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Increasing the efficiency of moisture resources in crop rotation by tillage optimization in Ukrainian Steppe zone

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Peculiarities of the formation of moisture reserves in the soil and the dynamics of moisture supply of different biotechnogenic landscapes were studied in a grain-fallow-row tillage 5-field crop rotation in a stationary field experiment. We found the most significant moisture accumulation capacity at moldboard plowing, which decreased along with the tillage depth reduction. The decrease of moisture reserves in the spring in 0–150 cm soil layer using direct seeding compared to intensive loosening was 8–21 mm. The role of crops as a form factor of soil moisture reserves was more significant in the autumn when the residual water volume was only 34-50 mm. The moisture reserves at the time of maximum seasonal moisture accumulation on recultivated areas using different quarry rocks reached 140-149 mm. Field-protective forest belts had the most significant accumulative capacity concerning moisture. The wetting depth of the arable layer after rains was established by the method of soil hardness control. We determined that the soil's water absorption capacity increased with the deepening of its tillage simultaneously with the increase in all crops' yield by 15.9-32.6%.
Keywords: agrotechnologies, crops, moisture, yield, water infiltration, tillage, mineral fertilizers.

Introduction

For the steppe zone conditions that belong to the areas of scarce moisture resources supply, the urgency of arid climate has never been removed from the agenda. Against the background of global warming, which has led to an increase in average annual temperature in the steppe zone over the past 20 years by 1.6ºC and expressiveness and unpredictability of hydrothermal characteristics during the year, the adaptively approximate of the production structure in agriculture and improvement of agrotechnologies in the direction of accumulative and conservative properties of agrocenosises become important (Kaminskyi et al., 2018; Kemper & Rosenau, 1986; Pabat, 1992; Shevchenko & Shevchenko, 2013; Shevchenko et al., 2013; Tsyliuryk et al., 2017; Volokh et al., 2007).

According to many famous researchers, moisture supply consists of 45-60% in the structure of factors that determine the productivity of arable land. Many reserves have not yet been used in the problem of efficient ways to use moisture. If in the arid Steppe of Ukraine 800–1000 m^3 of moisture is used for the production of 1 ton of grain, then in the USA the moisture consumption coefficient under similar conditions in experiments decreased to a record 280 m^3 (Bogunovic et al., 2018; Cerdan et al., 2010; de Almeida et al., 2018; Jigau, 2011; Kachmar et al., 2018; Kisic et al., 2002; Marinkovic et al., 2018; Medvedev & Plisko, 2018; Rusui & Adamos, 2013). In some technological and organizational fragments, agriculture does not respond synchronously to climate change and slowly uses the opportunities of technical and chemical modernization of agricultural production associated with moisture conservation and balanced water circulation in agricultural systems (Andriuca et al., 2016; Barz et al., 2006; Boincean, 2013). The scale of unproductive moisture loss can be reduced by 30-40% or more by decrease the weediness in crops, reducing erosion runoff, improving soil infiltration properties, reducing moisture evaporation from the field surface, selecting adaptive technologies and varieties (Blouin et al., 2013; de Lima et al., 2017; Roger-Estrade et al., 2010; Voloshchuk, 2017; Vynokurov et al., 2015). In this set of agrosystem issues, perhaps the most critical - water-regulating mission belongs to crop rotations and primary tillage.

The expansion of shallow disk tillage (in particular, a heavy disc harrow) is primarily a reaction to the economic situation in which it is essential to reduce production costs and increase productivity. It is a way to transfer the main part of the functional load to the 0-12 cm soil layer and model all soil processes by analogy with deep loosening. The disk tillage can be solved some issues related to the creation of favorable soil conditions, but the application of fertilizers to the root layer depth, soil compaction, and a high degree of crop weediness remain problematic.

Direct drilling or No-till system has not yet found its equal place in the primary tillage system due to insufficient study of its environmental and economic efficiency. The main question is "Can increase the use of chemicals to protect crops from pests, diseases, and weeds be justified in balance with the cost savings of resource and energy materials, which occurs when reducing technological operations in the No-till system?". The points of overcoming the No-till system's shortcomings are the effectiveness of weed control measures, plants' response to soil compaction, and water regulation ability (Kaminskyi et al., 2018).

