

IRSTI 06.71; 06.35.51

UDC 338.43

<https://doi.org/10.52269/SKVC2621303>

## AGROCLIMATIC DETERMINANTS OF WHEAT YIELD AND WHEAT PRODUCTION PROFITABILITY

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*Climate change has become a major challenge for agricultural production, particularly in regions characterized by high climatic variability and frequent weather extremes. This study investigates the relationship between climatic factors, wheat yield, and economic performance in the Kostanay Region of Northern Kazakhstan during 1990–2024. The research combines correlation analysis, regression modeling and geospatial analysis to identify the key drivers of yield variability and to develop a predictive framework for agricultural decision-making.*

*The results demonstrate that precipitation during the growing season, particularly in June and July, has the strongest positive influence on wheat productivity, whereas increasing summer temperatures negatively affect yields. The analysis also reveals a strong relationship between yield levels and economic indicators, including profitability and profit per unit of production. A Random Forest model achieved high forecasting accuracy ( $R^2 = 0.79$ ), identifying July precipitation, June temperature, precipitation concentration, and drought duration as the most important predictors.*

*The findings highlight the importance of climate-informed forecasting tools for improving agricultural resilience and support the development of adaptive strategies aimed at reducing climate-related risks in Northern Kazakhstan.*

**Key words:** *climate change, wheat production, agricultural economics, production profitability, agroclimatic factors, yield variability, climate risks, economic efficiency, yield forecasting, Northern Kazakhstan.*

## БИДАЙ ӨНІМДІЛІГІ МЕН ӨНДІРІС РЕНТАБЕЛЬДІЛІГІН АЙҚЫНДАЙТЫН АГРОКЛИМАТТЫҚ ФАКТОРЛАР

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*Климаттың өзгеруі ауыл шаруашылығы өндірісі үшін, әсіресе климаттық құбылмалылығы жоғары және экстремалды ауа райы құбылыстары жиі байқалатын өңірлерде, негізгі сын-қатерлердің біріне айналды. Осы зерттеуде 1990–2024 жылдар аралығындағы Солтүстік Қазақстанның Қостанай облысындағы климаттық факторлар, бидай өнімділігі және ауыл шаруашылығы өндірісінің экономикалық тиімділігі арасындағы өзара байланыс қарастырылған. Зерттеу өнімділік өзгергіштігінің негізгі факторларын анықтау және аграрлық секторда басқарушылық шешімдер қабылдауға арналған болжамдық негіз қалыптастыру мақсатында корреляциялық талдау, регрессиялық модельдеу және геокеңістіктік талдау әдістерін біріктіреді.*

*Зерттеу нәтижелері вегетациялық кезеңдегі жауын-шашынның, әсіресе маусым мен шілде айларындағы жауын-шашын мөлшерінің, бидай өнімділігіне ең күшті оң әсер ететінін көрсетті. Ал жазғы ауа температурасының жоғарылауы өнімділікке теріс ықпал етеді. Сонымен қатар, талдау өнімділік деңгейі мен экономикалық көрсеткіштер, соның ішінде өндіріс рентабельділігі мен өнім бірлігіне шаққандағы пайда арасындағы тығыз байланысты анықтады. Random Forest моделі жоғары болжау дәлдігін көрсетті ( $R^2 = 0,79$ ), мұнда шілде айындағы жауын-шашын мөлшері, маусым айындағы ауа температурасы, жауын-шашынның шоғырлану индексі және құрғақшылық кезеңдерінің ұзақтығы*

өнімділіктің ең маңызды предикторлары ретінде айқындалды. Алынған нәтижелер ауыл шаруашылығы өндірісінің орнықтылығын арттыру үшін климаттық факторларды ескеретін болжау құралдарын пайдаланудың маңыздылығын дәлелдейді және Солтүстік Қазақстандағы климаттық тәуекелдерді төмендетуге бағытталған бейімделу стратегияларын әзірлеудің ғылыми негізін қалыптастырады.

**Түйінді сөздер:** климаттың өзгеруі; бидай өндірісі; аграрлық экономика; өндіріс рентабельділігі; агроклиматтық факторлар; өнімділік өзгергіштігі; климаттық тәуекелдер; экономикалық тиімділік; өнімділікті болжау; Солтүстік Қазақстан.

## АГРОКЛИМАТИЧЕСКИЕ ФАКТОРЫ ФОРМИРОВАНИЯ УРОЖАЙНОСТИ И РЕНТАБЕЛЬНОСТИ ПРОИЗВОДСТВА ПШЕНИЦЫ

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Изменение климата стало одним из ключевых вызовов для сельскохозяйственного производства, особенно в регионах, характеризующихся высокой климатической изменчивостью и частыми экстремальными погодными явлениями. В настоящем исследовании рассматривается взаимосвязь между климатическими факторами, урожайностью пшеницы и экономической эффективностью сельскохозяйственного производства в Костанайской области Северного Казахстана за период 1990–2024 гг. Исследование основано на применении корреляционного анализа, регрессионного моделирования и геопространственного анализа с целью выявления основных факторов, определяющих вариацию урожайности, а также разработки прогностической основы для поддержки принятия решений в аграрном секторе.

Результаты показали, что наибольшее положительное влияние на продуктивность пшеницы оказывают осадки в период вегетации, особенно в июне и июле, тогда как повышение летних температур оказывает отрицательное воздействие на урожайность. Анализ также выявил тесную взаимосвязь между уровнем урожайности и экономическими показателями, включая рентабельность и прибыль на единицу произведённой продукции. Модель Random Forest продемонстрировала высокую точность прогнозирования ( $R^2 = 0,79$ ), определив осадки июля, температуру июня, индекс концентрации осадков и продолжительность засушливых периодов в качестве наиболее значимых предикторов урожайности. Полученные результаты подтверждают важность использования климатически ориентированных инструментов прогнозирования для повышения устойчивости сельскохозяйственного производства и обосновывают необходимость разработки адаптационных стратегий, направленных на снижение климатических рисков в Северном Казахстане.

**Ключевые слова:** изменение климата; производство пшеницы; аграрная экономика; рентабельность производства; агроклиматические факторы; вариабельность урожайности; климатические риски; экономическая эффективность; прогнозирование урожайности; Северный Казахстан.

### Introduction.

Climate change has emerged as one of the principal factors influencing the sustainability of agricultural production worldwide. Its impacts are particularly pronounced in regions characterized by high climatic variability, where crop productivity depends not only on the total amount of precipitation but also on its seasonal distribution throughout the growing period. The Kostanay Region of the Republic of Kazakhstan is one of the country's leading grain-producing areas and is located within the zone of high-risk rainfed agriculture. A defining climatic characteristic of the region is the uneven seasonal distribution of precipitation. During recent decades, climate variability has intensified, resulting in excessive rainfall during spring and autumn and increasing moisture deficits throughout the summer growing season. These changes substantially increase production risks because spring wheat cultivation depends on a narrow sowing window extending from mid-May to early June. Deviations from the optimum sowing period adversely affect crop establishment, delay maturation, and ultimately reduce both yield and economic performance.

