Spatiotemporal dynamics of spring soil moisture reserves in a slope agricultural landscape

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Abstract. This study conducted a systematic analysis of agroclimatic conditions, relief morphology, and soil moisture dynamics over a five-year period to identify territorial differences and temporal changes in productive moisture reserves on arable slopes with chernozem soils. The results show that changes in spring productive moisture reserves are primarily linked to variations in hydrothermal conditions from the previous hydrological year, encompassing both the cold and warm periods. The heterogeneity of moisture reserves within the agricultural landscape is influenced by the heat supply of the slopes.

1 Introduction

Reserves of productive moisture in the soil are the main resource necessary for the growth of biomass of the agrocenosis and, ultimately, for the formation of crop yields [1].

According to various scientific institutions, yield fluctuations are most dependent on hydrothermal conditions [2]. The moisture accumulated in the root layer of soil by spring is the main source of water supply for agricultural crops during their growing season.

Key factors that have a great influence on soil moisture can be identified: the amount of precipitation in a certain area, the groundwater level, relief features, soil structure and its ability to retain moisture [3]. Based on the amount of spring moisture reserves, it is possible to forecast crop yields and, in case of shortages, take measures to minimize damage. At the present stage, issues of both short-term and long-term forecasts of soil moisture reserves are resolved on the basis of an analysis of their accumulation due to precipitation in the autumn-winter period, and, first of all, due to snow cover. As noted above, soil moisture depends on many factors [4, 5], including relief, where the main differences are determined by slope exposure [6]. Therefore, areas with complex terrain require an integrated approach.

The purpose of the research is to establish patterns of formation of productive moisture reserves in chernozem soils depending on climatic conditions and relief parameters.

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2 Materials and methods

The research was carried out using a comprehensive analysis of the results of periodic monitoring (2019 - 2023) of the experimental site of the Kursk FARC (Medvensky district, Kursk region, N 51.52385969, E 36.13463254) with a dome-shaped relief, an area of 86 hectares, with a sampling step of 50 m. Test site located on the Central Russian Upland at an altitude of 190-217 m above sea level. The terrain of the landfill is typically erosive, with pronounced undulations. The soil cover is represented by chernozems of varying degrees of erosion on loess-like loam.

To construct terrain maps, the method of instrumental topographic survey using an ADA 32x level was used. The average slope is 2.52^0 with a variation of 52.8%, the azimuth directions of the slopes vary by 58.6%. The coefficient of relative heat supply for slopes was assessed according to the equation [7]:

$$S/S_0 = COS((\alpha /360) \cdot 6{,}28)-(TAN((h /360) \cdot 6{,}28))^{-1} \cdot SIN((\alpha /360) \cdot 6{,}28) \cdot COS(((A - 45)/360) \cdot 6{,}28),$$

where S/S_0 – heat supply coefficient of slopes relative to the watershed plateau; α – slope steepness in degrees; h – sun altitude in degrees; A – azimuth in degrees.

The coefficients of relative (compared to the watershed) heat supply of slopes varied across the territory from 0.923 to 1.075.

Hydrothermal conditions during the study period varied significantly. The sum of active temperatures more than 10 C° of the previous year (ST), the sum of precipitation of the warm period of the previous year (OT), the hydrothermal coefficient (GTK) and the sum of precipitation of the previous hydrological year (SO) for April - March were taken into account (Table 1).

Table 1. Parameters of hydrothermal conditions during the research period.

Parameters	Years					5 years
	2019	2020	2021	2022	2023	
ST	2902	2771	2731	2788	2730	2784
OT, mm	297	231	326	402	467	345
GTK	1.02	0.83	1.19	1.44	1.71	1.24
TX, C°	-2.80	-1.10	-3.30	-1.70	-1.30	-2.05
OX, mm	260	217	271	248	355	271
SO, mm	557	448	597	650	822	616

Cold period precipitation for October-March (Ox) varied from 217 to 355 mm (17.1%), and the average temperature for this period (Tx) varied from -3.3 to -1.1 °C (42.2%). The hydrothermal coefficient for the entire period averaged 1.24, varying from 0.83 to 1.71 (25.0%).

