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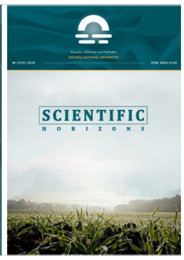

Efficiency of winter precipitation accumulation measures in climatic conditions of the North Kazakhstan region

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Abstract. The study aimed to establish the patterns of formation of soil water resources due to winter precipitation using various agrotechnical methods in the steppe zone. The research methodology included field trials of various agronomic backgrounds with and without snow retention, followed by analysis of winter precipitation accumulation, changes in soil water regime and spring wheat productivity. The average snow depth in the variants with snow retention increased by 26.6-32% compared to the control without snow retention. Soil moisture reserves before sowing increased by 27.1-31.6% on fallow land and by 16-30% on stubble plots. Winter precipitation assimilation was most efficient on stubble backgrounds, where the moisture increase ranged from 21.8 to 37.5% compared to the initial values. The yield of spring wheat in areas with snow

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retention exceeded the control figures by 0.15-0.47 t/ha, reaching maximum values of up to 2.76 t/ha on the backstage pairs. The correlation coefficient between total water consumption during the growing season and yield was 0.83, indicating a high influence of the water regime on productivity. The established relationship between the amount of moisture in the snow and yield was moderate, with a coefficient of 0.42, especially in stubble plots. The obtained results confirm the high efficiency of snow retention technologies for increasing the water supply of crops and the sustainability of yields in the steppe conditions of Northern Kazakhstan. Their use is recommended to optimise the system of agrotechnical measures in the face of increasing climate instability

Keywords: snow accumulation; soil moisture; snow retention; backstage steam; autumn tillage; yield

INTRODUCTION

Global climate change, manifested in higher average winter temperatures, changes in the structure and volume of atmospheric precipitation, reduced snow cover and more frequent droughts, are significantly transforming hydrological processes in the agricultural landscapes of arid and semi-arid regions, including Northern Kazakhstan, where a high proportion of the annual water balance is formed by winter precipitation, while the decline in snow resources and temperature instability pose significant risks to the sustainability of agricultural productivity. The loss of winter moisture necessitates the development and implementation of effective agrotechnical measures aimed at optimising the accumulation and retention of snowfall on fields. This task is particularly important in the context of ensuring the resilience of agricultural production systems to climate change and the adaptation of agriculture to new hydrothermal conditions.

Changes in snow cover and winter precipitation vary significantly depending on the climatic conditions of different regions of the world (Shahini, 2024). In Asian mountain systems, according to P. Kraaijenbrink *et al.* (2021), a decrease in snow moisture threatens the sustainability of water supply, especially in the face of rising temperatures. The study by Y. Qin *et al.* (2020) noted an increase in agricultural risks as a result of disruptions in snowmelt in areas dependent on snow resources. In northeastern China, as shown by M. Pan *et al.* (2022), a decrease in snow cover thickness leads to a decrease in soil moisture content in spring, which negatively affects the initial phases of crop growth. In European mountainous regions, according to P. Ebner *et al.* (2021), effective management of snow resources is becoming a key element of adaptive agricultural strategies in the face of climate instability. In Northern Kazakhstan, climate change is particularly acute, posing significant risks to the sustainability of agricultural ecosystems (Oshergina & Ten, 2023). As shown in the study by V. Salnikov *et al.* (2023), since the beginning of the 21st century, the region has seen a steady trend of increasing winter temperatures and decreasing total precipitation, which leads to a deterioration in the accumulation of snow moisture. M. Karatayev *et al.* (2022) highlighted that the instability of winter moisture increases the risk of spring droughts, which have a critical impact on the productivity of cereals, especially wheat. These changes necessitate a review of traditional agricultural practices to optimise the accumulation of winter precipitation and stabilise the water balance of arable land.

Adaptation of agricultural systems to changes in the winter water regime remains one of the least developed problems in modern agroclimatic research (Chabaniuk *et al.*, 2024). The high degree of vulnerability of agricultural production to changes in temperature and winter precipitation regimes was established in the study by A. Islyami *et al.* (2020), emphasising the insufficient development of adaptation scenarios that consider the specifics of snow moisture. A significant contribution to the development of spatial planning methodology was made by S. Baisholanov *et al.* (2024), proposing an agroclimatic zonal classification that integrates the impact of winter precipitation into the system for assessing the adaptive potential of agricultural land. Despite this, comprehensive models focused on optimising snow retention as one of the key factors in stabilising spring water availability remain underdeveloped. Optimisation of snowfall management methods to increase spring soil moisture remains one of the insufficiently studied areas of agrotechnical research (Pavlova & Litvinov, 2024). Increase in the content of organic matter in the soil is considered a promising direction, which contributes to an increase in its water-holding capacity and more efficient use of winter moisture, as confirmed by the results of numerical modelling presented in M. Feifel *et al.* (2024). An integrated approach to assessing the impact of different tillage technologies on seasonal moisture dynamics was first implemented by G. Blanchy *et al.* (2020) using geophysical survey methods, which revealed a high spatial heterogeneity of moisture distribution.

Despite the existence of studies on climate change and agronomic approaches to snow resource management, complex snow retention models and their impact on spring water supply in steppe agricultural landscapes are still insufficiently studied. The study aimed to evaluate the effectiveness of various agronomic backgrounds and snow retention technologies in ensuring the accumulation of winter moisture and its subsequent impact on the soil water regime.