The research purpose was the moisture supply level optimization for grain-row crop rotation based on the different tillage methods was conductive to the effective soil moisture accumulation and productive moisture use of crops.

Methods

Field stationary experiments were performed in 2015–2018 on ordinary chernozems in the northern Steppe zone on the experimental base of the Institute of Grain Crops of NAAS. At the stationary plot, the humus content in the arable soil layer was 3.98%, the density in some periods ranged from 1.18 to 1.34 g/cm^3, hardness - 13.4 to 36.0 kg/cm^2. According to the level of agrochemical supply, chernozem in the stationary plot belongs to the middle and advanced class: nitrate-nitrogen - 21 mg per 1 kg of dry soil, mobile phosphorus - 142 mg, and exchangeable potassium - 187 mg (Shevchenko et al., 2013; Tsyliuryk et al., 2017).

In a stationary experiment established in 1998 and underwent several innovative reconstructions, a 5-field crop rotation was mastered: "peas – winter wheat – sunflower – spring barley – corn for grain". During the years of research, hydrothermal conditions in the generally accepted global warming trend were of exclusive importance for crops with different development cycles. Of all the months of the year, the temperature increased most significantly (by 2.5–3.4 ºC) in February and August, which on the one hand, accelerated the recovery of spring vegetation growth of winter crops and, on the other hand, caused accelerated ripening of late crops. Among the unique meteorological phenomena should be noted the prolonged drought in the autumn of 2015 (up to 80 days), the fact of obtaining a sufficiently high yield of winter wheat despite the weak autumn-winter development and restoration of spring vegetation growth in 2016 in the 3-4 cm germination phase, snowfall in mid-April 2017 and the preservation of snow cover with a moisture volume of 850 m^3/ha. 2017 can be considered rare in the distribution of isotherms, which positively affected early and late crops. In 2018, a relatively late restoration of vegetation growth (20.03) turned into an intensive increase of effective temperatures. The deficit of sufficient precipitation lasted during April-May. The stationary experiment studied the systematic application of radically individual methods of primary tillage by the mechanisms of soil mass movement, the volume of the loose part of the arable land, the field surface's anti-erosion nature the concentration of nutrients and weed seeds. Tillage methods characteristics and their impact on the moisture resources use and crop yields were studied in experiments. The range of tillage implements included a moldboard plow, a conservation chisel plow, a heavy disc harrow, and a No-till drill.

The soil moisture reserves were determined using the thermostat-weight method at their maximum and minimum at the beginning and end of the growing season. The reserves of productive moisture in the soil reach their maximum values during the active moisture accumulation period, from the beginning of seeding winter crops to the restoration of spring vegetation growth. The productive moisture reserves in the soil at the beginning of the growing season characterize the role of precursors, tillage and its moisture accumulation properties (Shevchenko et al., 2013) (Table 1).

Table 1. Scheme of the field experiment.

		Factor A – crop		
Peas Tsarevich Variety	Winter wheat Rozkishna variety	Sunflower Zlatson hybrid	Spring barley Adapt variety	Corn Veles hybrid
		Factor B – primary tillage		
Plowing 25–27 cm	Shallow disk tillage 10–12 cm BDV (БДВ)	Chiseling 4–10 cm KR-4,5 (КР-4,5)	Shallow disk tillage 10–12 cm BDV (БДВ)	No-till Great Plains
		Factor C – fertilizers		
Without fertilizers			N45P45K45	

Results and discussion

Our experimental studies have shown that the yield of early grain crops by 50-60% depends on the initial reserves of soil moisture and 40-50% of the precipitation amount during the growing season. For late crops, the value of vegetative rains increases to 55-70%. At the same time, the relevance of soil moisture naturally increased in dry years.