Soil moisture was assessed by thermostat-weight method. Correlation-regression and dispersion methods of data analysis were used using Microsoft-Office (MS Excel), STATGRAPHICS, STATISTIKA software.

3 Results and discussion

Each year of the survey of the test site was characterized by the fact that the elementary survey areas (31 - 32 units) included the most typical relief elements. The directions of the slopes varied from 14 to 350 degrees, and the slopes - from 0.25° to 5.92° (52.5...63.9% and

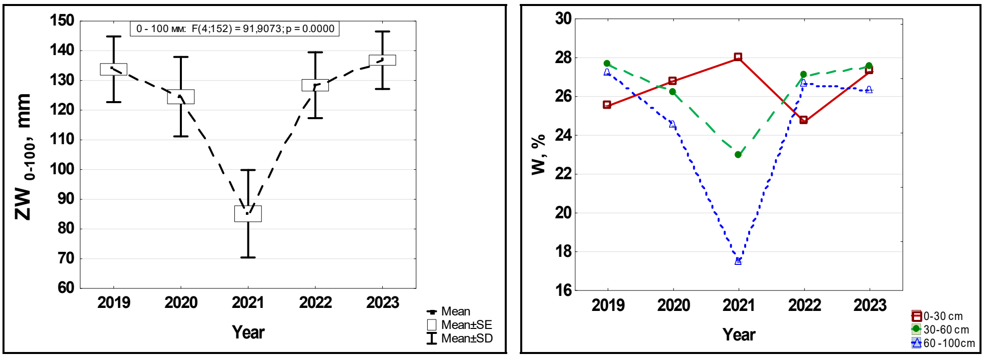
46.8...58.1% of variation), as a result of which the relative heat supply coefficients changed from 0.92 to 1.08 (3...4%). Therefore, the average calculated S/SO values for each year corresponded to 1.00 (Table 2). Thus, differences in moisture accumulation values over the years were attributed to the influence of weather and climatic factors, which are currently undergoing significant changes [8]. The largest average amounts of productive moisture in a meter-long soil layer were formed in 2019 and 2023 (134 and 137 mm) under completely different conditions (Fig. 1a). If the first year was characterized by an increased temperature background (ST = 2902) of the previous warm period with average precipitation for the entire hydrological year and for the cold half of the year, then the last year corresponded to the high humidity of the warm period (HTC = 1.71), a large amount of precipitation in the cold period (355 mm) at slightly negative temperatures (OX = -1.3° C).

The smallest amount of moisture reserves in the soil was recorded in 2021, which was characterized by average amounts of heat and moisture for all periods, but a colder winter period. As a result, winter precipitation did not penetrate into the deep layers when the soil froze to a greater extent [9]. This situation is clearly visible from the analysis of spring soil moisture in various layers (Fig. 1b). The moisture content of the upper soil layer significantly exceeded the underlying ones $W_{0\text{-}30\ \text{cm}}$, (28.0%) > $W_{30\text{-}60\ \text{cm}}$ (23.0%) > $W_{60\ \text{-}100\text{cm}}$ (17.4%), while in years with large reserves the moisture distribution gradient had the reverse order $W_{60\ \text{-}100\text{cm}} > W_{30\text{-}60\ \text{cm}} > W_{0\text{-}30\ \text{cm}}$.

Table 2. Morphometric parameters of the relief, soil moisture by layers and reserves of productive moisture for the research period (2019-2023).