Long-term observations indicate that under moderate air temperatures (25–27 °C), wheat yields may exceed 10 centners per hectare even under relatively limited precipitation. In contrast, combinations of high temperatures (above 30 °C) and moisture deficits frequently reduce yields to below 7 centners per hectare. When adequate precipitation occurs during the growing season and dry weather prevails during harvesting, yields commonly exceed 15 centners per hectare. These observations demonstrate the high sensitivity of

wheat production to hydrothermal conditions and emphasize the necessity of incorporating climatic factors into agricultural adaptation strategies.

Increasing climatic instability has also intensified the economic vulnerability of agricultural production by directly affecting crop yields, production costs, farm income, and profitability. Under these conditions, quantitative assessment of climatic impacts and the development of reliable yield forecasting models have become essential components of agricultural decision-making, enabling producers and policymakers to improve production efficiency and strengthen climate adaptation. Although numerous studies have examined the effects of climate change on crop productivity, the relationships between climatic factors, wheat yield, and the economic performance of wheat production in Northern Kazakhstan remain insufficiently investigated. In particular, relatively few studies integrate long-term climatic observations, yield dynamics, and economic indicators within a unified analytical framework using modern statistical techniques and machine-learning methods.

The objective of this study is to identify the agroclimatic factors determining wheat yield and production profitability in the Kostanay Region and to develop a predictive model for assessing the effects of climate variability on agricultural production efficiency.

To achieve this objective, the following research tasks were addressed:

- to analyses long-term trends in climatic variables and wheat yield during 1990–2024;
- to evaluate the statistical relationships between climatic factors, wheat yield, and the economic performance of wheat production;
- to identify the principal climatic predictors affecting yield formation;
- to develop a wheat yield forecasting model using machine-learning techniques;
- to assess the effects of climate variability on production profitability and formulate recommendations aimed at improving the climate resilience of the regional agricultural sector.

The remainder of the paper is organized as follows. The next section reviews the relevant literature and presents the theoretical background. This is followed by a description of the research methodology, presentation and analysis of the empirical results, discussion of their economic implications, and concluding remarks outlining practical recommendations for climate adaptation in wheat production.

**Materials and methods.** Climate change and its consequences for the agricultural sector have been the subject of active scientific discussion around the world over the past two decades – particularly intensifying in the last five years. Researchers largely agree that while several climatic factors affect the yield of agricultural crops, the most critical are changes in air temperature and variations in the amount of precipitation during the plant growing season [1,2,3,4,5].

At the global level, numerous studies have assessed the impact of climate change on wheat yields, recognizing wheat as one of the most strategically important food crops. According to research groups from the United States and the European Union, extreme weather events – particularly heatwaves, droughts, and floods during seasonal rains – cause substantial damage to agricultural production. For instance, the study by Lobell and Field identified a persistent negative correlation between rising average air temperatures during the growing season and wheat yields in countries with continental climates [1].

In Kazakhstan, the impact of natural and climatic factors on wheat yield has also been studied across various grain-producing regions. A team of researchers led by Zhumagulov [6] and Teleubay [7] examined the effects of atmospheric precipitation on the yield spring wheat and barley in the dry steppe zone of Northern Kazakhstan. Identifying a strong correlation between precipitation in June-July and crop yield. Suleimenov and Akshalov evaluated summer following practices negatively in northern Kazakh soils, arguing there are ineffective for reducing climate-related risks [8]. In contrast, Walet et al., presented an opposing viewpoint, emphasizing the potential of fallow crop rotations and agroforestry as climate change adaptation strategies that enhance the economic efficiency of production [9].

Recent publications in MDPI journals (e.g., *Agronomy*, *Agriculture*) have contributed to the body of research on climate change effects on crop productivity, particularly wheat. In particular, the journal *Agronomy* published a study that employed the SALTMED model to evaluate the effects of different irrigation levels and nitrogen fertilizer rates on weak growth under climate change conditions. The results indicated that climate change poses new threats to wheat growth in the future, thereby requiring the development of technologically resilient production strategies [10]. In the journal *Agriculture*, a study was presented assessing the impact of climate change on winter wheat yields in five major counties in Texas. Using the APEX model and CMIP5 climate projections, the researchers found that despite the expected rise in air temperature, winter wheat yields may increase in the future due to the accompanying rise in precipitation. This trend is seen as contributing to the improved efficiency of wheat grain production in northern Texas counties [11].

In addition, a study published in the *Agro-Geoinformatics* proceedings applied machine learning models to produce a high-precision forecast of crop yields. The authors utilized remote sensing data, end (NDVI, EVI), climate indicators and historical statistics. The study assessed the long-term effects of air temperature, precipitation, fertilizer use, electricity consumption, sown area, and labor input on wheat production in Hubei Province, China. The results showed that air temperature, precipitation, fertilizer application, electricity consumption, and labor input all had a strong positive influence on agricultural output, whereas the sown area was negatively correlated with production [12].

Researchers in Turkey, using Copernicus (EU) data, examined the influence of climatic variables – temperature, humidity, and precipitation – on wheat yield dynamics over the period 1990-2024. A neural network model was developed to assess both the positive and negative effects of climate change on agricultural productivity [13]. Convolutional neural networks [14], as well as research conducted under the conditions of Pakistan, have demonstrated that integrating diverse data sources (NDVI, EVI, ARVI) with climatic variables and machine learning algorithms (e.g. Random Forest Gradient Boosting) enables effective yield prediction and adaptation to arid environments [15]. This approach is highly relevant for regions such as Kostanay, where forecasting accuracy is essential due to the area's classification as a risk-prone agricultural zone. In Sweden, Sentinel-1 satellite data and meteorological indicators have been incorporated into LGBM and neural network models to forecast wheat yield with R<sup>2</sup> values reaching 0,86 illustrating the effectiveness of this technology under conditions of climate instability. Similarly, researchers at the University of the Witwatersrand, Johannesburg, used machine learning algorithms and combined Sentinel-1 and Sentinel-2 imagery to enhance precision in data acquisition – an essential factor for precision agriculture and resource management [16].

Chinese researchers have developed an ensemble AdaBoost-LSTM model that demonstrates strong resilience to extreme droughts and climate variability. A key feature of this model is its ability to generate accurate yield forecasts 1-2 months before the harvest season. The model has shown high performance under both wet and dry seasonal conditions [17].