The indicators range of productive moisture reserves in the 0–150 cm soil layer depending on the crop rotation and primary tillage was 169–191 mm. This insignificant level of variation in the productive soil moisture reserves indicates that the intensity of moisture accumulation processes was aimed at leveling this indicator on different agrosystem backgrounds (Table 2).

Table 2. Productive moisture reserves at seeding of early spring crops depending on predecessors and methods of tillage, mm (average for 2015–2018).

Crops	Soil layer, cm	Tillage			
		Plowing	Chiseling	Shallow Disk	No-till
Peas	0-50	64	65	63	60
	0-100	136	138	130	127
	0-150	180	181	175	169
Winter wheat	0-50	68	68	65	63
	0-100	144	143	138	133
	0-150	191	190	186	180
Sunflower	0-50	67	66	65	62
	0-100	141	142	136	132
	0-150	187	188	184	179
Spring barley	0-50	62	64	60	59
	0-100	134	135	128	124
	0-150	184	185	178	173
Corn	0-50	67	68	65	62
	0-100	142	143	137	132
	0-150	188	189	182	179

$LSD_{0.05}$ for 0-50 cm soil layer = 2.6 mm; for 0-100 cm soil layer = 4.1 mm; for 0-150 cm soil layer = 5.7 mm

There was a clear tendency to reduce the moisture accumulation while reducing the primary tillage's depth for all crop rotation crops. So, for example, maximum moisture reserves reached 188-191 mm under deep plowing and chisel tillage, then they were inferior - 179-186 mm under shallow disk tillage and direct seeding. The distribution of moisture in the soil profile was characterized by the fact that most of the moisture was concentrated in the 50-100 cm layer, and it was slightly lower (6-10 mm less) in the 100-150 cm deeper layers. Thus, from the perspective of the influence of different tillage methods on moisture accumulation, soil density, and depth of the primary accumulative layer, or, more simply, the loose soil volume, are the decisive factors.
The moisture consumption level and the nature of moisture use by predecessor crops also extended to the spring productive moisture reserves before seeding of subsequent crop rotations. Large amounts of moisture used by late crops, such as corn for grain and sunflower, and intensive transpiration up to the first decade of August made it impossible to restore soil moisture to the level of field capacity fully. At the same time, the end of the early grain crops' maximum water consumption period came much earlier, at the end of June's second decade. The agrocenosis of the early crops group passed from the stage of moisture consumption to the stage of its accumulation. As a result of regulating the moisture consumption mechanism, the reserves of productive moisture before seeding winter wheat, sunflower, and corn for grain (after peas, winter wheat, spring barley) were higher and amounted to 187-191 mm. After late crops before seeding peas, spring barley, the initial moisture reserves were slightly lower - 180-184 mm. The indicators of residual soil moisture after the end of the growing season of crops indicate the volume of water use by agrocenosises and set the task of choosing a system of moisture-preserving tillage. For winter crop seeding, moisture reserves' determination showed that they have radically decreased to 14-50 mm in the 0-150 cm layer. The influence of both crop rotations and primary tillage methods affected the moisture level and remained a determining factor in the formation of moisture reserves. Preference was given to early crops: peas, winter wheat, and spring barley, which left after chisel tillage 50-51 mm, and in the No-till system 42-45 mm (Table 3).

Table 3. Moisture distribution in crop rotation during seeding of winter crops, mm (average for 2015–2018).

Crops	Soil layer, cm	Tillage			
		Plowing	Chiseling	Shallow Disk	No-till
Peas	0-50	26	24	22	20
	0-100	35	34	33	29
	0-150	50	50	47	43
Winter wheat	0-50	28	27	25	22
	0-100	37	37	35	33
	0-150	50	51	48	45
Sunflower	0-50	19	18	17	15
	0-100	26	25	23	21
	0-150	37	38	35	32
Spring barley	0-50	25	25	21	19
	0-100	34	35	30	30
	0-150	48	50	44	42
Corn for grain	0-50	19	18	16	14
	0-100	25	24	23	20
	0-150	34	35	31	30