Indicator	Valid N	Mean	Minimum	Maximum	Std.Dev.	V, %
2019						
Azimuth, degrees	32	201	30	355	106	52.5
Slope, degrees	32	2.33	0.45	5.13	1.18	50.7
S/S_O	32	1.00	0.95	1.08	0.03	3.4
$W_{0\text{-}30\ \text{cm}}$, %	32	25.5	23.5	27.6	1.00	3.9
$W_{30\text{-}60\ \text{cm}}$, %	32	27.6	25.1	30.5	1.35	4.9
$W_{60\ \text{-}100\text{cm}}$, %	32	27.2	24.5	31.0	1.57	5.8
$ZW_{0\ \text{-}\ 100\ \text{cm}}$, mm	32	134	116	158	11.05	8.3
2020						
Azimuth, degrees	31	180	20	348	115	63.9
Slope, degrees	31	2.92	0.26	5.92	1.50	51.3
S/SO	31	1.00	0.92	1.06	0.04	4.0
W0-30 cm, %	31	26.8	23.0	28.5	1.32	4.9
W30-60 cm, %	31	26.2	23.7	28.6	1.26	4.8
W60 -100cm, %	31	24.5	20.8	27.8	1.76	7.2
ZW0 - 100 cm, mm	31	125	94	150	13.39	10.8
2021						
Azimuth, degrees	32	176	29	330	105	60.0
Slope, degrees	32	2.79	0.26	5.69	1.36	48.6
S/SO	32	1.00	0.93	1.07	0.04	3.9
W0-30 cm, %	32	28.0	24.9	30.7	1.42	5.1

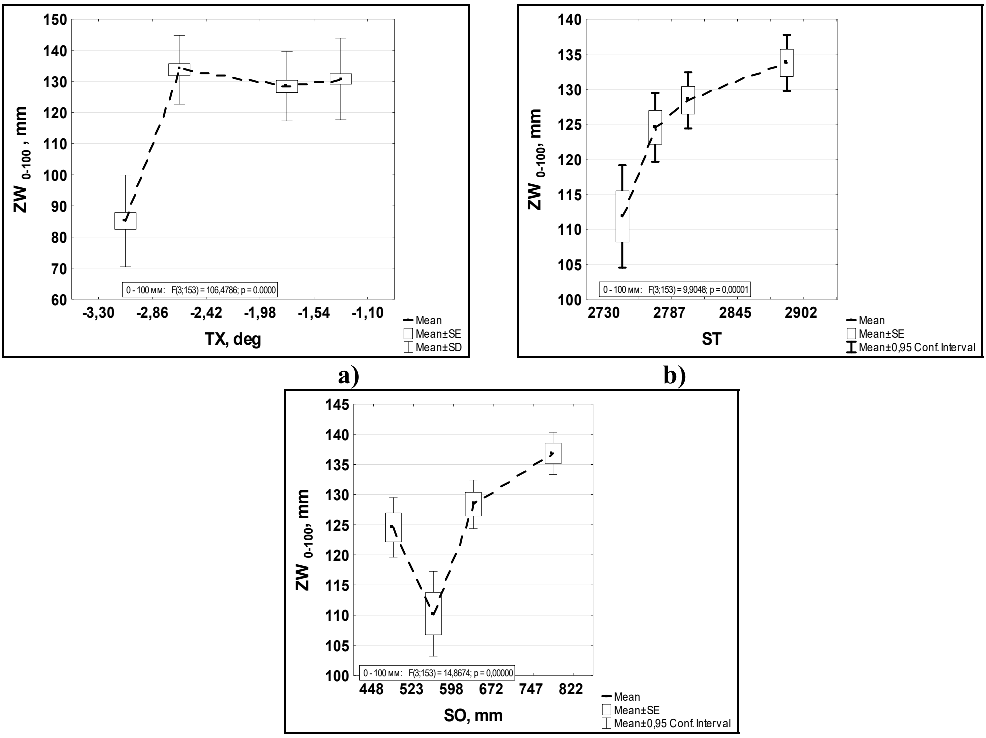
W30-60 cm, %	32	23.0	17.8	30.8	3.07	13.3
W60 -100cm, %	32	17.5	14.2	25.0	2.40	13.7
ZW0 - 100 cm, mm	32	85	61	111	14.73	17.3
2022						
Azimuth, degrees	32	177	25	338	105	59.0
Slope, degrees	32	2.31	0.25	4.21	1.08	46.8
S/SO	32	1.00	0.93	1.06	0.03	3.4
W0-30 cm, %	32	24.7	19.9	28.0	1.82	7.4
W30-60 cm, %	32	27.1	25.1	28.9	1.03	3.8
W60 -100cm, %	32	26.7	24.3	28.9	1.22	4.6
ZW0 - 100 cm, mm	32	128	106	148	11.11	8.7
2023						
Azimuth, degrees	32	176	14	327	107	60.7
Slope, degrees	32	2.25	0.31	5.26	1.31	58.1
S/SO	32	1.00	0.94	1.06	0.03	3.0
W0-30 cm, %	32	27.3	23.8	29.0	1.23	4.5
W30-60 cm, %	32	27.5	26.0	30.0	1.07	3.9
W60 -100cm, %	32	26.3	22.8	28.4	1.39	5.3
ZW0 - 100 cm, mm	32	137	115	156	9.70	7.1