MATERIALS AND METHODS

Experiment object and conditions. The field experiment was conducted in 2021-2024 at the experimental station of the North Kazakhstan Agricultural Experimental Station located in the steppe zone of northern Kazakhstan. The region was chosen due to a sharply continental climate, winter precipitation plays a key role in shaping the annual water balance, and the level of water availability in the spring is critical for the sustainability of crop yields. The study covered the winter period (November-March), during which snow cover and moisture accumulation dynamics were monitored, as well as the 2022-2024 growing seasons (May-August), including spring wheat sowing, development and harvesting. The object of the research was agronomic systems of soil preparation and snow retention aimed at regulating the water regime in the cold season. Fallow fields with flat-cut, minimal and zero tillage, backstage fallow, stubble plots after peas, spring wheat and oilseed rape, as well as autumn ploughing on grain stubble, were studied. Each background was studied in two variants: with and without mechanised snow retention. To evaluate the influence of water regime on productivity, spring wheat (*Triticum aestivum* L.), the most widespread and economically important crop in the region, was used, which is highly sensitive to moisture availability. Sowing was conducted in the third decade of May when the soil reached optimum physical maturity. Yields were measured on 50 m^2 plots in triplicate using the direct weighing method with the grain brought to standard moisture content (14%). Field studies in 2022-2024 were combined with an analysis of the dynamics of the soil water regime and accumulation of solid precipitation.

Characteristics of the soil and climatic conditions of the experimental plot. Characteristics of soil and climatic conditions of the experimental site. The climate of the experimental station is characterised by sharply continental conditions with a pronounced seasonal temperature amplitude and moderately low precipitation. The average annual amount of solid precipitation for the period November-March is 89 mm with an average air temperature of -12.5°C. The hydrothermal coefficient for the winter period is 0.85, indicating a deficit water regime (Kazhydromet, 2024). The soils of the site are carbonate-heavy loamy chornozems of medium power profile with neutral or slightly alkaline reaction (pH 7.2-8) and humus content of 4.5-5%. The mechanical composition is characterised by a predominance of fine particles. The relief is flat, with shallow closed depressions and the absence of forests, which contributes to the intensification of wind processes and affects snow accumulation conditions.

Methods of observation and analysis. Observations of snow cover were carried out following international standards set out in the World Meteorological Organisation (2024). Snow gauge surveys were carried out three times during the winter: in the third decade of December, in the first decade of February and before the snow melt in the second decade of March. At each stage, the snow cover height and water equivalent of precipitation were recorded using standard snow gauges and stratified transects to estimate snow density. The research covered agrotechnical backgrounds with mechanised snow retention (flat-cutting, minimal, zero, stubble plots after peas, wheat and flax, autumn tillage) and control plots without snow retention (flat-cutting, wheat stubble after peas, autumn tillage, backstage steam). For a comprehensive assessment of the water regime, the pre-winter soil moisture reserves, the moisture reserves in the snow at the time of melting and the moisture reserves before sowing were determined based on gravimetric measurements and the calculation of the water equivalent of snow. Winter precipitation absorption was calculated as the ratio of soil moisture gain to the water content of the snow cover, incorporating the initial moisture content. Soil moisture was determined by the gravimetric method with samples dried to a constant weight at a temperature of 105 ± 5°C following the recommendations of the Food and Agriculture Organisation (2020).

Statistical processing of the results was performed using one-way and two-way analysis of variance (ANOVA) with Microsoft Excel and Statistica 10. The reliability of differences between variants was assessed at a significance level of $p < 0.05$. Mean values, standard deviations and confidence intervals were calculated for all indicators. Correlation analysis included the calculation of pair coefficients (r) to assess the relationships between pre-winter moisture reserves, moisture reserves in snow and precipitation assimilation. The coefficients were interpreted using the Chaddock scale: $r = 0.5 - 0.7$ – moderate correlation, $r > 0.7$ – strong correlation. The research conducted complies with current ethical standards aimed at adhering to the principles of environmental responsibility when working with elements of agroecosystems. Agricultural practices used in the field experiments were in line with sustainable agriculture standards and did not harm biodiversity, soil structure or the environment. The research methodology correlated with the provisions of the Convention on Biological Diversity (1992), which regulates the principles of sustainable use of ecosystem components and conservation of agrobiodiversity.

RESULTS AND DISCUSSION

Meteorological conditions for the study period 2021-2024. During the 2021-2024 winter seasons in Northern Kazakhstan, there was a pronounced interannual variability in meteorological conditions, including the amount of precipitation and temperature. The data obtained showed both years with a deficit of precipitation relative to the average annual norms and seasons with a significant excess, which led to differences in the dynamics of snow moisture accumulation and potential water availability for agricultural land in spring. For a more detailed analysis, the total precipitation and average monthly temperatures for each winter period of the study are presented (Table 1).

***Table 1**. Meteorological indicators for the winter period, 2021-2024*

Year	Month	Metric		Year	Month	Metric	
		Precipitation, mm	Temperature, °C			Precipitation, mm	Temperature, °C
2021-2022	November	16.8	-7.1	2023-2024	November	74.4	-1.1
	December	17.6	-10.7		December	44.5	-14.2
	January	17.2	-14.4		January	31.6	-16.5
	February	3.8	-12.3		February	8.8	-16.3
	March	8.4	-9.2		March	12.6	-7.2
	Over the winter	63.8	-10.7		Over the winter	171.9	-11.1
	Average perennial	89	-12.5		Average perennial	89	-12.5
	+/- to the long-term average	-25.2	1.8		+/- to the long-term average	82.9	1.4
2022-2023	November	45.7	-8.4	Average (for 3 years)	November	45.6	-5.5
	December	10.7	-15.7		December	24.3	-13.5
	January	21.6	-13.5		January	23.5	-14.8
	February	16	-13.3		February	9.5	-14
	March	28	-3		March	16.3	-6.5
	Over the winter	122	-10.8		Over the winter	119.2	-10.9
	Average perennial	89	-12.5		Average perennial	89	-12.5
	+/- to the long-term average	+33	1.7		+/- to the long-term average	30.2	1.6

***Source:** compiled by the authors*

The obtained meteorological data for the winter periods of 2021-2024 indicate a pronounced interannual instability of moisture conditions, manifested in the alternation of seasons with a deficit and excess of solid precipitation. In 2021-2022, the amount of precipitation was 63.8 mm, which is 25.2 mm below the average annual norm (89 mm), indicating a deterioration in snow moisture accumulation and a potential decrease in water supply to agricultural land in the spring. In contrast, in the winter seasons of 2022-2023 and especially 2023-2024, the above-normal precipitation was recorded by 33 mm and 82.9 mm, respectively, which creates the preconditions for an increase in soil moisture reserves. Along with changes in precipitation, the 1.6°C increase in winter temperatures over the three years of the study increases the risk of premature snow melting and a shorter period of snow accumulation, which requires a new approach to the traditional timing of snow retention measures.