A study published in *Genes* (MDPI) analyzed yield variability in durum wheat in Italy. It simulated genotype responses to biotic stressors (such as drought and heat) using field trials and predictive modelling approaches [18]. These findings underscore the importance of integrating climatic indices and agricultural technologies for accurate yield forecasting and for improving agronomic and agrotechnological decision-making. In conclusion, a simple and reproducible wheat yield forecasting method has been proposed at the national scale, based on the combination of agrometeorological data and the APSIM model (Agricultural Production Systems Simulator). The model is currently being developed and tested in the United States and Brazil, encompassing various agroclimatic zones. It relies on basic weather inputs (precipitation and temperature) and a limited set of agronomic parameters. Its main advantage lies in its simplicity and low cost, enabling accurate yield predictions even in countries with limited computational capacity [19].

The study period covers the years from 1990 to 2023, aligning with the period of Kazakhstan's independence [20]. Starting from 1990 enables the analysis of trends in the country's post-Soviet agricultural policy, the transformation of economic mechanisms, and the intensification of climate-related trends, while also allowing for the identification of structural patterns and cyclical phases. As previously noted, the geographical scope follows a general-to-specific principle: global analysis provides a comparative context, while the regional level focuses on high-risk farming zones that are critically vulnerable to climatic fluctuations yet strategically important for national food security. The global analysis includes leading wheat-producing countries such as the United States, Canada, Australia, India, and the European Union. The regional analysis is centered on data from the Kostanay Region, which, as noted earlier, is located in a high-risk agricultural zone within the sharply continental climate of Northern Kazakhstan [21].

The methodological strategy follows a stepwise approach: first, the identification of stable relationships between climate change and wheat yield; second, the construction of predictive forecasting models; and finally, spatial visualization and the assessment of economic indicators and consequences resulting from the impact of climate change on the target variable [22, 23, 24].

The main independent variables include:

1. The average seasonal air temperature during the vegetation period May-August;
2. Monthly precipitation levels, with particular emphasis on May, June, August, and September;
3. Indices of precipitation irregularity;
4. Climatic extremes – temperature peaks, drought periods, and heavy rainfall events;
5. Timing of agrotechnological operations, including sowing and harvesting dates.

The dependent variable in this study is wheat yield, measured in centners per hectare (c/ha). In addition, key economic indicators will be included: the cost of wheat production, selling price, profit, and profitability of wheat cultivation and processing.

The selection of climatic and environmental variables is based on their direct physiological impact on wheat growth during key developmental stage: germination, emergence, tillering, stem elongation, heading, flowering, grain filling, and maturation. The irregular distribution of precipitation affects the timely execution of agrotechnical operations. We yield – as the region's primary food crop – serves as the central outcome variable linking climate change to the agricultural sector's economic performance. The inclusion of economic variables enables the evaluation not only of biological losses but also of their translation into production and financial consequences, which is critical for ensuring the efficiency, resilience and profitability of the agricultural economy.

As previously noted, the analytical methodology is based on identifying relationships between climatic and production indicators using correlation analysis methods (Pearson and Spearman) [25], linear and multiple regression, machine learning techniques, and geospatial analysis.

Analytical Methods:

- Calculation analysis was used to identify dependencies between climatic variables (Independent features) and wheat yield (dependent variable);

- Regression analysis was applied to construct predictive models of yields based on climatic and economic factors.
- Geospatial analysis was conducted using GIS technologies for spatial data analysis and visualization of the results.

During the study, threshold values of climatic indicators were calculated – those at which wheat yield exhibited a sharp decline or increase. The impact on the agricultural sector's performance was assessed through the analysis of yield variability and sensitivity to climate change, particularly in the context of increasing climatic instability.

**Results.** Correlation analysis of data from the Kostanay Region for 1990–2023 revealed a strong dependence of wheat yield on climatic conditions, particularly precipitation during the growing season. Stable yields were associated with a more uniform rainfall distribution in May–July, while moisture deficits in key growth periods resulted in substantial yield reductions. The strongest correlation was observed between wheat yield and July precipitation ( $r = 0.89$ ), highlighting the decisive role of moisture availability during grain formation. These findings confirm the high climatic sensitivity of wheat production in the region (Figures 1 and 2).

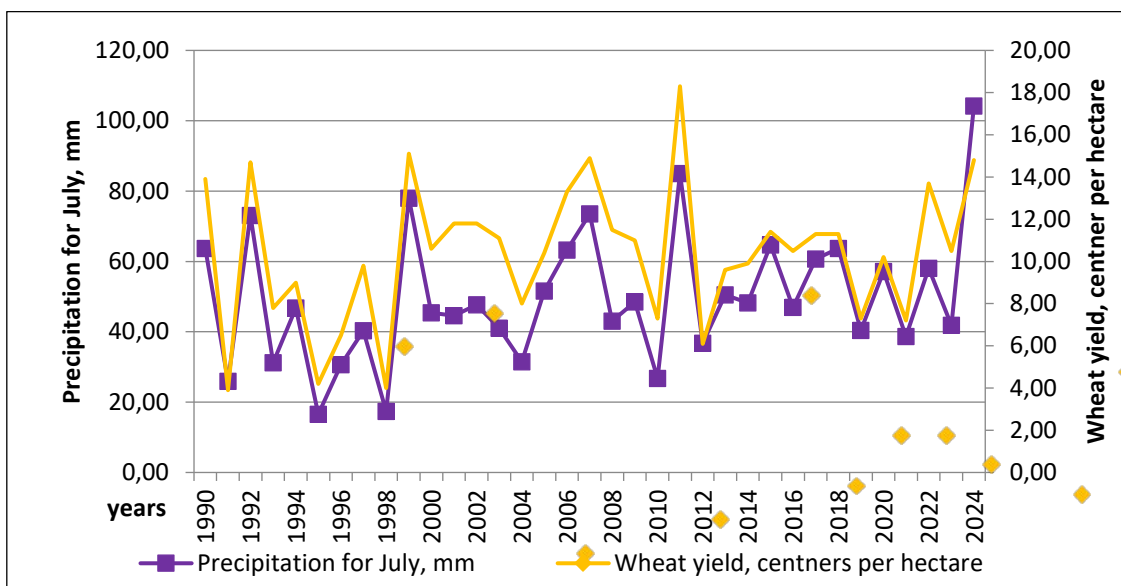


Figure 1 – This is a figure. Schemes follow the same formatting

A similar pattern is demonstrated in Figure 2.

A moderate positive relationship was identified between June precipitation and wheat yield ( $r = 0.56$ ), while May precipitation demonstrated a weaker association ( $r = 0.42$ ). This finding confirms that moisture availability during the critical stages of crop establishment and vegetative development substantially influences wheat productivity.