a) b)

Fig. 1. Reserves of productive moisture in the 0 – 100 cm soil layer (a) and distribution of moisture among soil layers in different years (b).

Based on their influence on the accumulation of spring reserves of productive moisture and statistical significance, factors such as the temperature of the cold period for October-March (Tx), the sum of precipitation of the previous hydrological year (SO), the precipitation of the cold period for (Ox), the sum of active temperatures, the sum of active temperatures (ST) of the previous year (Fig. 2).

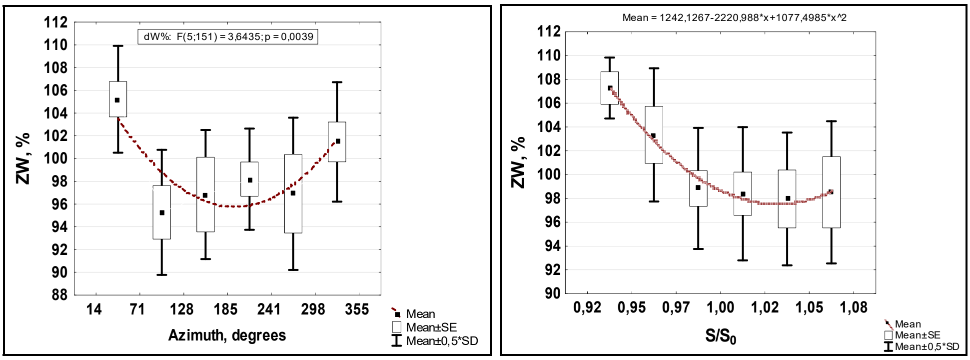


a) **b)**

c)

Fig. 2. Dependence of the territory's average reserves of productive moisture on the temperature of the cold period (a), the sum of active temperatures (b), the sum of precipitation of the previous hydrological year (c).

Analysis of spatial heterogeneity in the formation of productive moisture reserves on the territory of the object revealed that the soil of the northeastern slopes accumulated 100...115% of the moisture reserves relative to the watershed areas, while on the slopes of the southeastern and southwestern directions - on average 95...98 % (Fig. 3 a). The reserves of productive moisture noticeably decrease with increasing heat supply to the slopes (Fig. 3 b).



a) **b)**

Fig. 3. Dependence of the relative values of productive moisture reserves (%) on the direction of the slopes (a) and the heat supply values of the slopes (b).

Relief had the greatest influence on the differentiation of productive moisture reserves in years with the least potential for its accumulation: the variation in relative reserves was 8.3; 10.8; 17.3; 8.7 and 7.1%, respectively, according to the years of research. In this case, the greatest influence was exerted by the humidity of the upper 0 - 30 cm soil layer, the dependence of which on the relative heat supply was - R = 0.397; 0.535 and 0.470 in 2020, 2021 and 2022, respectively.