The tendency for winter moisture instability and an increase in average temperatures identified in the study is consistent with the results of W. Qi *et al.* (2020), which emphasises the crucial role of snow cover as a natural moisture accumulator, especially in agricultural ecosystems with a short spring growing season. Under conditions of insufficient accumulation of winter precipitation, as shown in this study for 2021-2022, the risk of moisture deficit in the early phases of crop growth increases significantly. The results of a study by G. Wilson *et al.* (2020) confirmed that even with an increase in total precipitation, changes in the physical structure of the snowpack and acceleration of melting processes are possible, which is also reflected in the recorded increase in average winter temperatures. These changes can lead to a decrease in the efficiency of the natural moisture reserve and an increase in the need for agronomic measures to preserve it.

The recorded fluctuations in the water regime were accompanied not only by a decrease in total moisture reserves in years with a deficit of precipitation, but also by the risk of premature snowmelt in seasons with increased precipitation, indicating instability of moisture accumulation processes. These results are comparable to the global trends of increasing snow drought described by M. Cowherd *et al.* (2023), which emphasise the need for agroecosystems to adapt to increasing climate instability. Additionally, the dependence of snowmelt rates on rising winter temperatures identified in the study is fully consistent with the findings of M. Meira Neto *et al.* (2020), demonstrating an increase in the sensitivity of hydrological processes to changes in snow cover characteristics. In the light of the data obtained on the threat of loss of stored moisture, the development of effective snow retention systems becomes a reasonable task, which is also confirmed by the results of Y. Xing and X. Wang (2024), who emphasise the importance of water-saving agricultural strategies to ensure the sustainability of agricultural production in the face of increasing climate risks. The fluctuations in winter precipitation recorded during the study period, from a deficit in 2021-2022 to an abnormal excess in 2023-2024, accompanied by a steady increase in average winter temperatures by 1.6°C above normal, indicate an increasing instability of the winter water regime. The established variability of snow moisture accumulation and the risk of its premature melting underline the need to improve snow retention technologies and adapt agricultural practices to new climatic conditions to ensure a sustainable soil water balance in spring.

Snow accumulation dynamics in winter. According to 1 snow accumulation measurement carried out in the third decade of December, 7.4 cm of snow was accumulated on the flat-cutting pair without snow retention, and moisture reserves amounted to 33.7 mm. At the same time, 14.9-16.3 cm of snow (+50.3-54.6%) was accumulated on the flat-cutting, minimum and zero tines with snow retention, and moisture reserves were 41.9-50.5 mm (+19.6-33.2%). The coulisse pair accumulated the maximum amount of solid precipitation of 20.6 cm, with moisture reserves of 59.7 mm (+43.5% of the flat-cutting pair), which is at the level of stubble of grain crops with snow retention. The difference was less pronounced in the context of the autumn tillage, with snow depth of 11.5 cm in the background of the autumn tillage without snow retention and moisture reserves of 40 mm, the increase in snow depth from snow retention was +5.3 cm (31.5%) and moisture reserves +5.9 mm (12.8%). The minimum efficiency at this stage was recorded for stubble backgrounds. Thus, when the snow depth and moisture reserves on wheat stubble without snow retention were 15.9 cm and 45.6 mm, the effect of snow retention provided an increase of 2.8-4.2 cm in height (+15-20.9%) and 4.7-8.7 mm in moisture (+9.3-16%). The dynamics of snow accumulation during the winter period by experimental variants are presented in Table 2.

***Table 2**. Dynamics of snow accumulation during the winter period in different agronomic backgrounds (November-March), average 2021-2024*

No.	Agricultural context	Height, cm	Water reserve in snow, mm	Height, cm	Water reserve in snow, mm	Height, cm	Water reserve in snow, mm
		1st measurement		2nd measurement		3rd measurement (before melting)	
		Snow retention					
1	Flat cutter steam	14.9	41.9	17	48.6	20.3	61.2
2	Minimal steam	15.3	48.9	18.3	55.3	22	66.1
3	No steam	16.3	50.5	19.9	59.9	22.9	68.8
4	Peas (on grain stubble)	16.5	50.6	19.9	62.7	23.1	73.5
5	Wheat (over pea stubble)	20.1	54.3	23.2	64.7	25.8	76.2
6	Wheat (on flax stubble)	18.7	50.3	21.5	62.8	24.2	69.5
7	flax (on grain stubble)	15.6	45.5	19.5	58.3	22.7	68.3
8	Crop stubble (grain stubble)	16.8	45.9	19.5	62.2	21.8	68.8
		Without snow retention (control)					
9	Flat cutter steam	7.4	33.7	8.7	34.7	9.5	37.3
10	Wheat (over pea stubble)	15.9	45.6	17.6	53	19	57
11	Crop stubble (grain stubble)	11.5	40	13.1	44.2	14.3	46.4
12	Backstage steam	20.6	59.7	26.6	69.8	30.3	85.7

***Source:** compiled by the authors*

The high amount of precipitation in the first half of winter (November, December, January) had a significant impact on snow accumulation by the time of the 2nd interim measurement in the first decade of February. According to the results of these measurements, there was an increase in water reserves in the snowpack by 16.1-22% for stubble backgrounds with snow retention, and only 14% for stubble backgrounds without snow retention, compared to the first accounting. Snow accumulation on fallow plots with snow retention amounted to 11.6-15.7% by the first accounting (exceeding the control by 8.7-12.8%), and on wedge fallow by 14.5% (exceeding the control by 11.6%). A high increase was noted on the backgrounds with autumn tillage, where the effect of snow retention provided an increase in moisture reserves of 26.2%, with an excess of 16.7% over the control.