The primary tillage during the summer-autumn fieldwork performed two functions: the preservation of moisture remaining after the harvest of predecessors and the accumulation of precipitation in the pre-winter season. Under the conditions of various compensatory processes in moisture consumption, the deep tillage - plowing, chiseling tillage had an insignificant advantage of 4-7 mm.
The experiments against the background of various technobiogenic models of recultivation origin in the area of manganese ore development were provided an expansion of the view about water-physical properties of evolutionary and technogenic soils and features of moisture consumption regimes of crops (Tsyliuryk et al., 2017; Volokh et al., 2007).
The study of soil moisture reserves dynamics in different technobiogenic systems showed that soil moisture content depended on the nature of vegetation, land use activity, and the qualitative origin of the soil mass. The field protective forest belts were distinguished with the most significant accumulative capacity from among natural ecosystems, in which in 0-150 cm soil layer were accumulated 163 mm of moisture in the spring. Due to the significant soil compaction on natural steppe pastures, moisture reserves were minimal - 140 mm (Table 4).

Traditional arable land due to regular loosening of the topsoil of chernozem created its preferences for moisture accumulation and provided 152 mm water in the 0-150 cm layer. The recultivation model of artificial agrolandscape based on deep-seated rocks with gray-green and red-brown deteriorated water absorption capacity to 140-143 mm. In the conditions of climatic moisture supply deficit of crops and natural lands, the annual cycles of minima and maxim dynamic for productive soil moisture were contained in the amplitude from 140-165 mm (spring) to 26-44 mm (autumn). According to the analysis of the productivity of agrobiocenosises, it does not always have a direct correlation with productive moisture reserves because, in this statistical combination, the level of precipitation of the vegetation period and features of strengthening of its influence depending on the technology of the use of agrobiocenosises is not considered (Kaminskyi et al., 2018; Medvedev & Plisko, 2018). For moisture cycle analysis, it is essential to know the precipitation features during the growing season (Andriuca et al., 2016; Barz et al., 2006; Boincean, 2013). We found that plants' best growth and development is observed in areas with deeper penetration of moisture into the soil immediately after rains. A hardness tester determined the line of demarcation of the wet and dry zone on the principle of a sharp increase in soil hardness with the entry into the dry part of the arable profile.

Table 4. Influence of technobiogenic land use models on productive moisture reserves and the level of its filtration into the soil (after precipitation 16 mm).

Soil type	Term for determination	Moisture reserves (mm) 0-50	0-100	0-150	Depth of wetting, cm
Natural pastures	S	54	102	140	8
	A	17	22	26	
Field protective forest belts	S	59	114	165	14
	A	29	36	44	
Land under cultivation	S	56	107	152	14
	A	24	32	37	
Recultivation model: Light loam rocks	S	53	104	147	15
	A	52	8	34	
Southern bulk chernozem	S	53	103	149	13
	A	24	30	36	
Gray-green rocks	S	51	51	143	9
	A	20	26	30	
Red-brown rocks	S	49	98	140	8
	A	19	25	28	

Note: S - Determination of moisture reserves at the beginning of spring fieldwork, A - during the seeding of winter crops

Table 5. Influence of crop rotation and tillage on depth penetration of precipitation with an intensity of 12 mm, cm.

Crops	Stage of plant development	Tillage: Plowing	Chiseling	Sallow disk tillage	No-till
Fallow	–	27	26	17	13
Winter wheat	Complete ripeness	16 / 94	16 / 92	15 / 90	12 / 87
Sunflower	Flowering	25 / 162	22 / 157	18 / 148	15 / 140
Spring barley	Complete ripeness	12 / 73	12 / 70	10 / 67	8 / 62
Corn	Ejection of the panicle	24 / 172	22 / 168	17 / 159	14 / 151

Numerator: depth of the hard layer of soil, cm; Denominator: plant height, cm.