The complex influence of weather-climatic factors and relief conditions on the formation of spring reserves of productive moisture is reflected by multiple regression equations (Table 3). It has been established that the hydrothermal conditions of the warm half of the year have a significant impact on the moistening of various soil horizons in spring and, accordingly, on the formation of productive moisture reserves.

Table 3. Equations of the relationship between the content and reserves of moisture in various layers of soil from the factors under study.

Equation	R	F	P
Layer moisture 0-30 cm, %			
W0-30 = 78,7493 - 13,2329 S/S0 - 0,0148 ST - 4,0154 GTK - 0,2769 TX + 0,0245 OX	0.706	29.6	$<10^{-5}$
Layer moisture 30-60 cm, %			
W30-60 = -50,1391 + 0,027307 ST + 2,95161 GTK + 1,6327 TX	0.769	73.1	$<10^{-6}$
Layer moisture 60-100 cm, %			
W60-100 = -130,726 + 0,2271 SL + 0,0553 ST + 5,5958 GTK + 3,2275 TX	0.924	220.9	$<10^{-8}$
Productive moisture reserves in the layer 0 – 100 cm, mm			
ZW = -487,207 - 88,7527 S/S0 + 0,2466 ST + 18,4583 TX + 0,1795 OX	0.849	98.1	$<10^{-4}$
ZW= -495,284 - 81,7928 S/S0 + 0,2487 ST + 17,7985 TX + 0,0694 SO	0.856	103.1	$<10^{-4}$

ST – sum of active temperatures of the previous year (May-September);
GTK—hydrothermal coefficient of the previous year (May-September);
Tx – air temperature for the previous period (October – March), C°;
Ox – precipitation for the previous period (October – March), mm;
SO – total precipitation for the year (April – March), mm;
SL – slope, degrees;
S/S^0 – relative heat supply of slopes.

In general, during the study period, the influence of the considered factors on the formation of productive moisture reserves was characterized by the following hierarchy SL < S/S0 < GTK < OX < ST < TX (Table 4).

Table 4. Contribution of the studied factors (%) to changes in soil moisture by layer and reserves of productive moisture in the 0-100 cm layer in spring.

Parameters	$W_{0\text{-}30}$	$W_{30\text{-}60}$	$W_{60\text{-}100}$	$ZW_{0\text{-}100}$
SL	0	0	4	0
S/S0	11	0	0	6
ST	21	28	42	37
GTK	33	15	21	0
TX	5	22	33	38
OX	30	0	0	19

Changes in moisture reserves over time significantly exceeded the spatial differentiation in the agricultural landscape and were determined, first of all, by the temperature regime of the cold and warm periods of the hydrological year (37...38%), as well as the amount of precipitation in the same periods - 19%. This combination appears to be a feature of sloping lands. The influence of relief in these studies was formed by a combination of slopes and slope exposures, characterizing the microclimatic differences of individual locations.

4 Conclusion

Thus, for conditions of slope relief, the temperature of the cold hydrological half of the year is one of the main regulators of the formation of productive moisture reserves. With depth, the share of influence of this factor increases from 5 to 22 and 33% in layers 0-30 cm, 30-60 cm and 60-100 cm, respectively. An increase in temperature contributes to an increase in reserves of productive moisture by 17...18 mm per 1° C. With an increase in precipitation in the cold hydrological half-year for every 100 mm, reserves of productive moisture also increase by 18 mm. An increase in the temperature regime during the warm period by 100° of the sum of active temperatures increased spring soil moisture by 1.5 to 2.7 and 5.5% in layers 0-30 cm, 30-60 cm and 60-100 cm, respectively, which ensured a cumulative increase in reserves layer 0 – 100 cm by 25 mm. The influence of the hydrothermal regime provides a variation in time of spring moisture reserves of 18%, and the influence of the relief provides a variation in space of 10%. An increase in the relative heat supply of slopes by 10% helps reduce moisture reserves by 8...9 mm.

The work was carried out within the framework of the Statetasks of FSBSI «Federal Agricultural Kursk Research Center» on topic No. FGZU-2023-0001.

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