According to the final record of solid precipitation, by the time of thawing in the second decade of March, high moisture reserves were noted on the background with snow retention and on the backstage steam. Thus, the increase in snow depth and water reserves in the steam plots, by the first accounting, is within the following limits: flat-cutting steam without snow retention (control) by 2.1 cm (+22.1%), and moisture by 3.6 mm (+9.7%), while for flat-cutting, minimal and zero pairs with snow retention by 5.4-6.7 cm (+26.6-30.5%), and by 17.2-19.3 mm (+26-31.5%) of accumulated moisture. The maximum efficiency of snow accumulation was observed on stubble backgrounds and autumn tillage with snow retention, as well as on the backdrop. Thus, the early winter tillage with snow retention additionally accumulated +5 cm (23%) of height and +22.9 mm (33.3%) of moisture, while the control showed an increase in height of 19.6% and moisture reserves of 13.8%. On the stubble of spring wheat, depending on the predecessor, 24.2-25.8 cm (+22.1-22.7%) and 69.5-76.2 mm of reserves (+27.6-28.7%) were accumulated, while the control showed an increase of 16% in height and 20% in moisture. On the stubble of legumes and oilseeds, the increase is also within the stubble background with snow retention, +28.6-31.3% in height, and +31.2-33.4% in moisture reserves. In the case of the wings, with a maximum snow layer height of 30.3 cm, the increase was 32%, while the moisture reserves increased by 30.3%.

The effectiveness of snow retention according to the results of snow accumulation assessment is expressed by an excess of moisture content by 16.5-25.2% on stubble backgrounds, by 32.6% on early winter crops, and by 39.1-45.8% on fallow plots, compared to plots without snow retention. This proves the extreme need for snow "reclamation", regardless of the year, accumulating almost all the transported snow. Long-term research by the North Kazakhstan Agricultural Experimental Station in this area shows that in the open steppe, on untouched backgrounds, no more than 50-60% of the total snowfall is retained by grain stubble and 30-40% by corn residues. In terms of moisture content, the black fallow exceeds the black fallow without snow retention by 56.5%, and the fallow with snow retention by 19.7-28.6%, which, based on 3 years of data, makes this type of fallow highly efficient in accumulating solid precipitation, both in winters with little snow (season 2022) and winters with medium and high precipitation (seasons 2023, 2024).

The results of the three-year monitoring of snow accumulation dynamics showed that the use of snow retention technologies provides a significant increase in soil moisture reserves by the time of spring thaw. The highest level of solid precipitation accumulation was recorded on the background of the winged plough, where the snow cover reached 30.3 cm and moisture reserves were 85.7 mm, which was 56.5% higher than on the flat-cutting plough without snow retention. These data emphasise the critical role of effective snow accumulation for water resources formation, which correlates with the conclusions of D. Molden *et al.* (2022), emphasising the importance of snowfall as the main source of water supply for water systems in Asian steppes and mountainous regions. Similarly, the study by G. Mezősi (2022) noted that disruptions in snow cover structure due to climate change significantly increase the risk of water shortages during spring vegetation growth, which is consistent with the trend identified in this study of the need for targeted management of winter precipitation.

Comparative assessment of agrotechnical backgrounds showed that systematic snow retention increases the efficiency of moisture accumulation not only on fallow plots, but also on stubble backgrounds. The water reserves in the snow cover on variants with snow retention exceeded the control values by 16.5-45.8%, depending on the agro-background and winter conditions. These results correlate with the findings of A. Canet-Martí *et al.* (2023) determined that minimum tillage methods and the preservation of crop residues contribute to improving the water balance in agroecosystems by increasing the water-holding capacity of the field. Similar trends were also identified by R. Amami *et al.* (2021), where the effectiveness of soil surface management techniques was directly correlated with an increase in water permeability and moisture accumulation in the profile, which confirms the validity of using snow retention as an element of adaptive farming technology in Northern Kazakhstan.

Additionally, the tendency for earlier snowmelt in areas without snow retention identified in the study correlates with the Q data. According to Q. Fu *et al.* (2015), the thermal interaction of snow and soil in conditions of insufficient snow accumulation leads to accelerated evaporation processes and reduced soil moisture recharge in the transitional winter-spring period. This further emphasises the importance of not only accumulating but also retaining snowfall to maintain the stability of the water regime of agricultural land in a changing climate. Thus, according to the results of the summary assessment of snow accumulation over the 3-year observation period, the highest amount of precipitation during the winter period, as well as its uniform accumulation, was noted for wing steam 85.7 mm, with a snow depth of 30.3 cm, wheat stubble over peas 76.2 mm, with a height of 25.8 cm, and pea stubble over wheat 73.5 mm, with a height of 23.1 cm (Fig. 1).

The minimum effect of snow accumulation was recorded on the pair of flat-cutting and fallow backgrounds without snow retention, where moisture reserves amounted to 37.3-46.4 mm (snow depth 9.5-14.3 cm), with most of the accumulated precipitation formed in early winter, by the time of the first accounting, up to 86-90%, and further had a weak accumulative effect by the end of the winter period. The monitoring results showed that the use of snow retention technologies provides a significant increase in soil moisture reserves regardless of variations in winter conditions. The highest efficiency in accumulating solid precipitation was demonstrated by the wing steam and stubble backgrounds with snow retention, which is confirmed by both quantitative indicators of snow cover and water equivalent and their stable dynamics during the winter period. The identified patterns emphasise the need for widespread implementation of snow retention measures to stabilise the water balance of arable land in the face of climate instability and the growing risk of spring moisture deficit.