During winter wheat grain filling after 16 mm of rain, two groups of agrobiocenosises were distinguished by the intensity of water infiltration: the first group with a depth of moisture penetration of 13-15 cm includes protective forest strips, traditional arable land, bulk chernozem; to the second group with 8-9 cm hard layer depth - natural pastures, gray-green and red-brown rocks. We pointed out that precipitation water use during the growing season depends on the biology and agricultural techniques of growing crops. We established that the systematic application of specific primary tillage methods has its long-term effect on the water permeability of the arable soil layer.

We registered that rain moisture accumulated more effectively on the background of moldboard plowing, where the moistened layer depth depending on the crop reached 12-25 cm. The depth of wetting on compacted soil after direct seeding decreased to a minimum of 8-12 cm (Table 5).

When winter wheat reached complete ripeness and the phase of ejection of corn panicles, row crops had an advantage over moisture infiltration, on which the moistened layer reached 13-25 cm against 8-16 cm in grain crops.

Table 6. Effect of tillage and fertilizers on crop yield (t/ha, the average for 2015–2018).

Crops	Doses of fertilizers. kg/ha ai	Tillage: Plowing	Boardless plowing	No-till
Peas	Without fertilizers	2.21	1.94	1.73
	N45P45K45	2.56	2.19	1.93
Winter wheat	Without fertilizers	4.10	3.98	3.76
	N45P45K45	4.60	4.35	3.97
Sunflower	Without fertilizers	2.38	2.19	1.92
	N45P45K45	2.76	2.43	2.20
Spring barley	Without fertilizers	2.50	2.28	1.99
	N45P45K45	2.75	2.53	2.22
Corn for grain	Without fertilizers	5.25	4.82	4.41
	N45P45K45	6.31	5.88	5.36

The application of a new methodology for assessing the water-regulating role of agricultural practices has revealed the mechanisms of correlations between moisture accumulation and productivity of grain and oilseed crops. All crop rotations responded positively to soil hardness and moisture filtration depth. For example, the height of spring barley plants was 73 cm at 12 cm wetting depth, and with the deterioration of filtration to 8 cm, this parameter decreased to 62 cm. A similar dependence was observed for corn: the height of plants reached 172 cm with wetting of the soil up to 24 cm, linear growth decreased to 151 cm with wetting of the soil to 14 cm on the background of No-till. Repeated fixation of the processes of change of water and physical properties of the soil after

precipitation during the growing season showed that the advantage of loose soil was formed due to the total cumulative effect, which manifested itself in the value of the yield (Table 6).
The gradual increase in tillage intensity from the No-till system to deep plowing was accompanied by an increase in the yield of corn grain from 5.36 t/ha to 6.31 t/ha, and spring barley 2.22 to 2.75 t/ha. A similar reaction of winter wheat and sunflower testifies to the stability and synchronicity of the influence of the water-physical complex indicators on the yield.
Our calculations indicated a high level of correlation for productive moisture content in 0-150 cm soil layer and crop yields (for corn r = 0.73, winter wheat - 0.68, spring barley - 0.75, and sunflower - 0.71).

Conclusions

Crop rotations and primary tillage methods have a significant impact on moisture regulation and productivity of agrocenosises. In crop rotation with the traditional plowing background, the largest reserves of productive soil moisture were accumulated in 0-150 cm soil layer under winter wheat (191 mm), sunflower (187 mm) and corn (188 mm) at the beginning of spring fieldwork. At the same time, the productive moisture reserves significantly decreased with No-till technology (by 9-11 mm).
The tillage intensity increasing (from No-till to deep plowing) enhanced the corn grain yield from 5.36 to 6.31 t/ha, spring barley - from 2.22 to 2.75 t/ha, winter wheat from 3.97 to 4.60 t/ha, sunflower from 2.20 to 2.78 t/ha on the fertilized background.
The moisture-regulating meaning of the primary tillage was manifested in all crop rotations and consisted of soil moisture reserves' growth with increasing depth of its loosening in both moldboard and boardless variants. The proposed method of monitoring the soil's water-physical properties with the determination of the wetting zone of the arable layer after precipitation made it possible to predict the high level of correlation between the dynamics of soil moisture reserves and crop rotation productivity (r= 0.68-0.75).

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