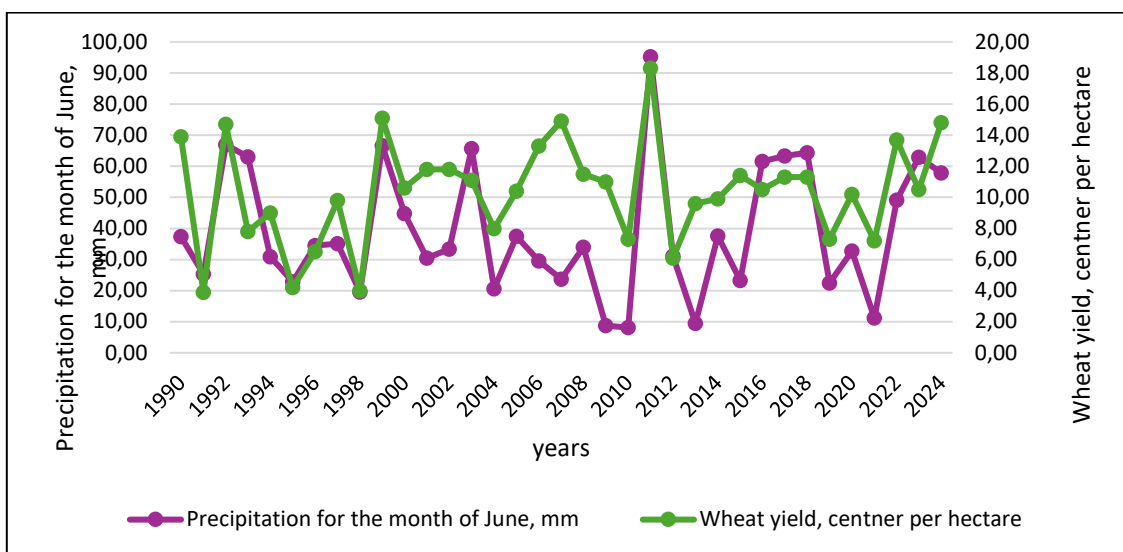


Figure 2 – Graph of the relationship between wheat yield and precipitation levels in June

Thus, as the analysis shows, precipitation during the active growth phase of the vegetation period has a decisive influence on yield formation.

Weak or negative correlations were observed for precipitation in December and March, which, as previously noted, have a cumulative effect and influence wheat yield through the total annual precipitation indicator (Figures 3 and 4).

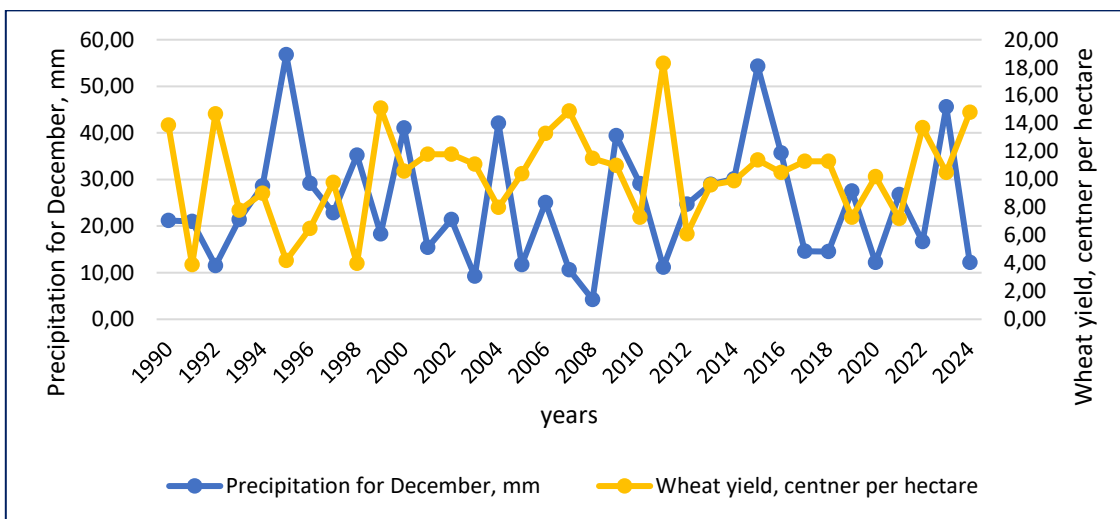


Figure 3 – Graph of the relationship between wheat yield and precipitation levels in December

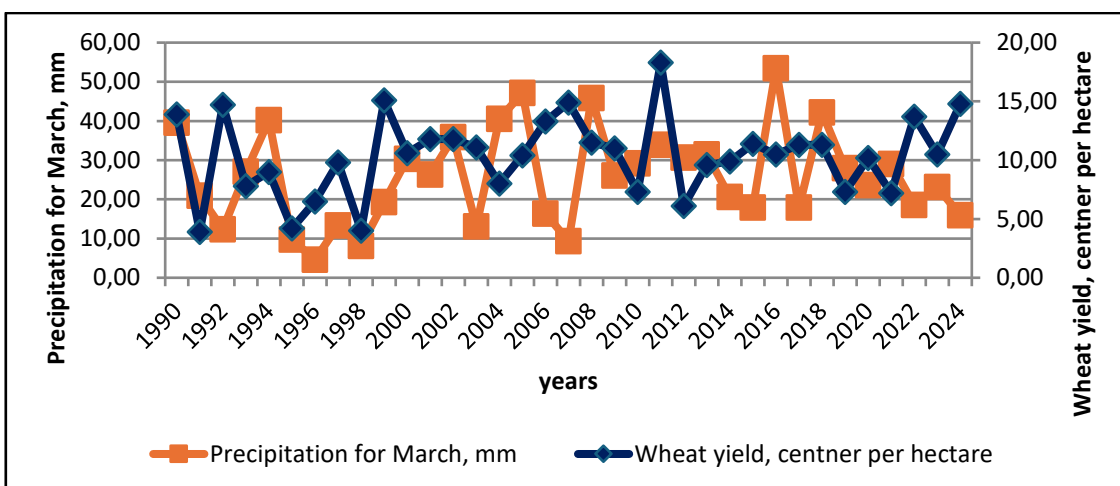


Figure 4 – Graph of the relationship between wheat yield and precipitation levels in March

Continuing the correlation analysis between wheat yield and precipitation, it is important to highlight a strong correlation between yield and total annual precipitation, with a correlation coefficient of  $r = +0,72$  (Figures 5).