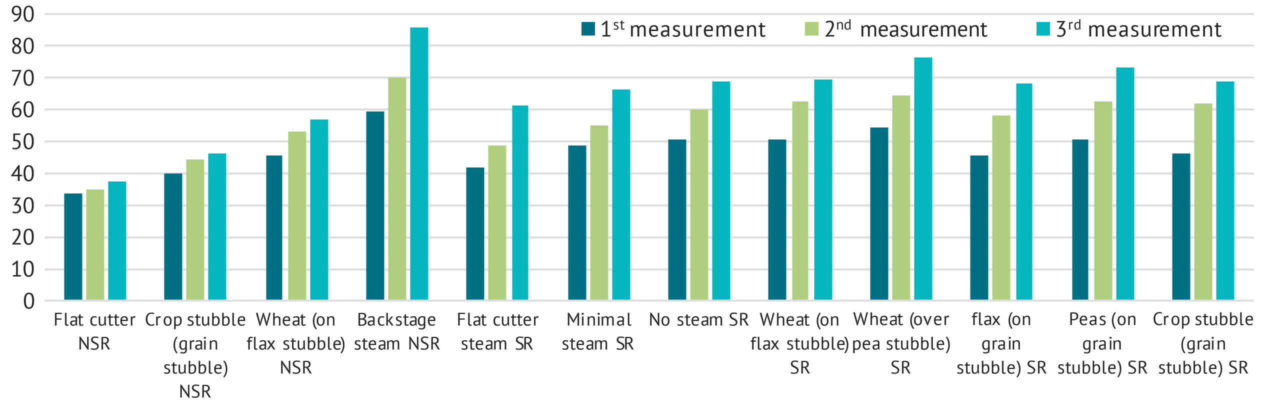

***Figure 1**. Dynamics of accumulation of moisture reserves in snow on different agrotechnical backgrounds based on the results of 3 measurements*

***Note:** NSR – no snow retention; SR – snow retention*

***Source:** compiled by the authors*

Impact of winter precipitation on soil moisture reserves. The main reasons for the difference in rainfall absorption, both by year and by crop rotation predecessors, are significant differences in the initial soil moisture reserves and the amount of precipitation during the period under consideration. The moisture content of the soil has a significant impact on the absorption of precipitation by the soil. In most cases, fields with lower moisture reserves in autumn experience more intensive moisture absorption and accumulation during snowmelt. In October-April, the average absorption of precipitation by the one-metre layer of soil for different predecessors in crop rotations ranged from 43.6 to 53.5%. According to the results of observations, the content of pre-winter moisture reserves in the soil was high and ranged from 74.2 mm (flax stubble) to 148.7 mm (zero fallow). At the same time, the maximum moisture content was recorded in the fallow plots at 117.2-148.7 mm, exceeding the stubble background by 36.7-41.4% (Table 3).

***Table 3**. Soil moisture balance by the sowing period, incorporating pre-winter moisture and moisture reserves in snow, average 2022-2024*

No.	Agricultural context	Snow retention	Pre-winter soil moisture reserves, mm	Moisture reserves in snow (by the time of melting), mm	+/- to control conditions, %	Moisture reserves in the soil before sowing, mm	Utilisation of winter precipitation, %
1	Flat cutter steam (control)	-	134.1	37.3	-	103.4	0
2	Wheat stubble (control)	-	79.7	57	-	88.7	10.2
3	Crop stubble (grain stubble) (control)	-	86	46.4	-	72.9	0
4	Backstage steam	-	117.2	85.7	+130	145.2	19.3
5	Flat cutter steam	+	134.1	61.2	+64	141.9	5.5
6	Minimal steam	+	141.1	66.1	+77	148.3	5
7	No steam	+	148.7	68.8	+84	151.3	2
8	Peas (on grain stubble)	+	87.2	73.5	+28	113.7	23.3
9	Wheat (over pea stubble)	+	79.7	76.2	+34	127.5	37.5
10	Wheat (on flax stubble)	+	83.2	69.5	+18	106.4	21.8
11	flax (on grain stubble)	+	74.2	68.3	+20	109.6	32.3
12	Crop stubble (grain stubble)	+	86	68.8	+48	106.3	19.1
	$LSD_{0.95}$			3.28			

***Source:** compiled by the authors*

In addition, to assess the soil moisture balance, the table shows data on the moisture reserves in snow at the time of melting (actual accumulated precipitation in snow over the winter period). Thus, on average, the variants of snow accumulation technology accumulated 20-130% more moisture on different backgrounds compared to the control variants. For steam backgrounds, the maximum effect was noted for the backstage steam +130% compared to the control (flat-cutting steam without snow retention), and for the zero steam +84% compared to the control (flat-cutting steam without snow retention). For stubble backgrounds, the difference is much lower, given the relatively high moisture reserves in the wheat stubble control without snow retention. At the same time, the maximum effect of snow retention was observed for stubble of wheat after peas +34%, and stubble of peas after grain +28% compared to the control. The effectiveness of snow retention on the background of early winter stubble was expressed by an increase in snow moisture of +48% compared to the control (winter stubble without snow retention).

