %, subsurface tillage – 13.6 %. Water consumption coefficient for the yield of fodder units in the control variant without fertilizers was Cw-c (f.u.) = = 50.0 on average, with the decrease by 20.5 % after the introduction of fertilizers. After ploughing, the decrease was 30 %, and in case of surface and subsurface tillage – 27–28 % with lower values of coefficients.

Water consumption for the yield of cereal units with the introduction of fertilizers decreased by 31 %, after ploughing – by 32 %, and in case of surface and subsurface tillage – by 30–31 % with lower water consumption coefficients.

Noteworthy is the increase in the productivity of 10-field grain-row crop rotation in 2010–2015 as compared with the initial period of the study, when the NPK sum increased 1.4 times and the introduction of 6 t/ha of humus in the crop rotation was substituted with 7 t/ha by-products of plant cultivation. In conditions of unstable moisturization of the Forest-Steppe zone, the dry matter yield increased by 35.8 %, that of fodder units – by 27.5 %, that of cereal units – by 22.0 %. The variation coefficient for the dry matter yield during the years of study decreased by 13.0 %, fodder units – by 20.5 %, cereal units – by 24.6 %.

The moisture supply for soil formation in the agrocenosis was improved due to 20–25 % more efficient consumption of summer precipitations due to the formed layer of plant mulch and a high level of agrophysical properties of the humus horizon in case of surface tillage. In summer, during long-term crop rotations (10–15 years) the atmospheric precipitations moisturized the humus horizon with surface tillage for a higher depth as compared with ploughing – 25–28 cm on average, which prolonged the period of biological activity (PBA) of chernozem in summer by 20–25 days due to the layer of organic mulch on the surface of chernozem. Under surface tillage, soil profile of chernozem is enriched with humus: the value of the coefficient of relative accumulation of humus (CRAH) reaches 1.15–1.19 (enhanced hydrophilization), whereas in case of ploughing – 1.03–1.05 (aridity increase).

Long-term (10–36 years) surface tillage promotes the increase in the hydrophilization degree for the depth of typical chernozem in the seasonal and annual cycles and enhanced humus accumulation which is diagnosed by the darkening of transitional horizons in soil profiles of typical chernozems (Demydenko OV, Velychko VA, 2013). In 10–15 years, the humus content in the typical chernozem layer (0–180 cm) increased by 0.23–0.24 %. Surface tillage for 25 years in conditions of the production enriched the chernozem layer with humus by 0.22–0.25 %. At the same time, in 10 years, the value of the coefficient of relative accumulation of humus was 1.08 against 1.02 for ploughing and after 15 years this coefficient amounted to 1.10, which was 105 % higher as compared with ploughing. In 25 years the CRAH value increased up to 1.31. The coefficient of profile accumulation of humus (CPAH) in the one-meter-deep layer (humus content per 1 % of PC or CRAH per 10 % of PC) was 105–111 % as compared with ploughing (0.85–0.98 against 0.78–0.88).

DISCUSSION

During the recent decade the problems of climatic changes in the Forest-Steppe of Ukraine have been discussed more frequently, as this factor has a considerable impact on the formation of the harvest of agricultural crops in agrocenoses with crop rotations of different duration. There are different forecasts regarding the consequences of global warming for the Forest-Steppe of Ukraine, thus, there are several scenarios for the development of agricultural industry, based on the acceleration of the development of plants, the change in productivity and stability of the production, the change in arable fields, the set of agricultural crops and specialization of agriculture, transformation of agrotechnology, etc. In addition, the global climate change is a complex problem, which covers different aspects of the development of the Forest-Steppe – ecological, economic, and social.

Two aspects are distinguished during the analysis of the "climate–agriculture" system: "climate as natural resources" and "climate as risk for producers". Thus, two approaches of studies have been formed: one of them is related to the assessment of slow changes in the average values of climatic parameters, and the other – to the assessment of the impact of changes in repeatability of climatic extremes which present a considerable source of risks for agriculture. Long-term changes in temperature or precipitation are known to be less relevant for agriculture than such extreme phenomena as droughts, severe frosts, excessive moisturization of soil, etc. The impact of these rather rare phenomena on the yield leads to economic stress which accelerates the adaptation of agriculture to climatic changes. The concepts of "slow changes" and "changes in risks" do not exclude but rather supplement each other while solving the task of identifying new functions of yield distribution and gross production of cereals, conditioned by climatic changes (Krakovska SV et al, 2008; Jacob DB et al, 2001).

The productivity of agricultural crops in agrocenoses with crop rotations of different duration in the Forest-Steppe zone is considerably dependent on agroclimatic factors (warmth, moisture, illumination), which are rather varied in time and space due to global climatic changes. The dynamics of agroclimatic resources in the Forest-Steppe zone had a positive impact on the productivity of many agricultural crops. The increased temperature background by the sum of active temperatures (+230–510 °C, on average +180 °C) and the increase in the amount of precipitation during the critical period of crop development conditioned the increase in the productivity of winter wheat, corn, sunflower, and soybeans. There were relevant changes in the dynamics of agroclimatic resources in the territory of the Forest-Steppe, namely: the increase in the sum of active and effective temperatures on average by +180–200 °C, the increase in the average annual air temperature (>+1.8 °C), the increase in the frequency of extreme temperatures in summer by +4.0–5.0 °C, the increase in summer duration up to 5 months, the decrease in the intensity of snow cover and duration of its occurrence led to the increase in the productivity of warm-weather crops with long-term vegetation and its insignificant decrease while cultivating spring grain crops.