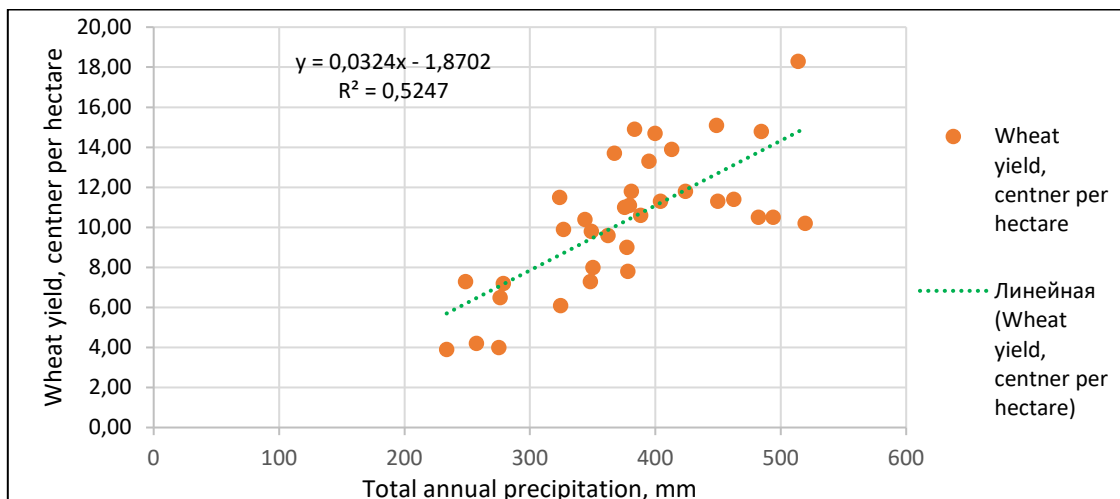


Figure 5 – Correlation between wheat yield and total annual precipitation [25, 26]

This supports the scientific hypothesis that not only specific precipitation during the vegetation period affects yield, but also the accumulated soil moisture -commonly referred to in agricultural technology as soil moisture recharge-formed from autumn, winter, and early spring precipitation plays a significant role in determining wheat and overall cereal crop yields. Stable reserves of soil moisture create favorable conditions for seed germination and early plant growth, even in the absence of sufficient summer rainfall. This pattern is particularly relevant for high-risk farming zones, where the amount of soil moisture available at the beginning of the sowing season is critically important during dry summers. Other influencing factors must also be considered. For instance, when comparing annual data: in 2011, total precipitation was 513,7 mm and the yield was 18,3 centners per hectare; in 1991, total precipitation was 233,6 mm with a yield of 3,9 centners per hectare; and in 2020, despite having the highest annual precipitation during the observation period, the yield was still below average at 10,2 centners per hectare. To improve forecasting accuracy, precipitation unevenness indices were calculated.

Precipitation unevenness indices and the coefficient of variation revealed that in several years particularly after 2010-there has been a noticeable shift in rainfall distribution toward the spring and autumn months. For example, in 2012, 2014, 2021, and 2023, May was one of the wettest months, which coincided with delays in the sowing campaign and reduced yields compared to years in which precipitation was more evenly distributed. In these cases, the PCI (Precipitation Concentration Index) exceeded 20, which is classified as a high concentration of rainfall. The increase in precipitation unevenness over the past 10 years has been reflected in deviations in the timing of the sowing campaign and a decline in yields.

Overall, the correlation matrix constructed to evaluate the strength of the relationship between wheat yield and seasonal temperatures (Table 1).

Table 1 – Correlation matrix assessing the strength of the relationship between wheat yield and seasonal temperatures (Lee Rodgers and Nicewander 1988; Benesty, J., et al. 2009; Pearson 1900)

Indicators	Wheat yield, centners per hectare	Sum of active temperatures °C, Autumn	Sum of active temperatures °C, Winter	Sum of active temperatures °C, Spring	Sum of active temperatures °C, Summer
<b>Wheat yield, centners per hectare</b>	1	-0,26677	0,866741	0,953385	-0,96048
Sum of active temperatures °C, Autumn	-0,26677	1	-0,2154	-0,07911	0,2628
Sum of active temperatures °C, Winter	0,866741	-0,2154	1	0,823169	-0,96738
Sum of active temperatures °C, Spring	0,953385	-0,07911	0,823169	1	-0,89576
Sum of active temperatures °C, Summer	-0,96048	0,2628	-0,96738	-0,89576	1

Showed that the sum of active temperatures in the spring months has the most substantial impact on yield formation (0,49), representing the strongest positive correlation. A warm spring contributes to better germination, tillering, and, overall, a more favorable start to the vegetation period. In the autumn months, the sum of active temperatures does not have a strong influence on yield, however, a moderately positive correlation is observed due to the creation of favorable conditions for harvesting mature crops – higher autumn temperatures increase the likelihood of a timely and efficient harvest. The effect of summer temperatures on yield previously discussed, shows a moderately negative relationship. Logically, the sum of active temperatures in winter has little effect on wheat yield, with a weak, inverse, and statistically insignificant correlation.

These findings are supported by seasonal comparative graphs of wheat yield and air temperature (Figures 6,7,8, and 9).

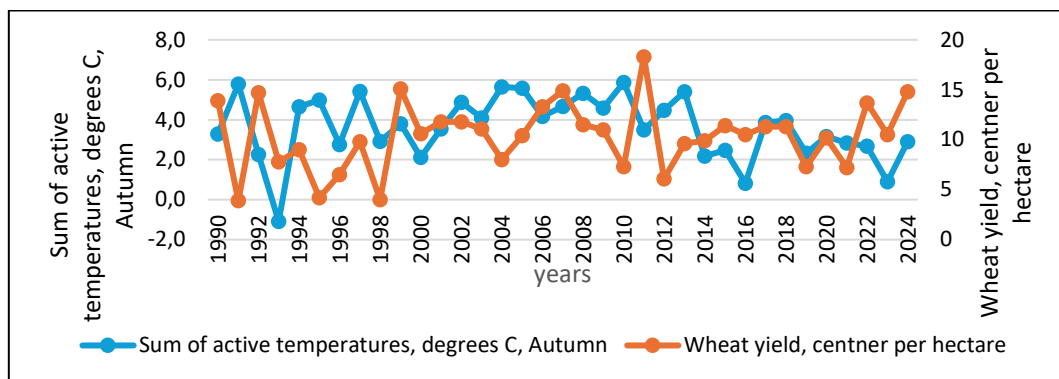


Figure 6 – Graphs illustrating the interaction between wheat yield and the sum of active temperatures during the autumn period

Figure 6 demonstrates clear, albeit weak, positive relationship, particularly when autumn precipitation from the preceding year is considered as a factor in soil moisture accumulation for the upcoming production cycle. Lower autumn temperatures reduce evaporation intensity, facilitating retention of accumulated precipitation, deeper soil infiltration, and the formation of a more substantial soil moisture reserve.

A similar relationship is observed between air temperature in the winter months and wheat yield (Figure 7). Low winter temperatures do not contribute to deep soil freezing or to significant evaporation or the freezing out of soil moisture. The correlation is weak and only slightly discernible. According to agrotechnological data, it is generally accepted that winter temperatures primarily affect the condition of perennial crops or winter wheat, rather than spring wheat. However, long term observations and farmer surveys suggest that low snow cover combined with low winter temperatures often precede a dry spring – summer season.