The use of snow accumulation measures, such as snow retention, leaving high stubble, sowing wings, etc., achieved a snow layer thickness of up to 35-40 cm. As a result of better snow accumulation, soil moisture reserves increase by 30-50 mm by the beginning of sowing, and spring wheat yields increase by 1.9-2.2 c/ha. Thus, according to this study, the moisture reserves before sowing were in the range of 103.4-151.3 mm on fallow plots, with the excess of fallow plots with snow retention (flat-cut, minimal, zero) being 38.5-47.9 mm (+27.1-31.6%), and the excess of wing fallow by 41.8 mm (+28.8%) compared to the control (flat-cut fallow without snow retention). On stubble backgrounds, the increase in moisture reserves for sowing is much lower, with an indicator of 88.7 mm on the control (wheat stubble without snow retention), 17.7-38.8 mm (16-30%) on grain stubble with snow retention, and 20.9-25 mm (19-22%) on oilseeds and legumes. In the context of early winter with snow retention, the increase was 33.4 mm, or 31%, compared to the control (winter without snow retention).

Incorporating the content of pre-winter moisture reserves in the soil, as well as the actual moisture content in the soil by the time of sowing, it is possible to calculate the proportion of winter precipitation absorption, depending on the agrotechnical background. According to the results obtained, a zero or even negative balance was observed on the backgrounds of stubble-free flat-cut, winter tillage pairs without snow retention. At the same time, the stubble background without snow retention has a certain increase, within 10.2%, provided by the accumulation of snow to the height of the stubble left in autumn. The minimum effect was observed in the follow-up plots, with snow retention not exceeding 2-5.5%, mainly due to high pre-winter moisture. The exception is the wing follow, with a level of winter precipitation absorption of 19.3%, obtained due to higher moisture reserves in snow and lower pre-winter moisture. Thus, according to the results of average annual observations, this type of steam provides equal moisture reserves for the sowing period, with zero and minimal steam having a stubble background during the entire period of moisture accumulation, and additional snow retention in winter. The maximum efficiency of winter precipitation assimilation was observed on stubble backgrounds with snow retention, for stubble of cereals 21.8-37.5%, legumes and oilseeds 23.3-32.3%, and early winter crops 19.1%, which indicates the urgent need for annual snow accumulation measures on these backgrounds.

Determination of correlations between pre-winter soil moisture reserves, snow moisture reserves at the time of melting and winter precipitation assimilation established distinct patterns of water regime. The high direct correlation coefficient between the moisture reserves in snow and the level of precipitation absorption ($r = 0.67$) indicates the leading role of winter precipitation in replenishing productive moisture, with insufficient autumn moisture. At the same time, an inverse relationship was found between the initial soil moisture in autumn and the absorption of snow water ($r = -0.65$), which reflects a decrease in the water absorption capacity of waterlogged soils. These results are consistent with the hydrophysical features of the soil profile structure, where saturation of the upper horizons limits further moisture penetration during snowmelt. Assessment of the degree of influence of both factors on the final water balance by the sowing period showed the presence of significant correlations of medium and high strength ($r = 0.57 - 0.66$), which emphasises the complex nature of moisture accumulation processes. Thus, improving snow retention efficiency is only possible with an integrated approach that takes into account the initial level of pre-winter soil moisture. In the steppe zone of Northern Kazakhstan, optimisation of agrotechnical measures to regulate the water regime, including both snow accumulation and control of autumn moisture reserves, is a necessary condition for stabilising crop productivity in the context of changing climatic conditions.

The analysis of the data obtained showed that the effect of winter precipitation on the water regime of arable land varied significantly depending on the agronomic background and pre-winter moisture reserves. According to the observations, on backgrounds with high pre-winter moisture (vapour), the absorption of winter precipitation was minimal (2-5.5%), while on stubble plots with snow retention, the absorption efficiency reached 21.8-37.5%. These results correlate with the findings of W. Yan *et al.* (2021), determining that under conditions of different soil cover and crop residue structure, the soil response to winter precipitation varies significantly, with surfaces with crop residues providing more efficient moisture accumulation. The role of pre-winter moisture reserves in determining the efficiency of precipitation absorption was indicated by the study by J. Martínez-Fernández *et al.* (2021), which emphasises the effect of soil "memory": the higher the moisture content before the start of winter, the lower the subsequent absorption of precipitation. This pattern was reflected in the present study, which found an inverse correlation between the level of autumn moisture and winter moisture uptake (r = -0.65), which is consistent with the concept of reducing the water absorption potential of waterlogged horizons. The role of winter precipitation accumulation in the water balance is confirmed by F. Avanzi *et al.* (2021), demonstrating that an accurate assessment of the winter precipitation regime (especially snow characteristics) is critical for predicting water storage. The present study revealed a similar trend: fields with effective snow retention accumulated up to 130% more moisture in the snow cover compared to control plots.

The results of the comparative analysis of agronomic practices showed that the wagon steam and stubble backgrounds with snow retention provided the highest moisture reserves by the sowing period. These results correlate with the data of A. Rucins *et al.* (2024), where long-term studies on chornozems confirmed the effectiveness of mulching and minimal tillage in stabilising spring moisture reserves. A significant increase in moisture by 30-50 mm, provided by snow retention measures, is critically important for agroecosystems in arid regions. A comprehensive analysis of the dynamics of snow accumulation and moisture uptake presented by B. Dafflon *et al.* (2023) confirmed that the structure of the vegetation cover determines both the rate of snowmelt and the amount of available soil moisture in spring. Incorporating the identified patterns, optimisation of agrotechnical measures to manage winter precipitation, including the introduction of snow retention and preservation of plant residues, is considered a priority area for adaptation of agriculture to climate risks, which correlates with the findings of A. Demo and G. Asefa Bogale (2024) on the need to integrate water-saving technologies.