Systematic soil-protective tillage promoted the optimization of water availability regime for the crops of grain-row crop rotation: during critical phases of crop development, the amount of soil moisture in the one-meter-deep soil layer increased by 25–35 mm as compared with ploughing. The optimization of water availability regime was based on reasonable and thoughtful ratio of the simultaneous effect of capillary and convective-diffuse mechanisms of soil moisture transition which ensured the highest content of productive moisture in chernozem of the Forest-Steppe zone during the critical phases of crop development. Soil formation in agrocenoses should be perceived as enhancing the cumulative effect of the biological factor of soil formation under agricultural use of typical chernozem due to improvement in hydrothermal soil conditions in the seasonal and annual cycles under systemic soil protective technologies, based on surface tillage, which ensured the process of managing functional-ecologic and facial regularities of humus accumulation in typical chernozems of agrocenoses in the Left-Bank Forest-Steppe of Ukraine (Demydenko A, Velychko V, 2013).

CONCLUSIONS

The accumulation of soil degradation processes during crop rotations of different duration due to systematic deep ploughing decreases the on-balance-sheet items of moisturization regime: inflow – due to incomplete (by 20–25 %) consumption of winter precipitation, and the increase in the outflow – due to the increase (by 25–30 %) of physical evaporation which leads to the aggravation of quantitative indices of moisturization and a considerable increase in the depth of active moisture circulation which shifts to May-July, conditioning deep summer drying (aridization) of typical chernozem layer in the agrocenoses of different crop rotations. In case of long-term (10–36 years) surface tillage, the efficiency of the use of productive moisture reserves increased by 25–40 % and the coefficients of water consumption by crops decreased by 35–40 %.

The comparative assessment of the productivity of 10-field grain-row crop rotation demonstrated that on average for 2010–2015 the dry mass yield of the main product increased 1.35 times, the yield of fodder units – 1.28 times, and that of cereals – 1.23 times. The increase in the productivity of grain-row crop rotation occurred due to the 2.7-fold increase in the yield of corn. The fraction of the dry mass yield was 12 % from the total yield which was 2.3 times higher as compared with 1965–1969.

Short-term crop rotations had higher productivity: there was strong direct correlation between energy accumulation in the dry matter and the dry matter yield, fodder and cereal units and energy accumulation per 10 t of spent moisture – $R > 0.70$, and the regression coefficients with variables (dry matter, fodder units, cereal units, dry matter per 10 t of moisture) in dependence equations were 3.06, 1.25, 7.25 and 2.89 times higher as compared with long-term crop rotations. It demonstrated higher efficiency of forming productivity and using the total moisture circulation, which had a 2.59-fold increase.

Adherence to ethical principles. This article does not relate to any studies using humans and animals as investigation subjects.
Conflict of interests. The authors deny any conflict of interests.
Financing. This study did not receive any specific grant from the financing institutions in state, commercial or non-commercial sectors.

Вологоресурсний потенціал агроценозів лісостепу України

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Мета. Визначити основні закономірності формування вологоресурсного потенціалу, нагромадження та використання ґрунтових запасів продуктивної вологи сільськогосподарськими культурами за вирощування в системах різноротаційних агроценозах сівозмін Лісостепу України. **Методи.** Польовий, стаціонарний, лабораторний, аналітичний, статистичний. **Результати.** У короткоротаційній зерно-просапній сівозміні витрати доступної вологи без внесення мінеральних добрив становили 317 мм, а у варіанті з добривами вони зростали на 107 %. Загальні витрати вологи за різних способів обробітку без внесення добрив найнижчими були при застосуванні поверхневого обробітку та зростали у 1,05 рази за оранки та у 1,08 разів за безполицевого глибокого обробітку. За внесення добрив загальні витрати вологи у середньому зростали на 23,0 мм або 107 %. За довгострокового (10–36 років) безполицевого обробітку ефективність використання запасу продуктивної вологи зростала на 25–40 %, а коефіцієнти водоспоживання культур знижувалися на 35–40 %. **Висновки.** Сівозміни з короткою ротацією були більш продуктивними, а між нагромадженням енергії в сухій речовині, виходом кормових і зернових одиниць та нагромадженням енергії в урожаї на 10 т витраченої продуктивної (доступної) вологи зв'язок був на рівні прямої сильної кореляції (R > +0,70). Коефіцієнти регресії при змінних: суха речовина, кормові та зернові одиниці, суха речовина на 10 т вологи у рівняннях залежності були вищими відповідно у 3,06, 1,25, 7,25 та 2,89 рази порівняно із сівозмінами з довгою ротацією, що свідчить про зростання продуктивності та використання загального обігу вологи у 2,59 рази в короткоротаційних сівозмінах порівняно з сівозмінами з довгою ротацією.

Ключові слова: різноротаційні сівозміни, попередники, нормативи чергування, вологозабезпеченість, властивості ґрунту, випаровування, агротехнічні заходи, культура вирощування.

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