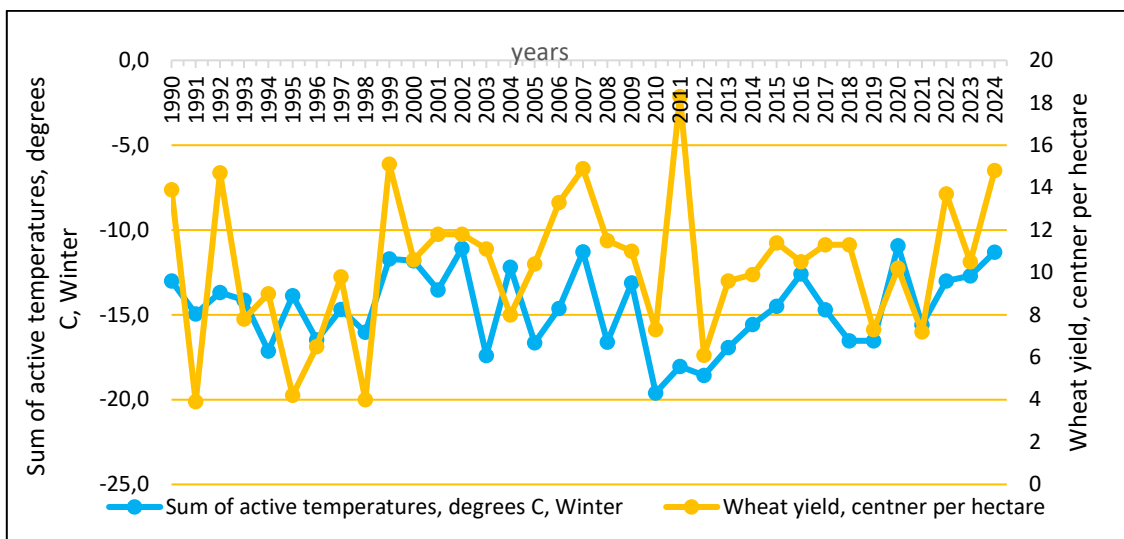


Figure 7 – Graphs illustrating the interaction between wheat yield and the sum of active temperatures during the winter period

The analysis of the graphical relationship between wheat yield and the sum of active temperatures during the spring period, presented in Figure 8, shows a clear positive trend – yield increases with rising spring temperatures.

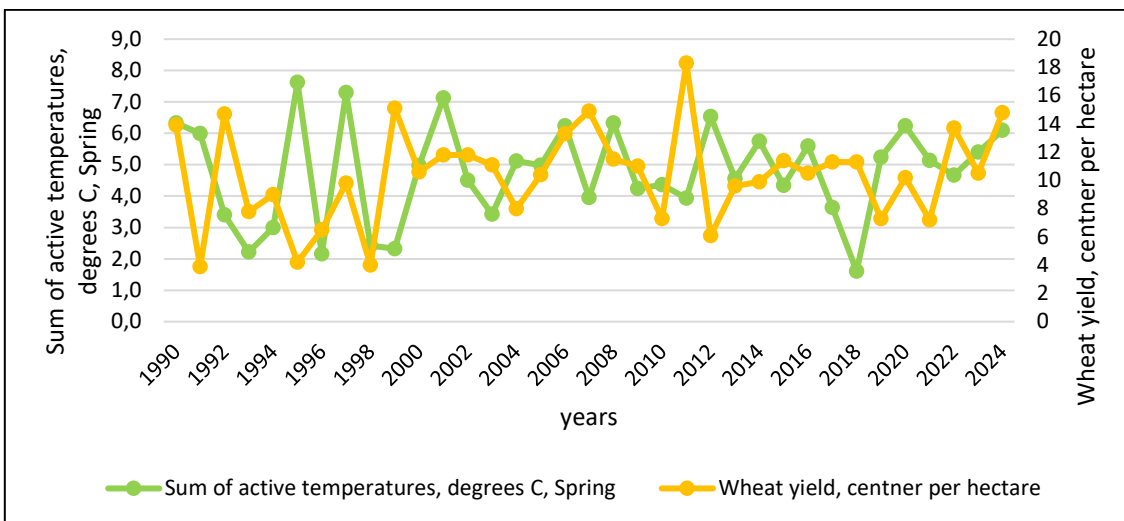


Figure 8 – Graphs illustrating the interaction between wheat yield and the sum of active temperatures during the spring period

This on again confirms the significance of temperature during the germination, tillering, and stem elongated phases. Uniform seedling emergence typically occurs at air temperatures between 12-17 °C, while intensive wheat growth takes place at 20-25 °C.

The graph of the interaction between wheat yield and the sum of active temperatures during the summer period (Figure 9) confirms the results of the correlation analysis: as the temperature threshold increases, yield begins to decline – sometimes reaching critical levels. This is consistent with wheat physiology: overheating (above 30 °C) during the grain-filling phase shortens the vegetation period and reduces grain weight.

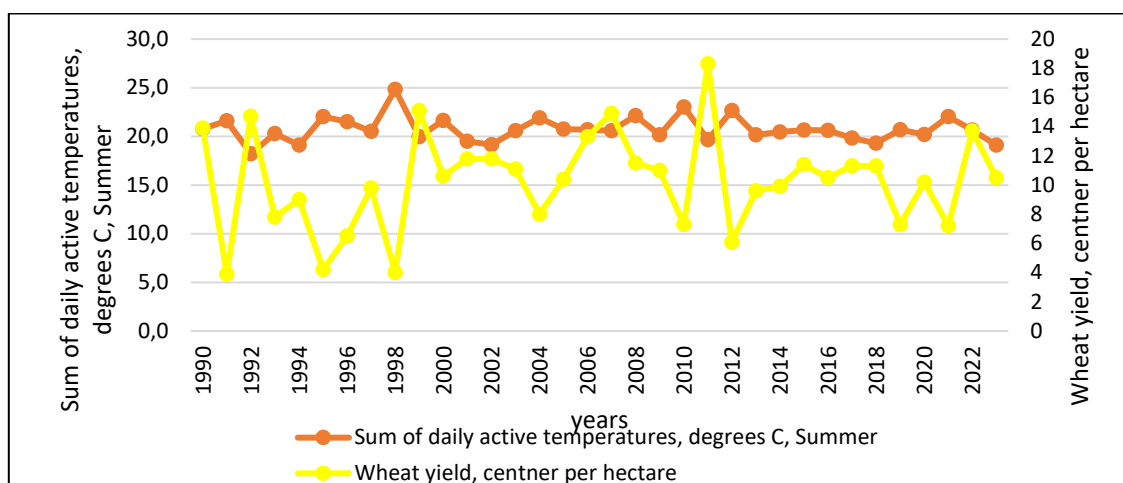


Figure 9 – Graphs illustrating the interaction between wheat yield and the sum of active temperatures during the summer period

For predictive modeling, spring temperatures serve as a key factor, while summer temperatures act as a limiting factor. Thus, temperature is important, but it is neither the primary nor the sole determinant of wheat yield. Yield fluctuations due to air temperature variation account for up to 38%, while the remaining variation is explained by other variables.