The analysis of the impact of agronomic measures on the dynamics of winter precipitation and soil moisture reserves showed the high efficiency of snow retention technologies on different backgrounds. The use of mechanised snow retention on fallow and stubble plots provided a significant increase in spring moisture reserves, which confirms the critical role of snow management in stabilising the soil water regime. The established correlation between the structure of plant residues and the efficiency of precipitation absorption underlines the need to integrate snow cover preservation technologies into adaptive farming practices. The results demonstrate that optimisation of winter water management methods is one of the keyways to increase the resilience of agroecosystems in the context of increasing climate risks. The data presented form the basis for further improvement of agrotechnical solutions aimed at stabilising the water balance of arable land in the steppe regions.

Influence of water regime on spring wheat productivity. The determining effect of moisture accumulation in winter is its impact on the final productivity of crops. According to the research results, the yield of spring wheat on backgrounds without snow accumulation was in the range of 1.74-2.29 t/ha, while snow accumulation measures increased productivity to 1.95-2.76 t/ha, with an increase of 0.15-0.47 t/ha on backgrounds (or +11-17%). The maximum yield increase was obtained in the fallow plots, within the range of 0.28 (zero fallow) to 0.47 t/ha (backstage fallow), as well as in the autumn tillage +0.38 t/ha (Table 4).

***Table 4**. Influence of water regime on spring wheat productivity depending on agronomic backgrounds, average for 2022-2024*

No.	Agricultural context	Snow retention	Moisture reserves in the soil before sowing, mm	Moisture reserves before cleaning, mm	Moisture consumption during the growing season, mm*	Spring wheat yield, t/ha	Increase in control, t/ha
1	Flat cutter steam (control)	-	103.4	55	256.4	2.29	-
2	Autumn tillage (control)	-	72.9	47.5	233.4	1.74	-
3	Backstage steam	-	145.2	61.8	291.4	2.76	0.47
4	Flat cutter steam	+	141.9	56.2	293.7	2.62	0.33
5	Minimal steam	+	148.3	67.5	288.8	2.68	0.39
6	No steam	+	151.3	71.6	287.7	2.57	0.28
7	Autumn tillage	+	106.3	53.6	260.7	2.12	0.38

***Note:** moisture consumption during the growing season is calculated covering the total precipitation in May-August (average 208 mm in 2022-2024)*
***Source:** compiled by the authors*

The average yield increase was significantly influenced by high precipitation during the growing season of 2022-2024, and it is logical to assume that with a decrease in the supply of precipitation during the growing season, the effectiveness of snow storage measures will increase by a multiple. The average moisture consumption during the growing season required for the formation of spring wheat yields was in the range of 233.4-293.7 mm. According to studies of winter precipitation conservation on the Great Plains, economically viable spring wheat production required an annual withdrawal of about 250-400 mm of water from the soil. At the same time, high moisture consumption rates were observed on steamy plots of 287.7-293.7 mm, which naturally affects the maximum yield in these areas. The increase in moisture consumption on the backgrounds with snow retention is in the range of 31.3-37.3 mm (+12.2-14.5%) on fallow plots, by 17.5-33.1 mm (+7.2-13.6%) on stubble plots, compared to plots without snow accumulation measures.

Assessment of the influence of the factors of the amount of moisture in the snow during the winter period and moisture consumption during the growing season on the final yield of spring wheat shows that the total moisture consumption during the growing season directly affects the formation of yield, while the amount of water in the snow correlates with the yield to a lesser extent, especially for stubble backgrounds (variants 8-12), where high water content in the snow has little effect on increasing productivity (Fig. 2).

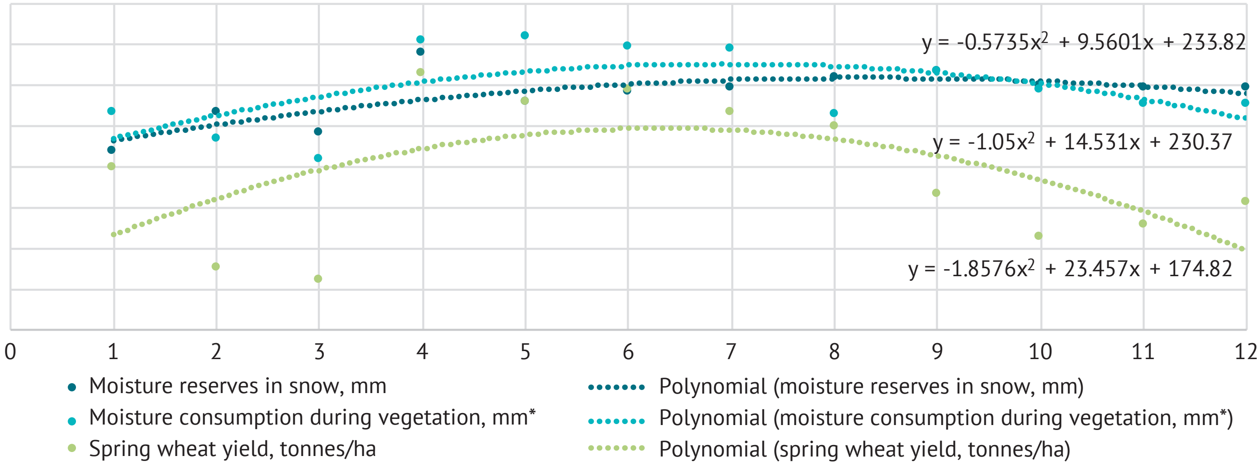

***Figure 2**. Relationship of spring wheat yield with the amount of moisture in snow and total moisture consumption during the growing season*

***Source:** compiled by the authors*

The correlation assessment of the data also confirms the obtained dynamics. Thus, the closeness of the correlation between the total moisture consumption during the growing season and productivity is 0.83, which, according to the Chaddock scale, corresponds to a high level of dependence, while the closeness of the relationship between the amount of water in the snow and productivity is 0.42, which corresponds to a moderate level of dependence. The assessment of the impact of water regime on spring wheat yield is consistent with the results of other studies. Thus, according to L. Kiewiet *et al.* (2022), the spatial and temporal variability of moisture supply has a decisive impact on the efficiency of water balance formation and the productivity of agricultural landscapes in the transitional rain-snow zone, which confirms the need to optimise agronomic measures for the accumulation of winter precipitation. The study by M. Khan *et al.* (2020) determined that agrometeorological drought events, assessed through standardised soil moisture and precipitation indices, significantly affect grain yields, especially when effective moisture reserves decrease during critical phases of the growing season, which is fully consistent with the observed decrease in productivity in variants with low snow retention.