Based on long-term observation, four conditional agroclimatic scenarios can be identified for the Kostanay Region (Table 2):

Table 2 – Types of agroclimatic scenarios for the Kostanay Region

Scenarios	Precipitation during the growing season, mm	Air temperature, °C	Wheat yield, centners per hectare
Moderate, moderate temperature	100-140	25-27	12,0-14,0
Low precipitation and moderate temperature	60-90	25-27	10,0-11,0
Drought and heat	<30	> 30	<7,0
Heavy precipitation during the growing season and high temperatures	> 140	28-34	> 15,0

These scenarios form the foundation for a structured predictive model that enables the estimation of the expected yield range under given climatic and environmental conditions. The application of the Random Forest model for yield forecasting demonstrated high accuracy on the test dataset, with  $R^2=0.79$ ,  $MAE=1,4$  c/ha. The most significant predictors included July precipitation, average air temperature in June, the PCI index, and the duration of drought periods.

Correlation analysis also revealed a strong positive relationship between wheat yield and economic indicators (Table 3).

Table 3 – Correlation analysis between wheat yield and climatic, environmental, and economic variables based on data from Kostanay Region for the period 1990-2024, highlighting the most significant positive relationship

Indicators	Correlation coefficient	Degree of dependence
Profitability of wheat grain production and cultivation	+0,90	Very strong
Precipitation in July	+0,89	Very strong
Annual total precipitation	+0,72	Very strong
Profit per 1 centner of wheat grain	+0,66	Strong
Precipitation in June	+0,56	Moderately positive
Precipitation in May	+0,42	Moderately positive

A comparative analysis of years characterized by adverse climatic conditions (2012, 2014, and 2021) and relatively favorable production conditions (2013, 2016, and 2019) revealed that a 30–40% decline in wheat yield was associated with a 1.5–2.0-fold reduction in production profitability.

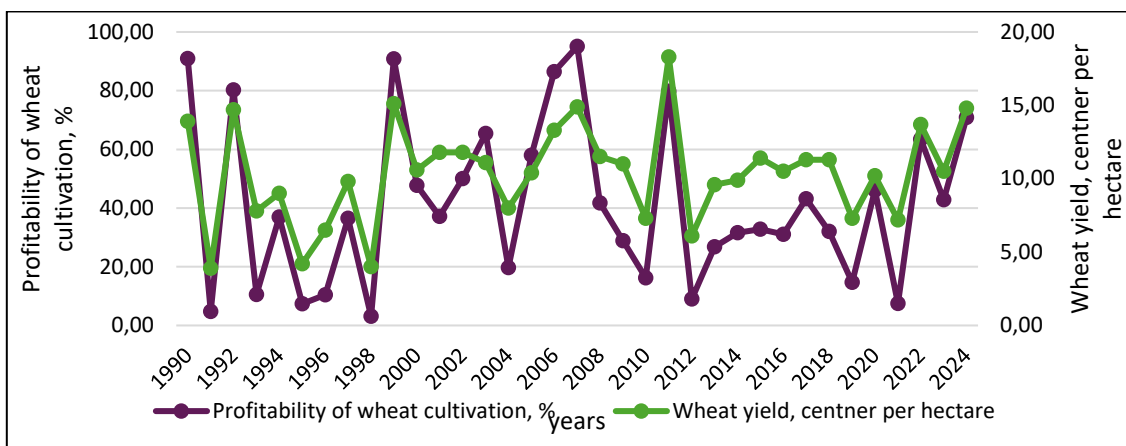


Figure 10 – Graphical relationship between wheat yield and profitability of wheat production

A fundamentally different relationship is observed between yield, production cost, and the selling price of 1 centner of wheat (Table 4).

Table 4 – Correlation analysis between wheat yield and climatic and economic variables based on data from Kostanay Region for the period 1990-2024, showing weak negative correlations

Indicators	Correlation coefficient	Degree of dependence
Production cost of 1 centner of wheat grain	-0,11	Weak negative
Precipitation in December	-0,48	Moderately negative

This analysis will be the focus of subsequent publications (the impact of macroeconomic indicators on the efficiency of wheat production in the Kostanay region will be examined in the next article).

The constructed visualization graphs clearly illustrate key correlation relationships. A near-linear positive dependences is observed: as precipitation increases to 100-120 mm, wheat yield rises to 12-15 centners per hectare (c/ha). and profitability consistently exceeds 50 %. In contrast, under low precipitation conditions (<30 mm), yield levels drop sharply to 6 -7 c/ha.

The analysis demonstrated a very strong positive correlation between wheat yield and production profitability ( $r = 0.90$ ), confirming that economic outcomes in wheat farming are highly sensitive to changes in productivity. This finding underscores the importance of yield stabilization as a prerequisite for improving the economic sustainability and climate resilience of the regional agricultural sector (Figure 11, Table 5).

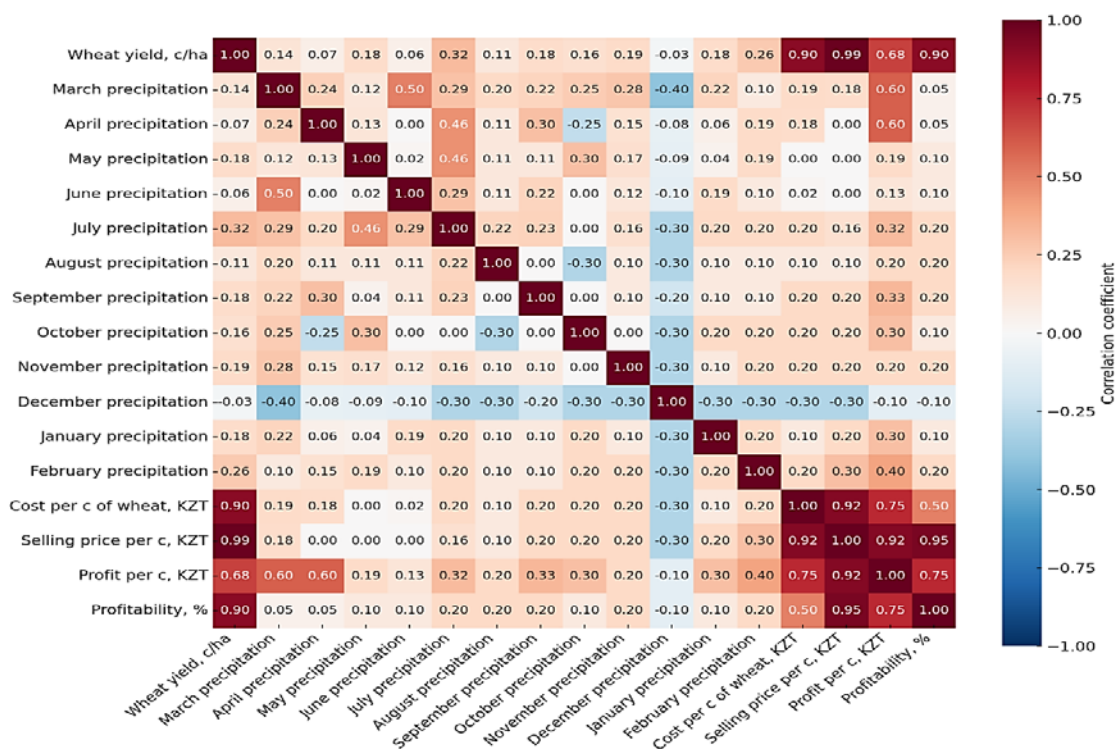


Figure 11 – Heatmap of Interactions Between Climatic Variables, Wheat Productivity, and Economic Efficiency Indicators in the Kostanay Region, 1990–2023 [24, 25, 26]

Figure 11 presents a heatmap of the correlation relationships between climatic and economic indicators for the Kostanay region over the period 1990-2023. A diagonal scale from -1 to +1, is used, where red indicates a positive correlation and blue indicates a negative correlation.

To construct a predictive model for forecasting wheat yield in the Kostanay region, the following key variables were selected (based on correlation values  $\geq 0.4$ ). [

Table 5 – Variables included in the predictive model for forecasting wheat yield in the Kostanay region.

Indicators	Correlation coefficient	Degree of dependence
Profitability of wheat production and cultivation, %	+0,90	Very strong
Precipitation in July, mm	+0,89	Very strong
Annual total precipitation	+0,72	Very strong
Profit per 1 centner of wheat grain, tenge	+0,66	Strong
Precipitation in June, mm	+0,56	Moderately positive
Precipitation in May, mm	+0,42	Moderately positive
Precipitation in December, mm	-0,48	Moderately negative

Algorithm for applying the proposed model in the agricultural sector of the economy.

1. Collection of required data:

- long term forecasts of precipitation and temperature;
- data on actual soil moisture recharge prior to the start of the sowing campaign.;
- expected scenario of precipitation distribution;
- selection of agricultural technology (traditional water saving or intensive selection of crop varieties and configuration of machinery and equipment);

2. Calculation of variables: based on climate models and current data the values are calculated as follows,  $P_{july}$ ,  $T_{summer}$ ,  $I_{precip}$ ,  $C$ .

3. Yield forecasting: based on the calculated values, the model equation is constructed and solved to obtain a yield forecast with an accuracy of  $\pm 1-2$  centners per hectare.

4. Forecasting economic indicators:

- based on the generated yield forecast, agricultural producers can estimate the expected profitability of production;
- formulate an optimal procurement plan for fuels and lubricants, fertilizers, equipment and machinery;
- developed logistics for sowing and harvesting operations;
- assess market related risks;
- mitigate risks associated with farming in a risk prone agricultural zone.

Based on data collected for the period 1990-2024, the predictive model takes the following form:

$$Y = 14,81 + 0,114 \cdot P_{july} - 0,471 \cdot T_{summer} - 2,22 \cdot I_{precip} + 1,75 \cdot C \quad (1)$$

Where:

- +0,114 c/ha for each additional mm of precipitation in July;
- 0,471 c/ha free extra degree of summer temperature, indicating that overheating reduces yields by suppressing plant growth.;
- 2,22 c/ha with an increase in the precipitation irregularity index, emphasizing the importance of stable precipitation.

+1,75 centners/ha when applying more productive in climate-resilient agricultural technology.

**Discussion and Conclusion** The results of the correlation analysis confirm the central hypothesis of this study: climatic parameters – particularly precipitation and air temperature during the summer period – have a significant impact on wheat yield in the Kostanay Region, which is classified as a high-risk farming zone. The high-risk farming zone of Northern Kazakhstan has been the focus of close scientific attention, primarily due to persistent fluctuations in weather conditions. The scientific and practical significance of these findings increases in the context of global climate change, which has led to more pronounced fluctuations in weather conditions. The study established a strong positive correlation between July precipitation and wheat yield ( $r=0,889$ ), indicating a critical dependence of the vegetation period on adequate moisture availability. It was also found that the amount of accumulated moisture during the autumn-winter period ( $r=0,724$ ) is an important parameter affecting yield, particularly during the germination and early sprouting phases. In addition, precipitation in June showed a moderate positive correlation with yield. As the study revealed, the uneven temporal distribution of precipitation – for example, excessive rainfall during the sowing campaign (which hampers agrotechnical operations scheduled within fixed timeframes) and drought in July during the grain formation phase – ultimately has a negative impact on wheat yield.

Summer air temperature exhibition a negative correlation with wheat yield ( $r=-0,61$ ), which can be attributed to temperature stress on plants. When air temperatures consistently exceed  $+30^{\circ}\text{C}$  and precipitation levels are minimal, wheat yield declines to as low as 7 centners per hectare. These findings are consistent with long-term agroclimatic observations and are highly relevant for developing adaptation strategies under climate change conditions aimed at increasing the resilience of agricultural production.

From an economic perspective, a strong positive relationship was identified between wheat yield and production profitability ( $r= 0,90$ ). This indicates that yield function not only as an agrotechnical and agrotechnological indicator, but also as a key economic indicator of the performance efficiency of agricultural enterprises. High yields contribute to lowering the unit cost of production by spreading fixed costs over a larger output volume, while simultaneously increasing profit per unit of output. At the same time, an inverse relationship was found between yield and market price at the intra-seasonal level, reflecting the price formation mechanism under conditions of increased or surplus supply.

However, an analysis of trends over the period from 1990 to 2024 reveals distortions in these relationships. This can be attributed to the influence of macroeconomic factors such as inflation, currency devaluation, shifts in agricultural policy, structural changes in agricultural production, and the broader transition from a centrally planned Soviet economy to a market-based model. Therefore, adequate predictive modeling must account not only for climatic and environment variables, but also for economic indicators – particularly profitability – as a direct measure of production efficiency.

A more in-depth, long-term analysis incorporating macroeconomic indicators will be undertaken and presented in a subsequent scientific publication. In summary, the findings confirm the feasibility and relevance of developing a predictive model for wheat yield (as the region's principal grain crop), with climate parameters serving as key predictors. Such a model may be useful both for long-term planning in the agricultural sector and for adapting production processes to climate-related risks. Moreover, the model demonstrates high predictive capacity, enabling a shift from retrospective statistical analysis to the strategic decision-making level. This is particularly important in the context of climate change, volatile market prices, and fluctuating production costs in high-risk farming zones.

**Funding:** This research is funded by the Ministry of Science and Higher Education of the Republic of Kazakhstan within the framework of the following project: AP25794477 Development and scientific justification of adaptive strategies using predictive models to increase agricultural resilience under climate change conditions. Priority: Sustainable development of the agro-industrial complex, agreement No. 56ЖФ-25-27, dated 27 February 2025, within the framework of grant funding for research by young scientists under the "Zhas Galym" project for 2025-2027.

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