Additionally, as shown by K. Gavahi *et al.* (2020), effective moisture management in agricultural systems requires integrated monitoring of soil moisture and transpiration flows, as underestimation of latent moisture losses can lead to underestimation of yield-limiting factors. This concept is in line with the high dependence of productivity on total moisture consumption during the growing season (r = 0.83), in contrast to the moderate influence of winter precipitation. In turn, according to R.P. Allan *et al.* (2020), changes in the global water cycle, including the redistribution of precipitation and increased aridity in some regions, require the adaptation of agricultural technologies to new water supply conditions, which emphasises the relevance of snow retention to stabilise production performance in the steppe zone of Northern Kazakhstan. The study confirmed that an increase in pre-season moisture reserves due to snow retention provides a significant increase in spring wheat yields in the steppe zone of Northern

Kazakhstan. The highest productivity was achieved on fallow plots with an optimised water regime. The high correlation between total moisture consumption and yield underlines the need for integrated water management in the face of climate instability. The results obtained substantiate the prospects of using snow retention and water conservation technologies for sustainable agriculture.

CONCLUSIONS

The study comprehensively assessed the impact of winter precipitation and snow retention measures on the formation of the water regime and spring wheat productivity in the steppe zone of Northern Kazakhstan. It was found that in the conditions of high interannual variability of winter precipitation (from -25.2 mm to +82.9 mm from the norm) and an increase in the average winter temperature by +1.6°C, the effectiveness of water regime regulation is critical for the stability of agriculture. The use of snow retention provided an increase in snow cover height by 26.6-32% and an increase in precipitation water equivalent by 26-33.4% compared to the control variants. The maximum moisture reserves in the snow cover were achieved on the background of wedge steam (85.7 mm), which is 56.5% higher than the steam flat-cutting background without snow retention. This indicates the high efficiency of structured surfaces in the accumulation of solid precipitation.

The soil moisture balance showed that the use of snow retention technologies increased moisture reserves by the time of sowing by 27.1-31.6% on fallow plots and by 16-30% on stubble plots. The most efficient absorption of winter precipitation was recorded on stubble plots, ranging from 21.8 to 37.5%. The correlation analysis revealed a high positive correlation between the moisture reserves in snow and the level of its absorption by the soil ($r = 0.67$) and an inverse relationship between the autumn level of soil moisture and the absorption of precipitation ($r = -0.65$). This emphasises the need to account for the initial soil moisture conditions to optimise water-saving measures.

Assessment of the influence of water regime on productivity showed that snow retention provided an increase in spring wheat yield by 0.15-0.47 t/ha, which corresponded to an increase of 11-17% depending on the agrotechnical background. The maximum yield (2.76 t/ha) was obtained on the wraparound fallow. The correlation between the total moisture consumption during the growing season and the yield was 0.83, indicating the crucial role of the total water balance in the formation of productivity. The influence of the amount of moisture accumulated in winter on yield was moderate ($r = 0.42$), especially on stubble plots, which confirms the importance of integrated water management throughout the growing season. The results reflect the peculiarities of soil and climatic conditions in the steppe zone of Northern Kazakhstan, which limits the possibility of their direct transfer to other agricultural landscapes with different natural characteristics. It is advisable to expand the research to include different climatic regions and soil types, as well as to address the projected changes in hydrothermal conditions in the context of global climate change.

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CONFLICT OF INTEREST

None.

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Ефективність заходів щодо накопичення опадів зимового періоду в кліматичних умовах Північно-Казахстанської області

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Анотація. Мета даного дослідження полягала у встановленні закономірностей формування водних ресурсів ґрунту за рахунок зимових опадів за використання різних агротехнічних прийомів в умовах степової зони. Методологія дослідження включала польові випробування різних агротехнічних фонів зі снігозатриманням і без нього з подальшим аналізом накопичення зимових опадів, зміни водного режиму ґрунту та продуктивність ярої пшениці. Середня висота снігового покриву на варіантах із застосуванням снігозатримання збільшувалася на 26,6-32 % порівняно з контролем без снігозатримання. Запаси вологи в ґрунті перед сівбою зростали на 27,1-31,6 % на парових фонах і на 16-30 % на стерньових ділянках. Засвоєння зимових опадів найефективніше відбувалося на стерньових фонах, де приріст вологи становив від 21,8 до 37,5 % відносно вихідних значень. Урожайність ярої пшениці на ділянках зі снігозатриманням перевищувала контрольні показники на 0,15-0,47 т/га, досягаючи максимальних значень до 2,76 т/га на кулісних парах. Коефіцієнт кореляції між загальним водоспоживанням за вегетаційний період і врожайністю становив 0,83, що свідчить про високий вплив водного режиму на продуктивність. Встановлена залежність між об'ємом вологи в снігу та врожайністю виявилася помірною, з коефіцієнтом 0,42, особливо на стерньових ділянках. Отримані результати підтверджують високу ефективність застосування технологій снігозатримання для підвищення водозабезпеченості посівів і стійкості врожайності в степових умовах Північного Казахстану. Їх використання рекомендується для оптимізації системи агротехнічних заходів в умовах посилення кліматичної нестабільності, що посилюється

Ключові слова: снігонакопичення; вологість ґрунту; снігозатримання; кулісний пар; зяблевий обробіток; урожайність